AWS Welding Handbook

Seventh Edition

Fundamentals of Welding

Welding Handbook

Seventh Edition, Volume 1

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Fundamentals of Welding

The Five Volumes of the Welding Handbook, Seventh Edition

1 Fundamentals of Welding

2 Welding Processes—

Arc and Gas Welding and Cutting,
Brazing, and Soldering

3 Welding Processes—

Resistance and Solid State Welding
and Other Joining Processes

4 Engineering Applications—Materials

5 Engineering Applications—Design

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Foreword

For those involved in the welding industry, 1976 marks not only the 200th birthday of the United States, but also the beginning of the Seventh Edition of the *Welding Handbook.* The need for a revised, updated *Handbook* has probably never been greater. During the period to be spanned by the Seventh Edition, welding manufacturers and fabricators will continue to face complex problems including product safety and liability, energy depletion, potential shortages of materials, availability of trained and qualified labor, and the rising cost of practically every aspect of production. This new edition is therefore offered as an aid to the user and producer of welded products in the beginning of the nation's third century. This edition should provide them with the information and reference material they will need as well as possible answers to some of the problems they will be confronting.

The Welding Handbook Committee has prepared an outline of the Seventh Edition based on its evaluation of the Sixth Edition and the anticipated needs of the industry. Five volumes are tentatively planned for this edition. This volume, *Fundamentals of Welding,* is the first of the five and focuses on basic welding technology. It is introduced and described in the Preface on p. xiv.

Welding and cutting processes will be covered in Volumes 2 and 3 of this edition. Volume 2 will include arc and oxyfuel gas welding, brazing, soldering, surfacing, and cutting, and Volume 3 will survey resistance and solid state welding and other miscellaneous joining processes such as electron beam and laser beam welding. In addition to basic process descriptions, each chapter will discuss equipment, materials, general applications, process parameters, welding procedure, types of welds, and weld quality.

The last two volumes will be devoted to engineering applications. Volume 4 will survey the materials used in welding in terms of their metallurgical and mechanical properties and their weldability. Volume 5 will focus on design and will present chapters on engineering applications, automation and control, safety and inspection, and economics and cost estimating.

In addition to outlining the contents of the Seventh Edition, the Handbook Committee also set up some guidelines for organizing and writing Handbook chapters and for presenting each volume in the most coherent manner possible. Their goals include—

- A fresh approach to each chapter with the introduction of new and important information
- Concise, well organized presentation of topics

- Inclusion of as much tabulated and factual (objective) information as possible
- Good reference material for each chapter
- A high degree of cross-referencing between *Handbook* volumes and chapters with a minimum of overlap and repetition
- A more useful index for each volume

The Committee has also recommended some format changes in the Seventh Edition which are reflected in the present volume. For one thing, the pages in each *Handbook* volume will now be numbered consecutively from beginning to end. This replaces the old practice of numbering the pages in each chapter as a separate unit and should help the reader find information more quickly and easily.

Another change involves the presentation of reference material. While the Committee stressed the need to condense *Handbook* data, it also felt the *Handbook* should be a good cross-reference to other important and more detailed publications. Recognizing that the *Handbook* can be neither timeless nor all-encompassing, the Committee requested each chapter chairman to compile lists of pertinent, up-to-date references for his chapter. These references should guide the *Handbook* user to other important documents such as codes, specifications, and technical reports and should supply him with the latest information on standardizing, qualifying, and controlling welding processes and materials. This reference material will take two forms: A Supplementary Reading List which will appear at the end of each chapter and an optional Reference List, also at the end of the chapter, corresponding to internal text references. (In this volume, Chapters 5 and 6 contain both types of bibliographical material.)

Another feature of the Seventh Edition is the use of metric units as the primary system of measurements in text, figures, and tables. This reflects the policy adopted by AWS for all its technical publications and is a response to the needs of an industry rapidly converting to the metric system. The metric units to be used in the Seventh Edition are those of the Système International d' Unités (SI) which is the internationally accepted metric system. SI units will be given first in text to be followed parenthetically by U.S. customary units. In tabular material, SI and U.S. units will be given in separate columns. As for figures, those that are not dual dimensioned will be accompanied by tables giving SI and U.S. customary equivalents.

As already mentioned, the Handbook Committee is anxious to implement a better system of indexing for the Seventh Edition. Since the *Handbook* is primarily a reference book, its usefulness is largely dependent on the ease with which the reader can locate the information he is looking for. Obviously, a thorough and well-organized index is essential. The Committee's aim is to present such an index for each volume. In addition, each volume will contain a running, cumulative index of all volumes published up to that point. This means that Volume 2 will contain a composite index for both Volumes 1 and 2 and so on through the publication of Volume 5 which will contain a composite index for the entire edition.

In developing plans for the Seventh Edition, the Handbook Committee is breaking with some long established traditions. In this regard, the Committee members urge *Handbook* readers to keep their copies of earlier editions because they contain data that may not be repeated in the Seventh Edition. This new edition will provide what the Committee judges to be the latest and most essential information available; it will *not* contain, for instance, information about lesser used or obsolete welding processes or specific welding applications such as industrial piping and automotive products.

Perhaps the greatest difficulty in publishing the *Handbook* is to recognize the needs of the individuals who will use it. Pinpointing the *Handbook* readership is a very complex task. Nevertheless, a decision had to be made regarding the level to which this publication would be aimed. Catering to engineers at the expense of shop or supervisory personnel or vice versa would be grossly unfair. The intent of the Committee is, therefore, to appeal to a large and diverse group by including information ranging from factual shop data to explanations of intricate processes and material properties.

This foreword would not be complete without acknowledging all the contributors to Volume 1 of the Seventh Edition. The authors of the chapters—the chapter chairmen and their committees—had an especially difficult task because they were actually writing new chapters rather than just updating old ones. In addition, individuals outside the chapter committees were contacted to review chapters and offer comments and suggestions. All of these participants were very generous in applying their own valuable time and creative ability to an often unrewarding and laborious assignment. The companies who supported these individuals also deserve mention. They not only contributed personnel to this project, but made their research and production information available for *Handbook* use. And so to all these contributors, the members of the Welding Handbook Committee extend their sincere appreciation.

The success of future Seventh Edition volumes is directly dependent upon the voluntary effort of qualified individuals such as those just mentioned. It is therefore appropriate to introduce the Seventh Edition by informing all of you of our urgent need for contributors to forthcoming volumes. The Handbook Committee hopes that you will step forward voluntarily or when requested to participate in creating this very important and unique publication—the *Welding Handbook.*

STANLEY WEISS
Chairman, Welding Handbook
Committee

Preface

The present volume on welding fundamentals deals only with the basic technology of welding. The practical applications of this technology will be taken up in later volumes. The traditional "first volume" chapters such as physics of welding, welding metallurgy, mechanical testing, and residual stresses and distortion are of course included, but most of the material in these chapters is new (that is, not extracted from the previous Sixth Edition volume). In addition, two new chapters have been added, one on heat flow in welding and one presenting a concise survey of the major joining and cutting processes. The latter chapter is less theoretical in nature than the others, but it is still essential basic information for someone starting out in the field. A capsuled, but comprehensive process survey of this type has not appeared in the *Handbook* previously.

Two appendices, extracted from documents prepared by the AWS Committee on Definitions, Symbols and Metric Practice, are included at the end of this volume. Appendix A presents a glossary of welding terms and definitions. Appendix B is a guide to the use of metrication in the welding industry. The recommendations outlined in it have been followed in "metricating" Volume 1.

The contributors to Volume 1 selected their topics and data carefully in the hope that approximately nine years from now, when this volume is superseded, the information presented here would not be drastically out of date. Consequently, we may have skirted with danger in a few cases by introducing or expanding discussions of somewhat controversial topics such as linear elastic fracture mechanics and vibratory stress relief. However, we felt it was important to present not only the traditional aspects of welding fundamentals, but those fields that will be gaining prominence in the near-decade to come. (We did not forget the classics, however. For example, the iron-carbon phase diagram and the Charpy V-notch test results are also included.)

We have also tried to give the *Handbook* an up-to-date appearance by using contemporary typefaces (and typesetting methods) and have introduced a new two-column page format. The two-column page format offers two advantages: It is more economical because it allows for about 20 percent more type characters per page and it is easier to read because the length of each text line is shorter.

As already mentioned in the Foreword, Volume 1 is dual dimensioned throughout with SI (metric) units the primary measurements and U.S. customary units the secondary measurements. This system, though essential in keeping abreast of the fast approaching switch to SI in the industry, posed some unique problems in both the selection and presentation of units. For instance, those who are accustomed to calculating the heat of chemical reactions in the calorie—a non-SI metric unit—will no doubt be surprised and probably not pleasantly so to find that these calculations are, in Volume 1, given in kilojoules. (See Chapter 2, pp. 42-43.)

Mathematical equations and formulas presented an even more perplexing problem in terms of dual dimensioning. In Volume 1 equations containing units of measurement, the original units (even if U.S. customary) have been retained in most cases to avoid changing coefficients. However, alternate versions of the equations using SI units have often been supplied. Where a series of calculations have been involved, only the final numerical result has been given in dual units.

As pointed out in both the Foreword and this preface, we are instituting a number of changes in the Seventh Edition starting with this volume. Changes, even though necessary, usually do not come about painlessly, and we are anxious to know how you feel about them. We welcome your comments on this volume as well as (and perhaps especially) on our plans for the other volumes in the Seventh Edition. Please address your comments to: Editor, *Welding Handbook,* American Welding Society, 2501 Northwest Seventh Street, Miami, Florida 33125.

Charlotte Weisman, *Editor*

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Survey of Processes for Joining and Cutting Materials

Prepared by a committee consisting of:

A. LESNEWICH, *Chairman*
Airco Welding Products
E. M. BREINAN
United Aircraft Research Lab
J. M. GERKEN
TRW, Inc.
R. L. PEASLEE
Wall Colmonoy Corp.
K. E. RICHTER
Union Carbide Corp.
R. K. SAGER, JR.
Aluminum Company of America

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Survey of Processes for Joining and Cutting Materials

INTRODUCTION

The purpose of this chapter is to introduce the conventional, better known joining and cutting processes to readers with minimal knowledge of the process(es) of interest and to provide insights into their selection and use. The chapter identifies the distinguishing features of the various processes as well as their attributes and limitations and draws comparisons where applicable. Operational characteristics, power requirements, pertinent welding skills, and cost considerations along with possible material and material thickness applications are discussed. It should be recognized, however, that the material presented in the chapter is a generalization of the subject and should not be considered the final source of information for selecting any process for specific applications. Where specific information and data are needed, the reader must consult additional sources including those appended to this chapter and other volumes of the *Handbook*.

Since the arc welding group of joining processes is by far the most widely used in the industry, it is accorded the most attention. Other well known and often used joining processes discussed in the chapter are oxyfuel gas welding, resistance welding, flash welding, brazing, and soldering. Diffusion, friction, electron beam, and laser beam welding along with adhesive bonding are also included because of their growing popularity and increasing value to the industry. However, ultrasonic welding, explosive welding, and surfacing, though important in highly specialized areas, are omitted from this chapter because of their narrow field of application. Finally, a section of the chapter is devoted to thermal cutting processes. Descriptions of several common methods of severing and removing metals are included.

Relatively few individuals develop an expertise in the use of all processes and probably no one has had the occasion to cut or join all of the currently available engineering materials. The goal of the chapter, therefore, is to familiarize readers with all the major contemporary processes so that consideration may be given to those processes that might otherwise be overlooked.

Frequently, several processes can be used for any particular job. The major problem is to select the one that is the most suitable in terms of technical requirements and cost. These two factors, however, may not be totally compatible, thus forcing a compromise. Selection of a process can depend on the number of components being fabricated, the acceptability

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Note: The SI (metric) and U.S. customary values given in this chapter are not, in most cases, exact equivalents. The SI values are the primary measurements used in this and all Volume 1 chapters. The secondary U.S. measurements (given parenthetically) are rounded off conversions from the SI values. For a further explanation of the system of measurements used in Volume 1, refer to the Foreword on p. xi.

of initial costs, joint location, structural mass, desired performance of the product, and so forth. The adaptability of the process to the location of the operation or the type of shop and the experience and abilities of the employees may also have impact on the final selection. These considerations are touched upon as they relate to the different processes.

The text of this chapter is complemented by Tables 1.1 (for joining) and 1.2, (for cutting). Table 1.1 indicates by "X" marks, the process, material, and material thickness combinations that are usually compatible. The left-hand column of the table lists a variety of engineering materials and four arbitrary thickness ranges. The major processes currently used by industry are listed across the top. Table 1.2, p. 30, for cutting is presented in a similar format and indicates the applicability of several major cutting processes to materials. These tables should be regarded as only general indicators, however, the combinations they suggest may not necessarily be valid for specific situations. Nevertheless, the information presented can serve as a guide in screening processes for a joining or cutting requirement.

ARC WELDING *

The term arc welding applies to a large and diversified group of welding processes that use an electric arc as the source of heat to melt and join metals. The formation of a joint between metals being arc welded may or may not require the use of pressure or filler metal.**

The arc is struck between the workpiece and an electrode that is manually or mechanically moved along the joint or that remains stationary while the workpiece is moved underneath it. The electrode will be either a consumable wire or rod or a nonconsumable carbon or tungsten rod which serves to carry the current and sustain the electric arc between its tip and the workpiece. When a nonconsumable electrode is used, a separate rod or wire can supply filler metal if needed. The consumable electrode, however, will be specially prepared so that it not only conducts the current and sustains the arc but also melts and supplies filler metal to the joint and may produce a slag covering as well.

The major arc welding processes and their unique features are described in the following pages.

SHIELDED METAL ARC WELDING†

Shielded metal arc welding (SMAW) is one of the oldest arc welding processes. It is also the simplest and perhaps the most versatile for welding ferrous base metals. The process uses a covered electrode consisting of a core wire around which a clay-like mixture of silicate binders and powdered materials (such as fluorides, carbonates, oxides, metal alloys, and cellulose) is extruded and baked to produce a dry, hard, concentric covering. This covering is a source of arc stabilizers, gases to exclude air, metals to alloy the weld, and slags to protect and support the weld.

The electrode is clamped in an electrode holder which is joined to the power source by a cable. The arc is initiated by touching the electrode tip against the work and then withdrawing it. The heat of the arc melts the base metal in the immediate area, the electrode metal core, and the electrode covering. The alloy produced from the molten base metal, core wire, and metal powders in the covering freezes to form the weld.

Covered electrodes are produced in a variety of diameters normally ranging from 2 to 6 mm (3/32 to 1/4 in.). The smaller diameters are used with low currents for join-

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*Arc welding is also discussed under "Electrical Sources of Welding Energy" in Chapter 2, p. 38.

**Although pressure is not generally used in arc welding processes, stud welding is one arc welding process that does require pressure. Stud welding is not covered in this chapter, but it is covered in Chapter 30, Section 2 of the *Welding Handbook*, Sixth Edition, and will tentatively be covered in Volume 2, Seventh Edition.

†Chapter 22 in Section 2 of the *Welding Handbook*, Sixth Edition covers this process in detail. In the Seventh Edition, a chapter covering SMAW is tentatively set for Volume 2.

Table 1.1—Overview of Joining Processes*

Material	Thickness	Joining Process																									
				GMAW																B							
		SMAW	SAW	ST	B	P	S	FCAW	GTAW	PAW	ESW	EGW	RW	FW	OFW	DFW	FRW	EBW	LBW	TB	FB	IB	RB	DB	IRB	DFB	S
Carbon Steel	S	X	X			X	X		X				X	X	X			X	X	X	X	X	X	X	X	X	X
	I	X	X	X	X	X	X	X	X				X	X	X		X	X	X	X	X	X	X	X		X	X
	M	X	X	X	X	X		X					X	X	X		X	X	X	X	X	X				X	
	T	X	X	X	X	X		X			X	X		X	X		X	X			X					X	
Low Alloy Steel	S	X	X			X	X		X				X	X	X	X		X	X	X	X	X	X	X	X	X	X
	I	X	X	X		X	X	X	X				X	X		X	X	X	X	X	X	X				X	X
	M	X	X	X		X		X						X		X	X	X	X	X	X	X				X	
	T	X	X	X		X		X			X			X		X	X	X			X					X	
Stainless Steel	S	X	X			X	X		X	X			X	X	X	X		X	X	X	X	X	X	X	X	X	X
	I	X	X	X		X	X	X	X	X			X	X		X	X	X	X	X	X	X				X	X
	M	X	X	X		X		X		X				X		X	X	X	X	X	X	X				X	
	T	X	X	X		X		X			X			X		X	X	X			X					X	
Cast Iron	I	X													X					X	X	X				X	X
	M	X	X	X				X							X					X	X	X				X	X
	T	X	X	X				X							X						X					X	
Nickel and Alloys	S	X				X	X		X	X			X	X	X			X	X	X	X	X	X	X	X	X	X
	I	X	X	X		X	X		X	X			X	X			X	X	X	X	X	X				X	X
	M	X	X	X		X				X				X			X	X	X	X	X					X	
	T	X		X		X					X			X			X	X			X					X	
Aluminum and Alloys	S			X		X			X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	I			X		X			X				X	X		X	X	X	X	X	X			X		X	X
	M			X					X					X			X	X		X	X			X		X	
	T			X							X	X		X				X			X					X	
Titanium and Alloys	S					X			X	X			X	X		X		X	X		X	X			X	X	
	I			X		X			X	X				X		X	X	X	X		X					X	
	M			X		X			X	X				X		X	X	X	X		X					X	
	T			X		X								X		X		X			X					X	
Copper and Alloys	S					X			X	X				X				X		X	X	X	X			X	X
	I			X		X				X				X			X	X		X	X		X			X	X
	M			X										X			X	X		X	X					X	
	T			X										X				X			X					X	
Magnesium and Alloys	S					X			X				X					X	X	X	X			X		X	
	I			X		X			X				X	X			X	X	X	X	X			X		X	
	M			X		X								X			X	X	X		X					X	
	T			X		X								X				X									
Refractory Alloys	S					X			X	X			X	X				X		X	X	X	X		X	X	
	I			X		X				X				X				X		X	X					X	
	M													X													
	T																										

*This table is presented as a general survey only. In selecting processes to be used with specific alloys, the reader should refer to other appropriate sources of information.

LEGEND FOR TABLE 1.1

Process Code

SMAW–Shielded Metal Arc Welding
SAW–Submerged Arc Welding
GMAW–Gas Metal Arc Welding
  **ST–Spray Transfer
  **B –Buried Arc
  **P –Pulsed Arc
  **S –Short Circuiting Arc
FCAW–Flux Cored Arc Welding
GTAW–Gas Tungsten Arc Welding
PAW–Plasma Arc Welding
ESW–Electroslag Welding
†EGW–Electrogas Welding

RW–Resistance Welding
FW–Flash Welding
OFW–Oxyfuel Gas Welding
DFW–Diffusion Welding
FRW–Friction Welding
EBW–Electron Beam Welding
LBW–Laser Beam Welding
B–Brazing
  TB–Torch Brazing
  FB–Furnace Brazing
  IB–Induction Brazing
  RB–Resistance Brazing
  DB–Dip Brazing
  IRB–Infrared Brazing
  DFB–Diffusion Brazing
S–Soldering

Thickness

S –Sheet: up to 3 mm (1/8 in.)
I –Intermediate: 3 to 6 mm (1/8 to 1/4 in.)
M–Medium: 6 to 19 mm (1/4 to 3/4 in.)
T–Thick: 19 mm (3/4 in.) and up
X–Recommended

**Not standard AWS letter designations. Pulsed arc and short circuiting arc are officially designated GMAW-P and GMAW-S respectively, but for brevity, the designations are given here as P and S. There are no official designations for spray transfer and buried arc.

†Not standard AWS letter designation. Electrogas welding is a process variation of GMAW and FCAW and should be designated as either GMAW-EG or FCAW-EG. (See discussion of electrogas welding on p.12.) For brevity, however, electrogas welding is designated as EGW here.

ing sheet and for welding in all positions. The larger diameters are designed for conducting high currents to achieve greater deposition rates in the flat and horizontal positions. Special alloy filler metal compositions can be formulated with relative ease by the electrode manufacturers.

The SMAW process has several advantages. Using the process, job shops can handle most welding problems with a relatively small variety of electrodes in their inventory. Another advantage is the simplicity and lightness of equipment.

An alternating current (ac) or direct current (dc) power supply, power cables, and an electrode holder are all that are normally required. The power supply can be connected to a primary line providing about ten kilowatts (kW) or less, or a gasoline engine driven power source can be used when portability is necessary. Also, welds can be made in confined locations or remote from heavy power supplies. For these reasons, the SMAW process has continued to dominate the construction, pipeline, and shipbuilding industries. Uncomplicated, portable rigs are in common use for maintenance and field construction work.

The total cost of a typical production package ranges from slightly under $500 to slightly more than $1000 although portable, engine driven systems cost substantially more.*

Some of the heavily covered electrodes, sometimes called "drag rods," are easily mastered for making welds in the flat and horizontal positions because they are allowed

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*Cost information given on SMAW and all other arc welding processes reflects 1974 prices.

to touch the plate. A sizeable tonnage of weld metal is deposited by relatively unskilled assembly line welders. Electrodes designed for all-position welding must be used by skilled individuals or the weld quality and soundness may be impaired. Such skills cannot be developed quickly and not all welders acquire the manual dexterity needed to weld in all positions. Equipment costs and maintenance are minimal since the power supplies are quite simple and reliable, and the holders are only slightly more complicated than a pair of pliers.

The SMAW process is suitable for joining metals in a wide range of thicknesses, but normally is best suited for a thickness range of 3 to 19 mm (1/8 to 3/4 in.). However, electrodes are frequently used for welding heavy-walled components which cannot be positioned for flat or horizontal welding, even though the deposition rates are lower in other positions. Sections thinner than 3 mm (1/8 in.) can be joined, although substantial skill is required as the thicknesses decrease. Butt joints in plate material are normally beveled to allow proper access to the root of the joint. Fillet welds are very easy to make, particularly with heavily covered electrodes. Surfacing is a common application of the SMAW process.

The typical current range used for SMAW is between 50 and 300 amperes (A), although some special electrodes are designed to be used with currents as high as 600 A, and others as low as 30 A, allowing weld metal deposition rates between 1 and 8 kg/h (2 and 17 lb/h). It is possible to deposit 4.5 kg (10 lb) per man hour in the flat position. However, a welder normally is not able to deposit more than 3.6 to 4.5 kg (8 to 10 lb) per day in all-position welding because small diameter electrodes and low currents are used and considerable manipulation is necessary. Also, cleaning of the slag covering of the weld joint is required after each pass. As a result, labor costs are high. Material costs are also high since less than 60 percent of the weight of the purchased electrodes is deposited as filler metal. However, in spite of these deficiencies, SMAW maintains a position of dominance because of its simplicity and versatility and because so many welders and engineers are comfortable with the process due to long experience with it.

SUBMERGED ARC WELDING*

In submerged arc welding (SAW), the arc and molten metal are shielded by an envelope of molten flux and a layer of unfused granular flux particles. When the arc is struck, the tip of the continuously fed electrode is submerged in the flux and the arc is therefore not visible. The weld is made without the intense radiation that characterizes the open arc processes and with little fumes.

The SAW process is used in both mechanized and semiautomatic operations, although the former is by far more common. High welding currents can be employed, providing substantial cost savings due to high metal deposition rates and low labor costs. Welds can be made in the flat and horizontal positions only.

Mechanized equipment systems utilize from 600 to 2000 A power sources, automatic wirefeed and control, and a system to propel electrode feeders such as a four-wheeled carriage or a moving component fixture. Standard three-phase primary voltage lines supply the main power systems. When single phase is required, it normally is derived from one phase of the three-phase line. Three-phase 220/440 volt (V) and single-phase 440 V systems are used.

Although a welding system can be purchased for under $2000, a majority of single electrode mechanized systems are in the $2000 to $10,000 range. Multiwire systems and systems installed on large fixtures could cost in excess of $50,000.

For mechanized equipment, welding operators can be trained to produce consistently high quality welds with a minimum of manual skill. Semiautomatic systems are also readily mastered, and the welding operator is not troubled by welding fumes or encumbered with dark face shields and protective clothing.

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*Chapter 24 in Section 2 of the *Welding Handbook*, Sixth Edition covers this process in detail. In the Seventh Edition, a chapter covering SAW is tentatively set for Volume 2.

The SAW process is useful for welding both sheet and plate. In welding relatively thin materials, speeds of up to 84 mm/s (200 in./min) can be achieved while high metal deposition rates (27 to 45 kg/h [60 to 100 lb/h]) and reliability are the advantages for heavy sections.

Many types of joints can be welded using the SAW process. Deep joint penetration can be achieved with direct current electrode positive (dcep). Therefore, the need for plate beveling is minimal. Joint fitup should be consistently tight to maximize the advantages of the SAW process and to minimize melt-thru. Seal passes deposited with SMAW or gas metal arc welding (GMAW) are effectively employed on poorly fitted joints prior to finishing with SAW. Joints may also be backed with copper bars, flux, various types of tape, or integral steel members.

The process is most widely employed for welding all grades of carbon, low alloy, and alloy steels. Stainless steel and some nickel alloys are also effectively welded or used as surfacing alloys with the process. Various filler metal-flux combinations may be selected to provide specific weld metal properties for the intended service. The flux may be highly reinforced with alloying elements. In general, one pound of flux is consumed for every pound of wire used.

If the particular job requires repetition, the highest percentage arc time possible, and consistent weld quality, a mechanized system is justified and the SAW process should be considered. In general, if the job can be performed with SAW, this process will be among the least expensive in terms of cost related factors such as welding speed, materials, equipment costs, and reliability.

GAS METAL ARC AND FLUX CORED ARC WELDING*

Gas metal arc welding (GMAW) and flux cored arc welding (FCAW) are classified by AWS as two separate processes, but because of their many similarities in application and equipment, it is useful to discuss them together. Both processes use a continuous wire or tubular filler metal to serve as a source of weld metal and as a terminal for the electric arc, and both use gas to shield the arc and weld metal. However, with GMAW, the electrode is solid and all of the shielding gas is supplied by an external source. With FCAW, the electrode is tubular and may be the source of some or all of the gas shielding needed. The flux cored arc welding process may use auxiliary shielding depending on the type of electrode employed, the material being welded, and the nature of the welding involved. Flux cored arc welding with a shielding gas is considered to be GMAW by the ASME Boiler and Pressure Vessel Code.

The shielding gases used by both processes have a dual purpose of protecting the arc and weld zone from air and providing the arc characteristics desired. A variety of gases are used depending on the metal reactivity and nature of the joint being welded. Also, a variety of power supplies have been developed to expand the versatility of the two processes.

Gas Metal Arc Process Variations

In GMAW, the common variations of shielding gases, power supplies, and electrodes have significant effects resulting in several different and important process variations. These variations can be designated by the nature of the shielding gas: argon which is inert and can be used to weld all metals, or carbon dioxide which can be either oxidizing or oxidizing and carburizing. They also can be designated by mode of metal transfer** from electrode to work as follows: spray transfer, buried arc, pulsed arc (GMAW-P), and short circuiting arc (GMAW-S). The first two of these require high currents while the latter two commonly are used with low average currents. The spray transfer and pulsed arc process

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*GMAW and FCAW are covered in detail in Chapter 23, Section 2 and Chapter 58, Section 3B respectively of the *Welding Handbook*, Sixth Edition. In the Seventh Edition, chapters covering these processes are tentatively set for Volume 2.

**For a thorough explanation of metal transfer, refer to Chapter 2, p. 59.

variations require argon-rich gas mixtures; the buried arc and short circuiting arc variations require carbon dioxide or carbon dioxide in gas mixtures.

Taken as a group, the GMAW process variations can be used to join virtually any metal in any type of joint configuration, and in any position. However, taken individually the variations have specific advantages and limitations.

Spray Transfer. Spray transfer is unique in arc welding and describes an axial transfer of small discrete drops of metal at rates of hundreds per second. Argon or argon-rich gas mixtures are necessary to shield the arc. Direct current electrode positive is almost always used and must be above a critical value proportional to the electrode diameter. The metal transfer is very stable, directional, and essentially spatter free.

Argon or argon-helium mixtures are used when joining reactive metals such as aluminum, titanium, and magnesium. However, when welding ferrous metals, small amounts of oxygen or carbon dioxide need to be added to these mixtures to prevent undercut and irregular welds. Unfortunately, the high arc energy associated with spray transfer limits the effectiveness of this process variation for joining thin sections or for welding steels in the vertical or overhead positions. However, it is used extensively for welding almost all metals and alloys including reactive metals such as aluminum, titanium, and magnesium in the flat and horizontal positions. Some of these materials cannot be welded with processes that are not shielded with inert gases.

Buried Arc. In the buried arc process variation, carbon dioxide-rich gases are used to shield the arc and welding zone. With these gases, spray transfer cannot be obtained at any current level. Instead, the transfer is essentially globular and, due to arc forces and uncontrolled short circuits, considerable spatter is produced, even when the arc is buried in its own crater.

Carbon dioxide is also reactive, so its use is limited to steels which can be properly alloyed to tolerate an oxidizing atmosphere and to those which do not have to be essentially free of carbon as, for example, low carbon stainless steels. However, the buried arc process variation permits much higher welding speeds than possible with argon, making it effective and relatively inexpensive for many mechanized or repetitive manual operations such as those common in the automotive industry. The arc is also more penetrating due to the high current ranges used.

Pulsed Arc. If intermittent, high amplitude pulses of current are superimposed on a low level steady current, the average current can be reduced appreciably while producing a metal spray transfer during the pulse intervals. Argon-rich gases are essential to achieve the spray. This type of metal transfer, produced through the utilization of a unique power supply, characterizes the pulsed arc process variation. With it, reasonably large electrode diameters can be employed to weld thin as well as heavy sections, in all positions and for many base metals.

Proper handling of the power supply may require additional training. Also, more skills are needed to achieve the weld quality possible with pulsed arc welding when used in all positions than with spray transfer welding in the flat position.

Short Circuiting Arc. The need for relatively high currents with either the spray transfer or buried arc process variations minimizes their applicability. Neither can be used to weld thin sections because the arc penetrates too deeply, and the deposition rates are too great to control a weld pool in vertical or overhead welding positions. However, with short circuiting arc welding the average current and deposition rates can be reduced by using power supplies which allow metal to be transferred only during intervals of controlled short circuits occurring at rates in excess of 50 per second. The short circuiting arc can be used to weld thin sections in all positions. This process variation has the advantage of being very easy to use, but unfortunately, because the energy input is low, incomplete fusion defects can be a problem when welding sections thicker than 6 mm (1/4 in.). Good welding technique is very important when welding these thicker sections.

Flux Cored Arc Welding

Flux cored arc welding uses cored electrodes instead of solid electrodes for joining ferrous metals. Minerals and ferro alloys in the core provide additional protection and help control the weld contour. Many cored electrodes are designed to be used with carbon dioxide-rich gases. Weld metal can be deposited at higher rates, and the welds can be larger and better contoured than those made with solid electrodes, regardless of the shielding gas.

Another family of cored electrodes is the "self shielded" variety. These electrodes are designed to produce their own protective environment and do not require an external source of gas. However, the FCAW gas shielded electrodes generally produce tougher welds than the self shielded and are easier to use in all positions. By controlling the ionizable materials in the core, the process can employ either dcep or dcen (direct current electrode negative). The self shielded electrodes can be used in drafts with minimal consequences resulting from the shield stream blowing away from the arc. The self shielded FCAW process is commercially available with mild steel, austenitic stainless steel, and nickel-iron filler metals.

Equipment Requirements

All of the GMAW process variations and FCAW, with few exceptions, use similar equipment which requires the following:

(1) A variable speed motor and motor control to power feed rolls which drive the electrode at a preset and uniform rate.

(2) A "gun" which houses a "trigger" to initiate and stop the electrode feed and flow of gas, electrical current to the arc, and, if used, water for cooling the torch; a nozzle which directs the shielding gas to the arc and weld pool (except for self shielded FCAW); a contact tube at the axis of the nozzle to transfer welding current to the electrode, and a system of cables, hoses, electrical connections, and casings to direct the gas, electrode, power, and water if used.

(3) A mount for the spooled or coiled electrode.

(4) A control station containing the relays, solenoids, and timers needed to integrate the system.

(5) A source of shielding gas, if needed, and a device for metering the flow rates of the gas.

(6) A power supply to provide an appropriate amount and type of current.

(7) A water supply for cooling if necessary.

The equipment described can be adapted for use in semiautomatic welding, or mounted on fixtures for automatic or machine welding. The cost of the equipment varies but in general it is in the range of $1000 to $2000. The power supplies for pulsed arc welding are more expensive than the conventional, raising the cost of pulsed arc welding slightly above the $2000 mark. Power requirements range from 2 kW for short circuiting welding to 20 kW for FCAW at high deposition rates.

Less manipulative skill is needed to master these processes when compared with the SMAW process. If the welding is highly repetitive and the equipment controls are preset, only a relatively short time is needed to train a welder. The short circuiting arc process variation is quite easy to master for use in all positions. Flux cored arc welding requires somewhat more skill, especially for making vertical and overhead welds. However, it can be used to produce vertical welds at rates in excess of 2 kg/h (5 lb/h). The spray transfer and pulsed arc process variations are somewhat more difficult to use because the arc length needs to be more carefully monitored for best results. As with everything else, the most proficient welders are those who understand the equipment and variables which control processes. Acquiring such knowledge requires time and training.

A reasonable amount of preventative maintenance is required to assure that the gas passages are clear and the contact tube is not worn. The feeders and control units are unsophisticated electromechanical devices and, therefore, quite reliable. Maintenance skills can be developed easily.

As indicated in Table 1.1, the thickness of joints that can be welded depends on the process. The short circuiting arc is almost ideal for welding ferrous materials in all positions if they are thinner than 6 mm (1/4 in.) and with open root joint designs. (This process variation can be used with very few other materials, however.) The pulsed arc is used to weld sheet as thin as 1 mm (3/64 in.) as well as heavy sections of all metals in all positions. The buried arc and spray transfer process variations are restricted to welding steels in the flat and horizontal positions. Both the spray transfer and pulsed arc process variations can be used to weld aluminum alloys in all positions. Cored electrodes, 1.6 mm (1/16 in.) in diameter, are most commonly used to weld ferrous materials in all positions. Larger diameters, primarily 2.4 mm (3/32 in.), are used for flat and horizontal welding.

Every type of joint can be welded with these processes if both the appropriate process and welding conditions are selected. Tight square butt joints or lap joints rarely exceed 4.7 mm (3/16 in.). Larger butt welds need to be beveled. Fillet welds can be made very easily. Surfacing is common, particularly with mechanized equipment.

Deposition rates vary considerably depending upon the mode of metal transfer and will range from 0.5 kg/h (1 lb/h) for short circuiting arc welding to over 13 kg/h (30 lb/h) for flux cored arc welding.

In general, the GMAW and FCAW processes are the most cost effective of all welding processes using filler metals. The deposition efficiencies are particularly high, approaching 95 to 100 percent with solid electrodes (depending on the shielding gas), 85 to 90 percent with gas shielded cored electrodes, and 80 to 85 percent with the self shielded cored electrodes. Welders can work continuously with both GMAW and FCAW since the wire is fed continuously and only fatigue or changing position requires the arc to be interrupted. These processes have had phenomenal growth and should continue to be of major industrial significance.

GAS TUNGSTEN ARC WELDING

Gas tungsten arc welding uses a nonconsumable tungsten electrode for one pole of the arc which is shielded with an inert gas. The arc fuses the metal being welded as well as filler metal if it is used. The gas shield protects the electrode and weld pool and provides the required arc characteristics.

The process may employ either dcen or alternating current. In general, ac is preferred for welding aluminum and magnesium and their alloys and some grades of stainless steels. Direct current electrode negative is preferred for welding most other materials and for automatic welding of thick aluminum. Thin magnesium sometimes is welded with direct current electrode positive.

When ac is used with argon shielding, an arc cleaning action is produced at the plate surface during the half cycle when the electrode is positive. This cleaning action removes contaminants and is particularly beneficial in reducing weld porosity in aluminum when welding in the horizontal and overhead positions. When using dc, helium may be selected as the shielding gas due to its ability to produce a deeper penetrating arc. However, stringent precleaning of the aluminum and magnesium parts is required with the helium shield. The use of argon and helium mixtures for gas shielding provides some of the benefits of both gases.

Regardless of polarity, a constant current (vertical volt-ampere characteristic) welding supply is required. In addition, a high frequency oscillator is generally an integral part of the power supplies intended for GTAW. High frequency can be employed with dc to initiate the arc instead of touch starting so as to minimize tungsten electrode contamination. It is therefore normally turned off automatically after arc ignition. High frequency is employed with ac for initiating the arc and to insure its reignition at each half cycle while welding. It is usually on throughout the welding.

Some specialized power supplies provide pulsating direct current at high or low frequency. With them, better control of penetration and weld metal solidification is possible, welders can be trained more quickly, and all-position welding is easier.

A variety of tungsten electrodes are used with the process. The thoriated and zirconiated electrodes have better current carrying and electron emission characteristics than pure tungsten, making them most suitable for dc operations. The electrode is normally ground to a point or truncated cone configuration to minimize arc wandering. The pure tungsten has the poorest electron emission but causes the least current imbalance with ac welding power supplies. This is advantageous when welding aluminum and magnesium.

The equipment needed consists of a welding torch, welding power supply, and a source of inert gas with suitable pressure regulators and flowmeters. Electric power requirements depend upon the thicknesses to be welded and range from 8 kW for a 200 A dc unit to 30 kW for a 500 A ac balanced wave unit. Portable engine driven power supplies are available, as well as standard line voltage units.

A small 200 A welding equipment setup will cost about $1000 while a simple automatic unit of 500 A capacity may cost $5000. The addition of arc voltage control, slope control, and other accessories will materially increase the cost.

Gas tungsten arc welding requires more training time, manual dexterity, and operator coordination than does SMAW or GMAW. The equipment is portable and usable with all metals, in a wide range of thicknesses and in all welding positions. Arc welds of the very highest quality can be produced with the versatile GTAW process.

The process allows welding of all types of grooves and joint geometries and overlays in plate, sheet, pipe, tube, and shapes. It is particularly appropriate for welding material 1.6 to 10 mm (1/16 to 3/8 in.) in thickness and for welding pipe 25 to 150 mm (1 to 6 in.) in diameter. Thicker sections can be welded but economics generally indicate the choice of GMAW or other processes.

The combination of GTAW for root pass welding with either SMAW or GMAW is particularly advantageous for welding pipe. The gas tungsten arc provides a smooth, uniform penetration pass while the fill and cap passes are made with a more economical process.

Gas tungsten arc welding is generally more expensive than SMAW due to the cost of the inert gas, and is only 10-20 percent as fast as GMAW. However, GTAW will provide the optimum weld quality and a superior penetration bead, while accommodating a wider range of thicknesses, positions, and geometries than either SMAW or GMAW.

PLASMA ARC WELDING*

The plasma arc welding (PAW) process provides a very stable heat source for welding most metals from 0.02 to 6 mm (0.001 to 0.250 in.). The PAW process has advantages over other open arc welding processes such as SMAW, GMAW, and GTAW because it results in greater energy concentration, improved arc stability, higher enthalpy (heat content), and higher welding speeds (than with GTAW) as a result of greater penetration capabilities. In the "keyhole" mode, it also produces narrower beads (higher depth-to-width ratio) and complete joint penetration, thus resulting in less distortion.

The basic elements of the plasma arc torch are the tungsten electrode and the orifice. A small flow of argon is supplied through the orifice to form the arc plasma. The arc and weld shielding is obtained from a second gas flow through an encircling outer nozzle cup assembly. The shielding gas can be argon, helium or mixtures of argon with either hydrogen or helium. The initial plasma is formed by an internal low current pilot arc between the electrode and the orifice insert (commonly referred to as a "non-transferred"

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*Chapter 54 in Section 3B of the *Welding Handbook,* Sixth Edition covers this process in detail. In the Seventh Edition, a chapter covering PAW is tentatively set for Volume 2.

arc). The pilot arc heats the orifice gas to very high temperatures so that it becomes ionized and produces a second plasma. The second plasma forms a conductive path between the electrode and the weldment to permit instant ignition of a welding arc (between electrode and workpiece) which, in this case, is called a "transferred arc." If filler metal is used, it is fed into the arc as in the GTAW process.

Three major welding variations are possible with the PAW process. These are the needle arc, the melt-in-mode, and the keyhole-mode arc. Needle arc welding is so named because of the long "needle-like" arc generated at low currents (1 to 25 A) and is especially useful for welding thin metals (0.02 to 1.5 mm [0.001 to 0.062 in.]). Manual welding of this thickness range represents a great departure from previous practice with the GTAW process which, with the same fixturing, would have required the torch movement to be precisely mechanized. With either process, however, the weld is smooth and made without filler metal.

High current manual PAW can be done in the melt-in mode. Melt-in welds on 0.8 to 3 mm (1/32 to 1/8 in.) thick butt joints or lap joints can be used to join most materials. Titanium and other reactive metals can be joined using helium as a shielding gas. Generally, the operating current is 100 A or less.

The term "keyhole" has been applied to a penetrating hole at the leading edge of the weld puddle which flows behind the keyhole to form the weld bead. Keyholing can be obtained on most metals in the thickness range of 2.4 to 6 mm (3/32 to 1/4 in.) and is one of the chief differences between the PAW and the GTAW processes. Operating current range is typically up to 275 amperes.

The PAW process requires the following equipment: control-power supply, torch, work clamp and lead assembly, shielding gas hose, orifice gas hose, inert gas regulator, and flowmeter. The operation of this equipment may be manual or mechanized. The typical input power requirements are 115 V, ac, 60 Hz, 15 A for the needle arc process and 208/230 V, ac, 60 Hz, 3ϕ, 60 A or 460 V, ac, 60 Hz, 3ϕ, 30 A for the keyhole mode and melt-in mode.

Typical costs for PAW equipment range from under $2000 for the needle arc mode to approximately $3000 for the keyhole-mode. Welder skill and training requirements would be slightly higher than for oxyfuel gas welding (see p. 17). Maintenance skill and training would be higher than for GTAW, due mainly to the complexity of the equipment.

The welding position is mainly limited to downhand (flat) for melt-in and keyhole-mode welding. Out-of-position welding is possible with the needle arc mode. Good uniform penetration is normally obtained with PAW, and inert atmospheres at the underside of the weld help to produce high quality penetration beads. The deposition rate is low; little or no filler metal is added up to 6 mm (1/4 in.) thick on most materials. Welding speeds are between 2 and 17 mm/s (5 and 40 in./min.) depending on material and thickness. Usually, this represents a 50 to 150 percent increase over GTAW speeds on stainless steel.

ELECTROSLAG AND ELECTROGAS WELDING*

Like GMAW and FCAW, electroslag and electrogas welding are two separate processes (only the latter being an arc welding process), but because of their many similarities in equipment and application, it is useful to discuss them together. Both processes are used primarily for vertical position welding and both can be classified as machine welding processes designed to produce joints in a single pass by depositing weld metal into a cavity created by separated plate edges and water cooled molding dams or "shoes." Both processes shield the weld pool, one using molten slag and the other a gas.

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*Chapter 48 in Section 3A of the *Welding Handbook*, Sixth Edition covers ESW in detail. In the Seventh Edition, a chapter covering ESW and GMAW-EG/FCAW-EG is tentatively set for Volume 2. In this volume, ESW is also discussed under "Electrical Sources of Welding Energy" in Chapter 2, p. 40.

Electroslag welding (ESW) uses molten conductive slags to protect the weld and to melt the filler metal and the plate edges. Since solid slag is not conductive, an arc is used to initiate the process by melting the slag and preheating the plate. After reasonable equilibrium is established, the arc is extinguished and the heat produced by the slag's resistance to the flow of current is used for welding. The heat keeps the slag molten and sufficiently hot to melt the plate edges and keeps the filler metal fluid during its transfer to the weld pool. Since resistance heating is used for all but the initial source of heat, ESW is not classified as an arc welding process.

The ESW process can be used by substituting a consumable guide for the conventional current contact tube or shoe. The guide is hollow and the wire is fed through it. The consumable guide is melted in the weld, and frequently is coated with the flux needed for replenishment. When such guides are used, both they and the dams are usually stationary and the length of the guide tube is determined by the length of the weld needed. Single or multiple electrode or consumable guide ESW systems are possible depending on the plate thickness.

Unlike ESW, electrogas welding is an arc welding process because it relies on an arc to melt the plate edges and to provide the energy used to melt the electrode. A source of gas is provided to shield the arc and weld pool and produce the stable arc characteristics needed. The problem is to prevent the arc from wandering along the electrode and plate edges in narrow joints. This is done by adding carbon dioxide to argon when welding carbon steels, or by adding helium when welding stainless steels or aluminum.

Electrogas welding is officially classified by AWS as a process variation of GMAW or FCAW depending on the type of electrode used. When the electrode is solid and applied using an external source of gas shielding, the process is designated as GMAW-EG. When the electrode is flux cored, either self shielded or with a carbon dioxide shielding, the process is designated as FCAW-EG.

Both processes use machine welding equipment. Often the vertical rate of progression of the ESW equipment is monitored by the welding operator. However, the movement of the equipment can be controlled automatically with a variety of devices. The movement of the electrogas welding head is usually automatic and uses arc voltage for control although other methods can also be used. Plate sections to be joined are fixed and the welding head is moved along the joint or, for circumferential welds, the head is fixed while the vessel is rotated with its axis in the horizontal position.

The machines for both processes vary in size from light portable units weighing about 35 kg (75 lb) to the more common massive equipment which is moved by cranes from one welded joint to another. The lightweight units are self-propelled while welding. The heavier electroslag units are supported on vertical columns and move on tracks or screws while welding. Electrogas welding units are commonly self-aligning and pulled by chains connected to a drive mounted at the top of the joint. Electroslag welding machines can incorporate single or multiple electrodes, allowing welds to be made in plate ranging in thickness from 50 to over 900 mm (2 to over 36 in.), depending on the number of electrodes used. Electrogas units are generally used to weld thinner plate ranging from 15 to 75 mm (1/2 to 3 in.) since they feed single electrodes.

Both processes are generally used to make single pass square groove butt welds, but are frequently modified to produce fillet welds, V-groove welds, T-joints, and so forth.

The welding current needed varies appreciably depending on the number of electrodes used and the plate thickness. In general, the electrogas machines operate at up to 400 A with solid electrodes and as high as 750 A with flux cored electrodes. Electroslag welding machines commonly require thousands of amperes to weld heavier sections with multiple electrodes. Primary power requirements vary from about 20 kW providing dc output for electrogas units, to as much as hundreds of kilowatts providing dc, or less frequently ac, to multiple wire ESW units. The cost of typical large systems range from $15,000 to $25,000, but can be greater if special features are required, and multiple electrode units can be priced in excess of $50,000. The more portable units are significantly cheaper, costing about $5000, but they cannot produce long uninterrupted welds.

Deposition rates for single electrode machines are typically 7 to 13 kg/h (15 to 30 lb/h), and with multiple electrode machines can approach 45 kg/h (100 lb/h). Obviously, the weld speed is related to plate thickness and deposition rate. The welds are sound and, because of uniform transverse shrinkage, the joints are essentially free of angular distortion. When a multiplicity of welds is to be made, the reduced labor costs and increased efficiency of depositing weld metal can justify the relatively high equipment costs.

The equipment is quite reliable and a welding operator can be trained to use it and understand the required procedures in a reasonably short time. More experience is needed to gain the familiarity required to troubleshoot and maintain the machines. However, since most machines are constructed with straightforward mechanical and electrical components, specialists are not required to keep them operational.

RESISTANCE WELDING*

Resistance welding incorporates a group of processes in which the heat for welding is generated by the resistance to the flow of electrical current through the parts being joined. It is most commonly used to weld two overlapping sheets or plates which may have different thicknesses. A pair of electrodes conducts electrical current through the sheets forming a weld. The two outer surfaces of the sheets are clamped to provide good electrical contact and pressure for containing the molten metal at the center of the joint. The surfaces must be clean, and special techniques often are needed to obtain acceptable electrical contact in aluminum.

The main process variables are welding current, current time, electrode force, and electrode characteristics. Although the current needed may be ten to one hundred times that used in arc welding, the time to make a single weld is usually less than one second. For example, a typical practice for spot welding two pieces of 1.6 mm (1/16 in.) mild steel sheet requires a current of approximately 12 000 A and a time of 1/4 s while 3 mm (1/8 in.) sheet requires approximately 19 000 A and 1/2 second.

There are three major resistance welding processes:** resistance spot welding (RSW), projection welding (RPW), and resistance seam welding (RSEW). In RSW, the welding current is concentrated at the point of joining using cylindrical electrodes having spherical tips. Spot welds are usually made one at a time. In RPW, a projection or dimple is stamped in one of the sheets prior to welding which concentrates the current conducted by flat electrodes on both sides of the joint. Several projections may be formed in one of the components and welded simultaneously. As an example, a stamped bracket may have three or four projections formed in it so that it can be welded to sheet metal in one current pulse.

In RSEW, leaktight welds can be made by a series of overlapping spot welds. These are produced by introducing pulses of current from rotating wheel electrodes. Typical welding speeds are 25 mm/s (60 in./min) for 1.5 mm (1/16 in.) mild steel sheet and 17 mm/s (40 in./min) for 3 mm (1/8 in.) sheet. A variation of RSEW, known as roll spot welding, is identical in operation and equipment to

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*Resistance welding is also discussed under "Electrical Sources of Welding Energy" in Chapter 2, p. 38.

**Chapter 26 in Section 2 of the *Welding Handbook*, Sixth Edition covers these processes in detail. In the Seventh Edition, a chapter covering these processes is tentatively set for Volume 3.

RSEW except that the spot spacing is increased so that spots do not overlap and the weld is not leaktight. A roll spot weld is used for structural purposes only.

Resistance welds are made with either semiautomatic or mechanized machines. With the semiautomatic machine, the welding operator positions the work between the electrodes and pushes a switch to initiate the weld; the weld programmer completes the sequence. In a mechanized setup, parts are automatically fed into a machine, then welded and ejected without welding operator assistance.

A typical resistance welding system consists of a welding machine, an electronic contactor, and a control panel. The welding machine itself consists of a rigid frame, a step-down transformer, an air cylinder or other means of applying a force to the upper electrode arm, a fixed but adjustable lower electrode arm, and heavy conductors connecting the electrode arms to the secondary leads of the transformer. The electronic contactor may be a pair of ignitron tubes, thyratrons, or silicon controlled rectifiers. The simplest control sets a fixed current magnitude and duration. More sophisticated controls provide means of varying the current during a weld and may also provide preheat and postheat after a cooling period or an off time. They are necessary for welding hardenable steels and other special alloys. Seam welding machine controls must provide an on-off sequencing of weld current and a control of wheel rotation.

Although the total power used is relatively small, the instantaneous power demand for RW is very high, and cables must be designed to carry the maximum kVA demand for the machine. Due to these factors, power companies may be reluctant to supply power for the process.

The cost of a complete RW machine including controls can vary over a wide range according to the type and thickness of material to be joined, the degree of sophistication required in the control panel, and the amount of tooling needed. A low kVA single-phase bench spot welding machine with controls costs about $1000* while a 100 kVA single phase spot welding machine costs around $7000. An RSEW machine costs twice as much as an RSW machine. Controls which incorporate preheat, postheat, pulsation, and up-down slope control will add to the cost.

A three-phase machine will generally cost about 2 1/2 times that of a single-phase machine of the same kVA rating, but it will have a better power factor. Large three-phase RW machines with complicated tooling and controls cost well over $50,000.

Resistance welding requires very little welding operator skill if machine controls are set by supervisors. The welding operator only positions parts to be welded and initiates the start of the weld sequence. In RSEW, the welding operator must guide the work through the wheels. The welding operator's maintenance duties would normally consist of replacing electrodes when the tips become worn or deformed, and of lubricating moving parts.

Resistance welding is used most frequently for joining thin gage material up to 3 mm (1/8 in.) in similar or differing thicknesses, and may be used to join sections as thick as 13 mm (1/2 in.).

The cost of the more sophisticated automatic machines is high and amortization cost can be a significant part of the overhead burden for the process. However, if used in highly repetitive operations, RW is generally considered to be a low cost process. There are no consumables in the usual sense although electrode tip wear and power may be categorized as such. Machining of electrode tips and their periodic replacement may be more properly classified as maintenance costs.

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*All cost information given on RW processes reflects 1974 prices.

FLASH WELDING*

Although flash welding (FW) is often classified as a resistance welding process, it is a unique process. Heat is created at the joint by its resistance to the flow of electric current, and the metal is heated above its melting point. Heat is also created by arcs at the interface. A force applied immediately following heating produces an expulsion of metal and the formation of a flash.

The usual flash weld involves butt welding rods or bars end to end or edge to edge. Both components are clamped in electrodes which are connected to the secondary of a resistance welding transformer. One component is moved slowly towards the other, and when contact occurs at surface irregularities, the current flows and initiates the flashing action. This flashing action is allowed to continue until a molten layer forms on both surfaces at which point the components are forced together rapidly to squeeze out the molten metal and debris, and upset the hot metal adjacent to it. This produces a hot worked weld free of any cast structure and, therefore, having mechanical properties often superior to other types of weld metal.

Flash welding is usually an automatic process. Parts are clamped in place by a welding operator who simply presses a button to start the weld sequence of accelerated travel during flashing which is followed by rapid travel for upset.

The FW machine is composed of a frame, a power transformer similar to an RW transformer, a movable electrode clamp, a fixed electrode clamp, and a drive system for the movable electrode. A programmer establishes the flashing rate and time, and the time for upset, upset current, and upset force.

Flash welding machines like resistance welding machines are available in a wide variety of sizes from about 10 kVA up to 1500 kVA, and power requirements vary accordingly. Their cost obviously varies depending on the kVA rating and level of automatic control involved. In 1974, prices ranged from $5000 for a 10 kVA welding machine to over $600,000 for a large 1500 kVA machine used to weld sheet in a steel mill.

Minimum welding operator skill is needed to position the parts in the electrode clamps so that alignment is correct and the correct amount of burnoff and upset occur. Once the parts are properly loaded in the machine, the flashing action and subsequent upset take place automatically after the initiation switch is closed. Experience is needed, however, to establish the proper sequence.

Generally, welds can be made in sheet and bar thicknesses ranging from 0.2 mm (0.01 in.) up to 25 mm (1.0 in.) and, for round bar diameters, from 1 mm (0.05 in.) to 50 mm (2.0 in.). At the small end of the range, the main problem is to prevent the sheet or wire from bending during flashing or upset and to make sure that long joints are properly aligned. At the upper end of the thickness range, the main consideration is the capability of the machine to deliver the power required and provide the upset force needed. The thicker parts require that at least one of the members be beveled to initiate flashing and heating at the weld center.

The normal joint design for FW is the square groove butt joint. The edges or ends of the parts to be joined should be flat, but one part can be slightly raised in the center to facilitate flash initiation.

No metal is deposited in flash welding. On the contrary, metal from the ends being joined is expelled as a shower of sparks. This loss must be accounted for in designing parts which are to be flash welded.

The cost effectiveness of FW is similar to the RW processes. Other than the materials consumed in flashing, there are no consumables except for maintenance items such as the conductor surfaces of clamps. The major cost factors are labor, power, and amortization of equipment.

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*Chapter 27 in Section 2 of the *Welding Handbook*, Sixth Edition covers this process in detail. In the Seventh Edition, a chater covering FW is tentatively set for Volume 3.

OXYFUEL GAS WELDING*

Oxyfuel gas welding (OFW) defines a group of welding processes that use the heat produced by a gas flame or flames for melting the base metal and, if used, the filler metal. Pressure may also be used. Oxyfuel gas welding is an inclusive term used to describe any welding process that uses a fuel gas combined with oxygen, or in rare instances, with air to produce a flame having sufficient energy to melt the base metal. The fuel gas and oxygen are mixed in the proper proportions in a chamber which is generally a part of the welding tip assembly. The torch is designed to give the welder complete control of the welding flame, allowing him to regulate the melting of the base metal and the filler metal. The molten metal from the plate edges and the filler metal intermix in a common molten pool and coalesce, upon cooling, to form one continuous piece.

Oxyfuel gas welding was originally developed with acetylene fuel gas. More recently, other gases, such as methylacetylene propadiene, have found some acceptance as the fuel for oxyfuel gas welding. These flames must provide high localized energy to produce and sustain a molten pool. With proper adjustment, the flames also can supply a protective reducing atmosphere over the molten metal pool which is maintained during welding. Hydrocarbon fuel gases such as propane, butane, natural gas, and various mixtures employing these gases are not suitable for welding ferrous materials because the heat output of the primary flame is too low for concentrated heat transfer or the flame atmosphere is too oxidizing.

Although the maximum hydrogen flame temperature is 2660 °C (4820 °F), hydrogen has found limited use in OFW due to its essentially colorless flame. The lack of a visible cone makes the hydrogen-oxygen ratio very difficult to adjust. In addition, the flame has relatively low heat content. Oxyhydrogen welding (OHW) is used primarily for welding low melting point metals such as lead and, to a limited extent, light gage sections and small parts.

Manual welding methods are most commonly used and require minimal equipment. A suitably sized torch, hoses, regulators, oxygen in a pressurized cylinder, fuel gas in a pressurized cylinder, welding rods, goggles, and protective clothing are needed.

In combination with pressure, oxyfuel gas flames can be used to make butt welds without filler metals. This process is called pressure gas welding (PGW). In PGW, abutting surfaces are heated with oxyfuel gas flame(s) and forced together to obtain the forging action needed to produce a sound interface. The process is ideally adapted to a mechanized operation, and practically all commercial applications are either partly or fully mechanized.

The low cost of OFW equipment is one of the main reasons for its widespread use. A complete manual welding unit including torch, hoses, regulators, tanks, and goggles was available for less than $300 in 1974. However larger units and special safety equipment will raise the price. Gas distribution systems vary widely in cost depending on the number of cylinders to be manifolded, the distance of the distribution lines, and the number of welding stations; thus the cost must be computed for each installation.

The equipment for PGW is generally mechanized and each machine must be built specifically for the part to be pressure gas welded. Thus equipment costs will be much higher and will cover a wide cost range.

Since the OFW processes are primarily manual, it is essential that the welder be adequately trained and highly skilled for specific critical welding jobs such as pipe welding. The skill required by the welding operator for the fully mechanized PGW machine would be lower than that required by the manual welder since the machine control, when set, performs the complete operation.

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*Chapter 41 in Section 3A of the *Welding Handbook*, Sixth Edition covers OFW in detail. In the Seventh Edition, a chapter covering OFW is tentatively set for Volume 2. In this volume, OFW is also discussed under "Chemical Sources of Welding Energy" in Chapter 2, p. 41.

Oxyfuel gas welding can be used for joining heavy thicknesses of plate, but welding is slow and high heat input is required. Welding speed is adequate to produce economical welds in sheet metal and thin-wall and small diameter piping. Thus, OFW is best applied on thin plates of about 6 mm (1/4 in.) maximum.

Pressure gas welding is used to join sections up to 25 mm (1 in.) thick, and special machines have been made to join bar stock up to 75 mm (3 in.) in diameter. The PGW machines, while somewhat slower than flash welding machines, provide equally suitable welds with less complex equipment.

The OFW processes are very versatile: they can weld most materials, and the equipment involved is easily portable. For those reasons the cost effectiveness is good. However, when parts are to be made in quantity, other welding processes are probably more suitable. Pressure gas welding has found many applications because the equipment is not as complex or as expensive as other comparable processes. The cost effectiveness is therefore adequate for small and medium size repetitive production runs.

SOLID STATE WELDING*

DIFFUSION WELDING**

Diffusion welding (DFW) is a specialized process generally used only when the unique metallurgical characteristics of the process are required. Components to be diffusion welded must be specifically designed and carefully processed to produce a joint successfully. It is useful for applications concerned with (1) the avoidance of metallurgical problems associated with other joining processes, (2) the fabrication of shapes to net dimensions, (3) the maintenance of joint corrosion resistance with titanium and zirconium, and (4) the production of heavy section parts with uniform through-thickness properties as with titanium laminates.

Diffusion welding occurs in the solid state when properly prepared surfaces are in contact under predetermined conditions of time, pressure, and elevated temperature. The applied pressure is set above the level needed to insure essentially uniform surface contact but below the level that would cause macroscopic deformation. The temperature is generally well below the melting point. A filler metal, usually preplaced as an insert or plating, may be used. The function of the filler metal generally is to lower the required temperature, pressure, or time required for welding or to permit welding in a less expensive atmosphere.

Heating can be accomplished in a furnace, retort, or by resistance techniques. Pressure is applied by dead weight loading, presses, differential gas pressure, or by differential thermal expansion of the parts or of the tooling used. The use of high pressure autoclaves or the differential gas pressure technique permits the welding of assemblies in which the joint surfaces are intersecting planar surfaces. Uniaxial methods of applying pressure are limited to welding parallel planar surfaces roughly perpendicular to the direction of load applications. All techniques are essentially mechanized and require appropriate equipment. Encapsulating or canning of parts for welding is necessary when differential pressure techniques are practical and is useful when using other techniques. Power is supplied for heating and pressure application.

The cost of equipment for DFW is roughly related to the joint area to be welded and in 1974, ranged between $1000 and $2000 for each 600 to 700 mm^2 (1 in.^{2}) of surface.

A high level of welding operator skill and

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*Solid state energy sources, including diffusion principles and mechanisms, are discussed in Chapter 2, p. 50.

**Chapter 52 in Section 3B of the *Welding Handbook*, Sixth Edition covers this process in detail. In the Seventh Edition, a chapter covering DFW is tentatively set for Volume 3.

training is required for most DFW operations. Only fully automated operations permit the use of semi-skilled personnel.

In diffusion welding, joints are always tightly contacting surfaces. Conventional welding joint terms and concepts are not appropriate for this method.

Diffusion welding is only economical when close dimensional tolerances, expensive materials, or special material properties are involved. Applications to date have been in the aerospace and nuclear industries. Although the process has been used to fabricate complex, one-of-a-kind devices, it is more suitable to moderate volume production quantities. Consumable material costs are high if precious metal filler metals or inert gases are used.

FRICTION WELDING*

Friction welding (FRW) machines are designed to convert mechanical energy into heat at the joint to be welded. The usual method of accomplishing this is to rotate one part of the component to be joined while forcing it against the other which is held in a stationary position. Obviously, the rotating end of the joint must be circular or must closely resemble a circle such as a hexagon. Frictional heat at the joint interface raises the metal temperature sufficiently to soften and squeeze the metal out by the axial pressure. Oxides and other surface impurities are removed with the softened hot metal, resulting in a sound weld.

Two major techniques for FRW exist. In the original FRW technique, the moving part is held in a motor driven collet which rotates the part at a constant speed while axial pressure is applied through it against the fixed part. The fixed part must be held rigidly to resist the axial force and prevent it from rotating. Rotation is continued until the entire joint is heated sufficiently. Then simultaneously, the rotation is stopped quickly by a brake, and an upset or forging force is applied to complete the weld. The process parameters are rotational speed, axial force, welding time, and upset force. During the welding period, the drive motor must provide energy at the rate necessary to make the weld. Therefore, a relatively high powered motor is required.

The second FRW technique is called inertia welding. With it, energy is stored in a flywheel which has been accelerated to the required speed by a drive motor. The flywheel is coupled directly to the drive motor by a clutch and to the collet which grips the rotating member. A weld is made by applying an axial force through the rotating part while the flywheel decelerates transforming its kinetic energy to heat at the joint. When properly programmed, the weld is finished when the flywheel stops. Sometimes an increased axial force is applied just before the flywheel stops to aid in welding while the material in the region of the interface is at an elevated temperature. The welding parameters are flywheel moment of inertia, flywheel rotational speed, axial force, and upset force if used.

After the parts are loaded in the friction welding machine, the process is automatic. If automatic loading and unloading devices are installed, the machines are made completely automatic.

Friction welding machines contain a driving head, a means for applying axial force, and a yoke or platform for mounting the tooling which holds the fixed part. At this time, only the inertia welding type machines are manufactured in the United States. They range in size from one which will weld a 15 mm (0.6 in.) maximum diameter steel bar to one which will weld a 100 mm (4.0 in.) maximum diameter steel bar. Power requirements for these machines vary from 25 kVA for the smaller machines to 175 kVA for the larger size machines.

Inertia welding machines in 1974 cost between $50,000 and $250,000 depending on their size and capacity. The cost of tooling depends on the specific parts to be welded, but it is generally about 35 percent of the basic machine cost.

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*Chapter 50 in Section 3A of the *Welding Handbook*, Sixth Edition covers this process in detail. In the Seventh Edition, a chapter covering FRW is tentatively set for Volume 3. In this volume, FRW is also discussed under "Mechanical Sources of Welding Energy," in Chapter 2, p. 44.

Little skill in terms of manual dexterity is needed for FRW since the process is fully automatic. However, a mechanical aptitude and an understanding of machine operation are required to set up jobs properly and to keep equipment in good operating condition.

The maximum diameter solid bar which can be welded depends upon the maximum axial force and flywheel energy available in the machine. The maximum size of hollow parts, such as tubes, depends upon the cross-sectional area of metal in contact. Normally, joints for FRW are of the square butt type as, for example, when a solid round bar is welded to another solid bar or a tube is joined to a tube of the same dimensions. In inertia welding, the range can be extended downward by removing flywheel increments until only the inertia of the spindle and collet remain. This determines the minimum size which can be welded.

The time required to make friction welds is measured in seconds. Inertia welds require from less than 0.5 s to approximately 15 s, exclusive of the time needed to accelerate the flywheel to the designated speed. In either type of machine, the time required to load and unload parts is longer than the actual weld time.

Factors contributing to the cost of FRW are electric power, material squeezed out in the flash, labor, and the maintenance and amortization of equipment. The last two of these are the major cost items.

ELECTRON BEAM WELDING*

Electron beam welding (EBW) is accomplished with a stream of electrons which is formed into a narrow beam providing a three-dimensional heating source. This beam produces intense local heating through the combined action of billions of electrons. Each electron penetrates its own short distance and gives up its kinetic energy in the form of heat to produce a hole or tunnel through the material.

The hole or tunnel is moved along the joint by moving either the gun or material and is maintained by the beam as it moves forward coming into contact with unmelted material at the vertical edge. The molten material flows around the bore of the hole and solidifies along the rear side of the hole to make the weld.

Electron beam welding has several major advantages. It produces deep, narrow, and almost parallel-sided welds with low total heat input and thus comparatively small heat-affected zones.

The depth to width ratio of electron beam welds is greater than 10:1 and ratios of 30:1 are possible. The process involves only four basic parameters — accelerating voltage, beam focus, welding speed, and beam current — and allows for superior control over penetration by the use of high response closed-loop, servo controls on all welding parameters. The evacuated work chamber creates a high purity environment for welding, resulting in freedom from impurities and contaminants. Finally, the process allows for high welding speeds (125 to 200 mm/s [300 to 500 in./min] on sheet material) and generally requires no filler metal flux or shielding gas.

The resultant low energy input minimizes distortion and shrinkage from welding and permits the welding of parts that have already been finish machined. It also allows for welding in close proximity to heat sensitive components, and the welding of dissimilar metals which are metallurgically compatible. Also, by projecting the beam several inches to several feet, it is possible to make welds in otherwise inaccessible locations.

Electron beam welding generally is per- ɔrmed in a hard vacuum (pressure of 0.13 to

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*Chapter 47 in Section 3A of the *Welding Handbook*, Sixth Edition covers this process in detail. In the Seventh Edition, a chapter covering EBW is tentatively set for Volume 3. In this volume, EBW is also discussed under "Optical Sources of Welding Energy," in Chapter 2, p. 44.

133 mPa [10^{-6} to 10^{-3} torr]), but the process can be adapted to weld in soft vacuum (pressure of 0.13 to 13 Pa [10^{-3} to 10^{-1} torr]), or at atmospheric pressure. However, penetration and depth to width ratio are reduced as the pressure increases. The basic equipment required includes a vacuum chamber; controls; an electron beam gun (rated at from 30 kV to 175 kV and 50 mA to 1000 mA); a three-phase power supply, 60 Hz, 440/480 V; an optical viewing system or tracking device; and work handling equipment. The operation of this equipment may be either semiautomatic or automatic. With automatic production equipment, the pumpdown time may be totally eliminated by the use of intermediate chambers or prepump stations.

The typical costs of an EBW facility range from \$75,000 to \$1,500,000*. General purpose hard vacuum equipment falls in the \$100,000 to \$300,000 range, special purpose hard vacuum in the \$150,000 to \$1,500,000 range, general purpose soft vacuum in the \$80,000 to \$150,000 range, and special purpose soft vacuum in the \$100,000 to \$350,000 range. Indirect savings in welding costs can result from the reduced costs of joint preparation, ability to weld in a single pass, high welding speed, and reduced distortion of parts which would reduce further machining or heat treatment.

An automatic EBW facility requires only a skilled welding operator while general purpose equipment requires a skilled welding technician to control the four basic EBW parameters. A mechanical and basic electrical background with solid state troubleshooting ability is necessary for equipment maintenance.

The EBW process can be used to weld almost any metal. Steel up to 100 mm (4 in.), aluminum up to 150 mm (6 in.), copper up to 25 mm (1 in.), and many other materials from foil to plate thickness are weldable in one pass.

Design is limited to either a tight butt or lap joint. As a general rule, fit-up is usually 0.12 mm (0.005 in.) or less. In most metals, the root opening (joint gap) should not exceed 0.25 mm (0.010 in.) for weld depths less than 13 mm (1/2 in.). The low voltage (low kV) equipment usually is capable of welding in any position.

LASER BEAM WELDING**

Similar to the electron beam, the focused high power coherent monochromatic light beam or laser beam used in laser beam welding (LBW) causes the metal at the point of focus to vaporize, producing the deep penetration column of vapor extending into the base metal. The vapor column is surrounded by a liquid pool, which is moved along the path to be joined producing welds with depth-to-width ratios greater than four to one. Ruby lasers may be used for spot welding thin gage materials, joining microelectronic components, and other tasks requiring precise control of energy input to the workpiece. Initial applications were limited by their low power, but later devices could produce 100 kW pulses having one millisecond duration. In seam welding, speeds were quite low because the welds were formed by a series of overlapping spot welds.

More recently, multi-kilowatt carbon dioxide gas laser systems have been developed with continuous power capability. Such systems produce an infrared beam which can be focused to provide power densities of 10 kW/mm^2 (6.45 MW/in.^{2}) or greater, a level previously attainable only with EBW equipment. This continuous power provides the high power carbon dioxide laser with deep penetration welding capability.

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*All cost information given for EBW reflects 1974 prices.

**Chapter 55 in Section 3B of the *Welding Handbook*, Sixth Edition covers this process in detail. In the Seventh Edition, a chapter covering LBW is tentatively set for Volume 2. In this volume, LBW is also discussed under "Optical Sources of Welding Energy" in Chapter 2, p. 44.

Although laser beam welding (LBW) is most effective for autogenous welds, the process is amenable to filler metal addition. Because the laser allows precise control of energy delivery to highly localized regions, the process is ideally suited to "narrow gap" geometries which allow for substantial savings in filler metal; preplaced filler metal has been used successfully.

Deep penetration welds produced with high power CO_2 lasers are similar to electron beam welds, but LBW offers several advantages:

(1) A vacuum environment is not required for the workpiece since the laser beam is easily transmitted through air, and reactive workpieces may be protected from the atmosphere by inert gas shields.

(2) X-rays are not generated by the beam.

(3) The laser beam may be readily shaped, directed, and focused with reflective optics thereby allowing easy automation.

(4) Due to the slightly lower power density of the focused laser beam, the tendency for spiking, underbead spatter, incomplete fusion, and root bead porosity is reduced.

Laser beam welding has been used successfully to join a variety of metals and alloys including low alloy and stainless steels which do not exhibit excessive hardenability; some aluminum alloys; lead; titanium and titanium alloys; and refractory and high temperature alloys. Porosity-free, generally ductile welds can be attained with average tensile strengths equivalent to or exceeding those of the base metal. Some hardness increases must be anticipated in alloys having microstructures related to cooling rates. Since laser beam welds typically involve low energy input per unit weld length, the cooling rates are high. In many cases, these high cooling rates offer substantial advantages. If undesirable, however, the cooling rates may be slowed by preheating, or the effects modified by postheating.

The impact strengths of laser beam welds in several low hardenable ferrous alloys have been reported to exceed those of the base metals. This characteristic has been ascribed to a lowering of the impurity inclusion content and a change in the inclusion size distribution.

Typical CO_2 LBW performance at a power level of 5 kW is represented by welding speeds in excess of 85 mm/s (200 in./min) in 2.5 mm (0.1 in.) thick carbon steel or stainless steel. For 5 mm (0.2 in.) material, welding speed is reduced to 42 mm/s (100 in./min) at 5 kW. For material of this thickness, welding speed is approximately proportional to power. At 10 kW, 5 mm thick aluminum can be welded at approximately 38 mm/s (90 in./min) and 5 mm titanium at approximately 57 mm/s (135 in./min). The maximum single pass penetration of about 18 mm (0.7 in.) has been achieved in Type 304 stainless steel at 15 kW and at a speed of 8 mm/s (20 in./min). At 25 mm/s (60 in./min) penetration at 15 kW is still in excess of 15 mm (0.6 in.), but a substantially narrower fusion zone is obtained in keeping with the reduced energy input per unit length of weld. Furthermore, sound laser beam welds have been formed in 25 mm (1 in.) thick steel by a dual pass technique and thin gage (0.2 mm [0.008 in.]) material has been welded at 1270 mm/s (3000 in./min) at 6 kW. The largest capacity laser produced by 1974 was a 25 kW carbon dioxide unit.

Laser beam welding requires good joint fit-up and is a high speed process ideally suited to automation. The high cost of equipment which ranged from $40,000 to $750,000 in 1974, currently relegates application to high volume production or to critical weldment applications requiring unique weld characteristics and reproducibility. The electrical efficiency of LBW equipment is between 10 and 20 percent. Welding equipment, with minor modifications to beam focusing provisions, can also be utilized for gas jet-assisted cutting* and for surface heat treating and alloying applications.

Although the equipment is very sophisticated, it is designed to be used by unskilled machine operators, but major maintenance must be handled by factory trained engineers.

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*See the discussion of laser beam cutting on p. 30.

BRAZING*

Brazing defines a group of welding processes in which the parts are heated to a suitable temperature and the filler metal used has a melting temperature above 450 °C (840 °F) and below the solidus of the base metal. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction. Braze welding is differentiated from brazing because the filler metal is deposited in a groove or fillet exactly at the point where it is to be used and capillary action is not a factor. Brazing is arbitrarily distinguished from soldering by the filler metal melting temperature. In soldering, filler metals melt below 450 °C.

To produce acceptable brazed joints, consideration must be given to four basic elements: joint design, filler metal, uniform heat, and protective or reactive cover. The processes developed to accomplish these requirements are varied and many overlap; they are primarily designated according to the sources or methods of heating. Those which are currently of industrial significance include torch brazing, furnace brazing, induction brazing, resistance brazing, dip brazing, infrared brazing, and diffusion brazing.

Torch brazing (TB) is accomplished by heating the parts to be brazed with an oxyfuel gas torch or torches using various fuels. While much TB is done with hand held torches, automated TB machines use preplaced fluxes and preplaced filler metal in paste, wire, or shim form.

Normally, torch and machine brazing are used to join relatively thin sections ranging from 0.25 mm (0.01 in.) to 6 mm (0.25 in.), making what are essentially lap joints. These are brazed rapidly, but, brazing speed decreases dramatically in heavy sections.

Manual torch brazing is most effective and economical when relatively few pieces need to be joined; basic equipment costs are about $200**. Automated torch brazing machines are very economical even though their costs range from $2000 to more than $50,000 depending on their complexity.

Furnace brazing (FB) requires a furnace to heat prefluxed parts on which filler metal is preplaced. Generally the furnace atmosphere is air. Batch furnaces with protective atmospheres are used, however, when relatively few parts are involved or special heating and cooling cycles are required for distortion control or heat treatment. Continuous furnaces are most effective for very high production rates and straightforward joint designs. Both types of furnaces have a wide cost range from $1000 for an air atmosphere batch furnace to above $300,000 for an automated vacuum furnace. Their selection depends on the desired rate of production and the size of the part to be processed.

Furnace brazing processes are particularly suited for fabricating brazements of complex design. The brazing operator skill required for the batch and continuous furnaces is low and in many cases the operator has only to load, unload, or apply the filler metal.

Induction brazing (IB) involves heat obtained from resistance to a high frequency electric current induced in the part to be brazed. The parts are placed in or near an ac-carrying coil and do not form a part of the primary electrical circuit.

The brazing filler metal is usually preplaced. Careful design of the joint and the coil setup are necessary to assure that the surfaces of all members of the joints reach brazing temperature at the same time. Flux is usually employed except when an atmosphere is specifically introduced to perform the same function. Joints should be designed to be self-jigging rather than fixtured.

The cost of a single station unit is in the $2000 to $10,000 range with smaller and larger units available. The brazing operator skill for IB is low, although the equipment

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*Chapter 60 in Section 3B of the *Welding Handbook*, Sixth Edition covers brazing in detail. In the Seventh Edition, a chapter covering brazing is tentatively set for Volume 2. The metallurgical characteristics of brazing are also discussed in this volume, starting p. 149.

**All cost information given in this section on brazing reflects 1974 prices.

setup, power and supply adjustments, and coil design are critical to producing a good quality brazement.

The thickness range of sheet normally does not exceed 3 mm (1/8 in.), but bar stock thickness can reach 25 mm (1 in.). Special attention must be given to the coil design and location when widely varying thicknesses are brazed. Production speeds are high: heating can be accomplished in four to ten seconds, and coils can be designed to allow a conveyor belt containing parts to pass through the coil.

Generally, IB is commonly used where many parts must be made continuously over a long period of time. But many job shops can handle short run jobs very economically.

Resistance brazing (RB) uses heat produced by the resistance of the joint to electric current transferred to the work by electrodes. The brazing filler metal used is preplaced or face-fed by some convenient method, and the fluxes used, unlike other fluxes, must be partially conductive.

The parts to be brazed are held between two electrodes which provide proper pressure and current, and the pressure is maintained until the joint has solidified. The thickness of base metal handled with this type of process equipment normally ranges from 0.1 to 12 mm (0.005 to 0.50 in.). Typical joints to be used with this type of processing equipment are lap joints.

The cost of equipment varies with the power required to accomplish the desired heating of the joint to the brazing temperature and the complexity of the electrical controls. Resistance brazing equipment varies from $500 for very simple machines to $5000 and above for the more sophisticated equipment with electronic controls and process monitoring equipment. Welding operator skill for this type of equipment is minimal, although the more sophisticated equipment may require added experience for setup and control operations. The brazing speed is very fast, particularly when the power source and resistance tongs are oversized for the specific joint being made. Resistance brazing is used most economically on special application joints where the goal is to confine the heat to a very localized area and to avoid overheating the surrounding parts.

Dip brazing (DB) is performed in a molten salt or molten metal bath. Both types of baths are heated in suitable pots to furnish the heat necessary for brazing, provide protection from oxidation, and fluxing action if suitable salts are used.

The cost of DB equipment varies from $500 to $15,000 for the small to average size molten metal or molten salt furnaces. The large installations with water and air pollution control equipment are in the $200,000 range.

Molten metal bath brazing is limited to small wires (0.12 to 2.5 mm [0.005 to 0.100 in.]), sheet, and fittings that can be dipped into the small heated pots. However, molten salt baths will handle thin sheets as well as much heavier parts and very complex assemblies such as aluminum radiators and other heat exchangers. Molten salt baths are also used to make clad plate.

The production speed and efficiency of the dip baths are extremely good since the heating rates are very fast and many joints can be brazed at one time. Careful precleaning and postcleaning of parts are essential and may limit the production effectiveness in some cases. Brazing operator skill is minimal although extensive engineering may be required to set up the larger operations.

The cost effectiveness of this process is demonstrated by the fact that larger parts may have as many as 100 to 1000 joints brazed at one time and that many miles of joints have been simultaneously brazed.

Infrared brazing (IRB) became commercially important with the development of the high intensity quartz lamp as a source of heat. The process is particularly suited to the brazing of very thin materials such as honeycomb panels for aircraft, but is not normally employed on sheets thicker than 13 mm (0.50 in.). Assemblies to be brazed are supported in a position which enables the radiant energy to be focused on the joint. The assembly and the lamps can be placed in evacuated or controlled atmosphere retorts.

Small hand held quartz lamps with focusing mirrors and without specific controls are available for approximately $300 while larger installations that would automatically heat both sides of large honeycomb panels are in the $30,000 range.

The cost effectiveness of the IRB process is best when the parts to be brazed are very thin such as in the honeycomb applications. The cost of brazing heavy material cross sections is comparable to FB in terms of cycle time, atmosphere, and equipment.

Diffusion brazing (DFB), unlike all of the previous brazing processes, is not defined by its heat source, but by the mechanism involved. A joint is formed by holding the brazement at a suitable temperature for a sufficient time to allow mutual diffusion of the base metal and filler metal. The joint produced has a composition considerably different than either the filler metal or base metal, and no filler metal should be discernible in the finished microstructure. The DFB process produces stronger joints than the normal brazed joint. Also, the DFB joint remelts at temperatures approaching that of the base metal.

The typical thicknesses of the base metal that are diffusion brazed range from very thin foil up to 25 to 50 mm (1 to 2 in.) thick. Much heavier parts can also be brazed since thickness has very little bearing on the process.

Many parts that are difficult to make by other processes can be diffusion brazed. Both butt and lap joints having superior mechanical properties can be produced, and the parts are usually fixtured mechanically or tack welded together. Although DFB requires a relatively long period of time (30 minutes to as long as 24 hours) to complete, it can produce many parts at the same time and at a reasonable cost.

Furnaces are most frequently used for this method of processing. They are similar to those used for the more sophisticated FB operations; they range in cost from $50,000 for small production equipment to $300,000 for the large furnace equipment.

SOLDERING*

Soldering, according to AWS definition, involves heating a joint to a suitable temperature and using a filler metal (solder) which melts below 450 °C (840 °F). The solder is distributed between the properly fitted surfaces of the joint by capillary attraction. Heat is required to melt the solder and to promote the action of a flux on the metal surface which permits the molten solder to wet and flow into the joint.

A successfully soldered joint involves shaping the parts to fit closely together, cleaning the surfaces to be joined, applying a flux, assembling the parts, and applying the heat and solder. Flux residues may be removed when the joint is cooled.

Different equipment, processes, and procedures, all having certain advantages and disadvantages, are employed to accomplish the soldering operation. In order to make a satisfactory solder joint by any of these processes, it is essential to have a proper joint design as dictated by the base metal and solder employed.

The soldering processes are primarily designated according to the source or method of heating. Those which are currently of industrial significance are: dip soldering (DS), iron soldering (INS), resistance soldering (RS), torch soldering (TS), induction soldering (IS), and furnace soldering (FS). Infrared soldering (IS), and ultrasonic soldering are also used.

The cost of equipment varies widely with the process and is similar to the costs given in the preceding section on brazing. Industrial

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*Chapter 46 in Section 3A of the *Welding Handbook,* Sixth Edition covers soldering in detail. In the Seventh Edition, a chapter covering soldering is tentatively set for Volume 2. The metallurgical characteristics of soldering are discussed in this volume, starting p. 149.

soldering irons and flame heating equipment could be obtained for less than $100 in 1974. The DS, IS, RS, FS, and ultrasonic soldering equipment costs vary widely; some small pieces of equipment cost in the $500 range in 1974 while high speed automated equipment, which can be very complex, cost in excess of $50,000.

A degree of skill is required to adequately handle the manual soldering operations particularly when critical electronic equipment or large complex or critical components are to be soldered. The more automated soldering processes require little operator skill since the process variables are set up prior to starting the operation.

Machine settings, process control, and inspection determine joint quality. A lap joint or modification of the lap joint is the most common type used. The electronics industry uses many special types of joints; some joints have no mechanical security prior to soldering while other types have partial or full mechanical security prior to soldering.

The soldering process is uniquely adaptable to joining a wide range of metal thicknesses, from very thin films to quite heavy components such as bus bars and piping.

The soldering speeds for nonrepetitive manual operations are relatively slow, although a solderer can become quite adept at repetitive operations. The automated equipment used in manufacturing tin cans, for example, is designed for very high rates of speed. Likewise, the electronics industry employs machines of various types for wave soldering of printed circuit boards. These machines produce the many joints of a circuit board in a matter of seconds with one circuit board following after another in rapid succession. Manual dip soldering is much faster than the manual soldering iron method and thus fills the production requirements between the manual soldering iron and automated machines.

The expensive automated equipment for soldering produces the highest quality joints at a low cost per joint because many joints can be soldered at one time. The manual soldering iron process is much slower, and thus more costly. Manual soldering of components is still economical when the production needs are low, or the components have a complex design.

ADHESIVE BONDING*

Adhesive bonding is a joining process which has achieved substantial industrial recognition and is gaining acceptance as an assembly method for joining metals. The method has several advantages and disadvantages. On the one hand, it is capable of joining dissimilar materials as, for example, metals to plastics; bonding very thin sections without distortion and joining very thin sections to heavy sections; joining heat sensitive alloys; and producing bonds with unbroken surface contours. Furthermore, bonding can be accomplished at a low per-pound cost.

On the other hand, joints produced by this method may not support shear or impact loads. Also, such joints must have an adhesive layer less than 0.1 mm (0.005 in.) thick and must be designed to develop a uniform load distribution in pure shear or tension. The joints cannot sustain operational temperatures exceeding 260 °C (500 °F), and autoclaves, presses, and other tooling may be essential to achieve adequately strong bonds. The surfaces to be bonded must be "surgically" clean and aging time is needed to achieve full bond strength. Some adhesives must be used quickly after mixing or they solidify in the pot. Finally, nondestructive testing of adhesive bonded joints is difficult.

A variety of adhesives can be used. The thermoplastic adhesives develop a bond through the evaporation of a solvent or the ap-

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*Chapter 49 in Section 3A of the *Welding Handbook*, Sixth Edition covers this process in detail. In the Seventh Edition, a chapter covering adhesive bonding is tentatively set for Volume 3.

plication of heat. The so-called "pressure-sensitive" adhesives produce a relatively weak bond the instant pressure is applied but retain their flow characteristics allowing them to sustain only very light loads. Some adhesives are stable in the presence of air but begin curing when the joint is assembled and air is excluded. Other adhesives, perhaps the most useful type for metals, react chemically with curing agents or catalysts. Generally, they require no pressure other than that needed to maintain intimate contact with the faying surfaces, and cure in times ranging from hours at room temperature to seconds at temperatures as high as 175 °C (350 °F). Some of the epoxy-based adhesives can produce joint strengths up to 70 MPa (10 000 psi) in shear or tension if cured at 175 °C for a few hours under pressures of about 1030 kPa (150 psi).

Very little training is needed for production workers in adhesive bonding, but considerable skill is needed to design suitable joints and select the most appropriate adhesive for the anticipated service requirements. Too frequently the joints are not properly cleaned and prepared to receive the adhesive. Metals in particular must be free of all contaminants. They must be treated to leave a surface which will be chemically receptive to the adhesive and will provide maximum wetting characteristics.

Equipment costs are difficult to define since some adhesives are set by heat alone, some by pressure alone, and some by both. Oven sizes are obviously dependent on the size of the parts being bonded and presses may have to be specially designed to accommodate their contours. When properly used, however, adhesive bonding can do a very effective job and can be accomplished at low cost.

WELDING PLASTICS*

Most industrial plastics are either thermoplastic** and weldable or thermosetting† and unweldable. (Thermosetting plastics may be joined by adhesive bonding, however.) A number of widely used plastics can be welded because they are thermoplastic. The most common of these are polyvinyl chloride (PVC), polyethylene, polypropylene, acrylonitrile budadiene styrene (ABS), and acrylics. Such plastics can be welded by melting the surfaces to be joined and allowing them to solidify while in contact. Plastics containing volatile components may form gas bubbles and impair both the appearance and strength of the joint.

Friction welding machines can be used to produce excellent welds in joints having circular cross sections. (These devices are described on p. 19 of this chapter.) The most common welding method uses hot gases as the source of heat and involves procedures which are very similar to those followed when welding metals with oxyfuel gas torches. Welding torches for plastic are designed to convey compressed gas through electrically heated coils which raise the gas temperature to between 175 °C (350 °F) and 315 °C (600 °F).

The gas is conducted through an orifice to form a narrow stream which can be directed into the joint to be fused. The torches are easy to use, and some are designed to both preheat and feed the filler rod as well as the base material while progressing along the joint.

Such torches and associated regulators and self-contained compressors ranged from $150 to $500 in 1974, depending largely on the auxiliary equipment purchased. Power requirements are minimal, rarely exceeding 500 W for the heating element in the torch. Air compressors need additional power, but since only 280 ℓ/min (600 ft ^{3}/h) are required, the horsepower needs can be provided with a 1/4 hp motor. Some thermoplastic materials such as polyethylene are easily oxidized at high temperatures and may require heated com-

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*Chapter 56 of Section 3B of the *Welding Handbook*, Sixth Edition covers the welding of plastics in detail. In the Seventh Edition, a chapter covering the welding of plastics is tentatively set for Volume 3.

**Capable of being softened and melted when heated.

†Hardened permanently into shape by chemical reactions.

pressed nitrogen instead of air as the hot gas for best results.

Fortunately, thermoplastics exhibit a wide range of temperatures from those at which they soften and melt to those at which they char or burn. However, because they are poor conductors of heat, it is difficult to obtain deep fusion, and a filler rod surface may char or burn before its core is fully softened. Since the rod shape doesn't change significantly, a plastic weld may appear to be incomplete even though it has been successfully fused into the joint as evidenced by the molten flow patterns at the edges.

THERMAL CUTTING PROCESSES*

A number of heat sources used for welding have been adapted to remove metal as well. Some of these are difficult to regulate or are not capable of concentrating energy sufficiently to produce good cuts. Nevertheless, the processes using these heat sources should be classified as cutting processes. Typical of this group are carbon arc cutting, shielded metal arc cutting, oxygen arc cutting, gas tungsten arc cutting, oxygen lance cutting, and oxygen piercing. Other processes, however, have been proved to have great merit for cutting or gouging metal cheaply and with enough precision to be considered viable production tools. These include oxygen cutting, plasma arc cutting, air carbon arc cutting, and laser beam cutting. Each of these has its special advantages and limitations.

OXYGEN CUTTING

Oxygen cutting (OC) is a commonly used method for severing or gouging metals which react with oxygen to produce enough heat to remove both molten metal and oxide slags. Many iron and titanium alloys can be cut with this process. The torches used are designed to (1) produce a small diameter high velocity stream of oxygen to oxidize and remove metal in a narrow section and (2) surround that stream with a ring of flame to preheat the metal to its ignition temperature. The torch is moved at a speed set to produce a continuous cutting action. Because the jet and flame are symmetrical, the torch can be moved in any direction, allowing curved shapes to be cut easily. The cut quality is dependent on the tip size and type and distance from the plate, the oxygen and preheat gas flow rates, and the cutting speed. All of these factors are dependent on the plate material and plate thickness. A supply of oxygen and fuel gas is needed. Nozzles are designed to use most fuel gases such as natural gas, propane, acetylene, or byproducts of the chemical industries.

The process is limited to cutting ferrous metals and titanium (see Table 1.2). For mild steels, it is almost always selected to make cuts in plate as thick as 300 mm (12 in.). Alloy steels are more difficult to sever, and the quality of cuts in such steels depends on the nature and amount of the alloying elements. Stainless steels cannot be cut easily, but mediocre severing cuts can be made by introducing fluxes or even powder into the oxygen cutting stream. Titanium can be cut faster than mild steel. The oxidized cut surfaces must be removed before welding titanium or the welds will be contaminated.

Modifications of this process are used for scarfing metal in steel mills, for gouging defective welds, and for grooving plate edges in preparation for welding.

Manual cutting operations are common. Only a few hours are needed to train an individual to make severing quality cuts. However, considerable skill is necessary to produce quality cuts of the type required for welding. Torches and regulators for cutting 13 mm (1/2 in.) steel can be purchased for less

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*Thermal cutting processes were covered in Chapters 42 and 43 of the *Welding Handbook*, Sixth Edition. In the Seventh Edition, a chapter covering thermal cutting processes is tentatively set for Volume 2.

than \$200.* Production equipment, however, will cost about \$500.

Equipment for mechanized cutting is more expensive and the skills required to use this equipment are dependent on its sophistication. Relatively little training is needed to produce good straight line cuts since all of the parameters can be preset using tabulated data. However, considerable skill is necessary to produce shape cuts with multiple torches since everything must be executed perfectly. Equipment costs will vary depending on the nature of the drive system and control system, the size of the plate to be cut, and the number of torches to be mounted. A simple, single torch, motorized drive for straight cuts will cost about \$1000. A coordinate drive system with optical tracking for shaped cuts will cost about \$20,000. A computer controlled, multiple torch package of the type used in ship lofting could cost more than \$100,000.

PLASMA ARC CUTTING

Plasma arc cutting (PAC) is accomplished with an extremely hot, high velocity jet produced by forcing an arc and inert gas through a small diameter orifice. The arc energy concentrated on a small area melts the plate, and the jet of hot expanding gases forces the molten metal through the kerf. When cutting carbon steels or cast iron, additional energy can be provided by introducing oxygen into the gas stream.

This process is very versatile. All metals can be cut with it (see Table 1.2) and mild steel can be severed faster than is possible with oxygen cutting. However, more metal is removed because the kerfs are wider and, in heavier plates, the kerfs are not as smooth or flat. Special nozzles are needed to produce parallel kerf walls, and special techniques are needed to produce shape cuts having controlled bevels.

The process requires high arc voltages, necessitating special power supplies with high open current voltages. Depending on the material and thickness to be cut, between 25 kW and 200 kW are needed. Mixtures of argon and hydrogen or nitrogen and hydrogen are generally used. Water is necessary to cool the torches.

Holders have been designed for manual cutting. Skill requirements are similar to those needed for OC, but more training is needed to master the greater number of adjustments required. Cut quality on thin plates can be better because travel speeds don't need to be controlled as carefully. Equipment costs are relatively high to cover a torch, control panel, high frequency generator, and power supply. About \$10,000 is needed for a single package.

Mechanized equipment is more common. A torch and other accessories are equivalent to those used for manual plasma arc welding. Additional costs may be necessary for the travel mechanisms which are similar to those used for oxygen cutting equipment, although they should be designed to track at higher speeds. Multiple torch packages need additional power supplies and control panels for each torch. In addition, water shrouds or water tables may be used to absorb both noise and fume. Therefore, mechanized equipment may cost between \$20,000 and \$100,000 depending on the tracking and drive systems and the plate thickness to be cut.

AIR CARBON ARC CUTTING

The air carbon arc cutting (AAC) process uses an arc to melt metal which is blown away by a high velocity jet of compressed air. The electrodes are hard rods made from a mixture of graphite and carbon and coated with a layer of copper to increase their current-carrying capacity. Standard welding power supplies provide the current. Air is supplied via conventional shop compressors, and most applications require about 550 kPa (80 psi). Manual holders are very similar in appearance to covered electrode holders and supply both air and current.

In gouging, the depth and contour of the groove are controlled by the electrode angle,

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*All cost information given in this section on cutting processes reflects 1974 prices.

travel speed, and current. Grooves up to 25 mm (1 in.) deep can be made in a single pass. In severing, the electrode is held at a steeper angle, but the air jet is kept parallel to the plate surface. Travel speed is important, the correct speed producing a hissing sound and a clean cut.

In manual work, the quality of grooves is dependent on the cutting operator's skill and, for this reason, semiautomatic or fully automatic holders are used to cut "U" grooves in preparing plates for welding. However, when removing weld defects or severing excess metal in castings, manual techniques are most suitable. Regardless of the equipment, training can be accomplished within a day.

The manual equipment which is used in fabrication and maintenance shops costs between $100 and $200 assuming that a power supply and compressed air supply are available. Semiautomatic equipment including the torch, a tractor, and miscellaneous items cost about $1000. Voltage controlled automatic torches and control units cost between $1000 and $2000. They are used for very precise gouging, holding tolerances of less than 0.8 mm (1/32 in.) and, generally, are mounted on available travel systems.

The applicability of AAC to most metals is indicated in Table 1.2.

Table 1.2 — Applicability of Cutting Processes to Materials*

Material	Cutting Processes			
	OC	PAC	AAC	LBC
Carbon Steel	X	X	X	X
Stainless Steel	X′	X	X	X
Cast Iron	X′	X	X	X
Aluminum and Alloys		X	X	X
Titanium and Alloys	X′	X	X	X
Copper and Alloys		X	X	X
Refractory Metals and Alloys		X	X	X

*This table is limited in content and scope and should be regarded as only a very general guide to process applicability. For processes to be used with specific alloys, appropriate sources should be referenced.

LEGEND

Process Code

OC — Oxygen Cutting
PAC — Plasma Arc Cutting
AAC — Air Carbon Arc Cutting
LBC — Laser Beam Cutting

X — Process may be applied.
X — Process applicable with special techniques.

LASER BEAM CUTTING

As in laser beam welding (LBW), the source of heat for laser beam cutting (LBC) is a concentrated coherent light beam which impinges on the workpiece to be cut. A combination of melting and evaporation provides the mechanism for removing material, although with some materials, such as carbon and certain ceramics, the mechanism is purely one of evaporation.

High power lasers exhibit unique advantages for cutting applications including:

(1) The ability to cut any known material regardless of hardness.

(2) Lack of "wear" and thus sharpening requirements as with mechanical cutters.

(3) Narrower kerf and heat-affected zone than that afforded by other thermal cutting processes.

(4) Lack of mechanical force on the workpiece.

(5) High cutting speeds.

(6) Ready adaptability to computer controlled contour cutting.

These advantages stem from the ease of beam transmission through the atmosphere and from the high power density which can be obtained. Typically, an equivalent processing temperature in excess of 11 000 °C (20 000 °F) can be obtained which is sufficient to vaporize all known materials.

Despite this high energy concentration, however, many cutting applications (particularly those involving metals) require the assistance of a gas jet to promote effective cutting. The gas used may be inert to provide a smooth, clean kerf or reactive, such as oxygen, to speed the cutting process. With appropriate selection of laser beam power, gas shielding parameters, and cutting speed, smooth cuts can be achieved and further edge finishing is often not required.

The absence of mechanical force is advantageous in the cutting of large and complex parts because minimal clamping and fixturing can be used as compared to that required by other means. The ease with which the motion of the focused laser beam spot can be adapted to computer control renders the process suitable for cutting large, complex, multicontoured parts without requirements for template fabrication and inventory.

One of the principal current disadvantages of LBC is the relatively high capital cost of laser beam equipment. This factor, coupled with the decrease (compared to other thermal processes) in cutting performance as material thickness increases, presently limits the cost effectiveness of LBC to metals of approximately 13 mm (1/2 in.) or less in thickness. However, since acceptable cuts have been made in 50 mm (2 in.) thick steel, the cutting of thicker material might be practical if accomplished by time sharing of the laser beam equipment with, for example, a welding application.

The most important utilization of LBC in metal cutting is in the severing of titanium alloys. One major aerospace manufacturer currently employs a single, 250 W, numerically controlled laser beam system for production cutting of all titanium sheet components up to 9.5 mm (3/8 in.) thickness. Computer controlled nesting and laser beam cutting of thin gage sheet metal components are currently receiving detailed scrutiny and significant industrial applications appear imminent.

Note: Refer to the Master Chart of Welding and Allied Processes in Appendix A p. 335.

SUPPLEMENTARY READING LIST

Brazing Manual, 2d ed. Miami: American Welding Society, 1963.

Current Welding Processes. Miami: American Welding Society, 1964.

Houldcroft, P.T. *Welding Processes.* Cambridge: Cambridge University Press, 1967.

Linnert, G.E. *Welding Metallurgy,* Vol. 1. 3d ed. Miami: American Welding Society, 1965.

Metals Handbook, Vol. 6. 8th ed. Metals Park, Ohio: American Society for Metals, 1971.

Modern Joining Processes. Miami: American Welding Society, 1966.

Paton, B.E., ed. *Electroslag Welding.* 2d ed. Translated from the Russian. Miami: American Welding Society, 1962.

Recommended Practices for Plasma Arc Welding, C5.1-73. Miami: American Welding Society, 1973.

Recommended Practices for Resistance Welding, C1.1-66. Miami: American Welding Society, 1966.

Recommended Practices for Resistance Welding Coated Low-Carbon Steel, C1.3-70. Miami: American Welding Society, 1970.

Recommended Practices for Spot Welding Aluminum and Aluminum Alloys, C1.2-53. Miami: American Welding Society, 1953.

Recommended Safe Practices for Gas-Shielded Arc Welding, A6.1-66. Miami: American Welding Society, 1966.

Resistance Welding, Theory and Use. Miami: American Welding Society, 1956.

Soldering Manual. Miami: American Welding Society, 1959.

The Procedure Handbook of Arc Welding, 12th ed. Cleveland: The Lincoln Electric Company, 1973.

Vill, V. I. *Friction Welding of Metals.* Translated from the Russian. Miami: American Welding Society, 1962.

Welding Handbook, Sect. 2. 6th ed. Miami: American Welding Society, 1969.

Welding Handbook, Sect. 3A. 6th ed. Miami: American Welding Society, 1970.

Welding Handbook, Sect. 3B. 6th ed. Miami: American Welding Society, 1971.

2
Physics of Welding

Prepared by a committee consisting of:

A. F. MANZ, *Chairman*
Union Carbide Corp.
C. M. ADAMS, JR.
University of Cincinnati
D. G. ANDERSON
*Quanta Welding Co.**
R. BAKISH
Bakish Materials Corp.
J. H. DEPPELER, JR.
Thermex Metallurgical, Inc.
K. E. DORSCHU
*Electrotherm Corp.***
O. KREISEL
Electric Arc, Inc.
J. W. McGREW
Babcock & Wilcox
F. R. MEYER
Sonobond Corp.
W. C. RUDD
Thermatool Corp.
J. WEBSTER
Coherent Radiation

---

*Now with Union Carbide Corp.
**Now with Franklin Institute Research Laboratories

2
Physics of Welding

INTRODUCTION

Most welding processes require the application of heat or pressure to produce a suitable bond. The physics of welding deals with the complex physical phenomena associated with welding including heat, electricity, magnetism, light, and sound.

Welding generally involves the application or development of heat, localized near the intended joint. The most frequently encountered autogenous means of heating for welding is electrical resistance, principally the contact resistance to the flow of electric current from one workpiece to another. Friction or electrical discharges (sparks and arcs) between members to be joined are also used quite successfully in specialized applications.

Friction or impact heating is generally regarded as incidental to such processes as ultrasonic or explosion welding, but, in fact, may contribute significantly to the joining action. Perhaps the only truly nonthermal welding process is cold welding which accomplishes joining through the mechanism of controlled cold plastic deformation of the members being joined.

Almost every imaginable high intensity heat source has been used at one time or another in welding. Externally applied heat sources of technical importance include arcs, electron beams, light beams (lasers), exothermic reactions (oxyfuel gas and thermit), and electrical resistance. Welding processes that acquire heat from these external sources are *usually* identified with and named by the type of heat source employed. The heat source may either move or remain stationary with respect to the workpiece, depending on the specific process and application. The processes in this category are listed below:

- Arc welding
  - Shielded metal arc welding (SMAW)
  - Gas metal arc welding (GMAW)
  - Flux cored arc welding (FCAW)
  - Gas tungsten arc welding (GTAW)
  - Electrogas welding (GMAW-EG; FCAW-EG)
  - Plasma arc welding (PAW)
  - Submerged arc welding (SAW)
- Resistance welding (RSW; RSEW)
- Electroslag welding (ESW)
- Oxyacetylene welding (OAW)
- Thermit welding (TW)
- Laser beam welding (LBW)
- Electron beam welding (EBW)

In terms of production volume (tonnage shipped, total sales, etc.), these processes are by far the most important, with shielded metal arc welding predominant.

As usually implemented, a high intensity

Note: The SI (metric) and U.S. customary values given in this chapter are not, in most cases, exact equivalents. The SI values are the primary measurements used in this and all Volume I chapters. The secondary U.S. measurements (given parenthetically in text) are rounded off conversions from the SI values. For a further explanation of the system of measurements used in Volume 1, refer to the Foreword on p. xi heat source (used by one of the processes just listed) is applied to the prepared edges or surfaces of the members to be joined, and is moved along the path of the intended joint. The power and intensity of the heat source must be sufficient to accomplish local melting. Filler metal may be added, in which case the heat source may also perform the function of melting the filler metal intermittently or continuously as it is delivered to the joint. (However, there are highly specialized exceptions. Auxiliary means for heating the filler metal may be employed as in hot wire applications.)

To be useful in this type of welding, a heat source must transfer sufficient energy at high intensity to produce local melting. The transferred power is the rate at which energy is delivered per unit time from the heat source to the workpiece, typically expressed in watts (joules per second). The intensity is the transferred power per unit area of effective contact between the heat source and the workpiece, generally expressed in watts per square metre or square millimetre (watts per square inch). The intensity is a completely unambiguous measure of "hotness," applicable to all kinds of heat sources. (Heat sources are sometimes qualitatively compared in terms of temperature, a fairly satisfactory index of intensity for arcs and oxyfuel gas flames, but it is meaningless to speak of the "temperature" of an electron or laser beam.)

The significance of *intensity* as a heat source property cannot be overemphasized. In fact, the way welding devices have evolved over the years has, in large measure, been predicated on the development and adaptation of high intensity heat sources. Thus, the oxyacetylene flame, as used for welding, has been almost completely displaced by the higher intensity metal arc, and some of the most recently developed welding devices (plasma arc, electron beam, and laser beam) are unique, primarily because they provide intensities far higher than can be developed by a conventional welding arc.

The transfer of energy to a workpiece from an arc, flame, or electron beam is a complex process, and the intensity of a welding heat source cannot generally be expressed as a precise number. In the first place, it is difficult to define the area of contact between the heat source and the workpiece, and, secondly, the intensity is distributed nonuniformly over the contact area, typically exhibiting a maximum near the center. Although the detailed nature of energy transfer is quite complicated, the concept of intensity contributes much to the understanding and comparison of welding heat sources.

One way of regarding a welding heat source, such as an arc, is to consider two distinct heat transfer processes. Heat is first transferred from the source to the surface of the workpiece and then, by conduction, from the contact area to colder regions of the metal. These two processes are somewhat competitive. With a very high intensity heat source, such as an electron beam, energy is delivered through the contact area so rapidly that local melting occurs before there is any significant loss of heat by conduction. At the other extreme, a very low intensity source, such as the flame from a Bunsen burner, can transfer a large quantity of energy to the workpiece without any melting at all because the heat is conducted away almost as rapidly as it is delivered. Clearly, a Bunsen burner does not constitute a heat source useful for welding. The effectiveness of a welding heat source depends fundamentally and critically on its intensity.

Fundamental to the study of heat flow in welding,* primarily from the standpoint of how the heat source affects the material being welded, is the concept of "energy input" or in the case of arc welding, "arc energy input." Arc energy input is the quantity of energy introduced per unit length of weld from a traveling heat source such as an arc, expressed in joules per metre or millimetre (joules per inch). The energy input is computed as the ratio of the total input power of the heat source in watts to its travel velocity in millimetres per second (inches per minute).

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*See chapter 3, p. 79.

$$H = \frac{P}{V} \tag{2.1}$$

where

H = energy input, joules per millimetre
P = total input power of heat source, watts
V = travel velocity of heat source, millimetres per second

If the heat source is an arc, to a first approximation:

$$H = \frac{EI}{V} \tag{2.2}$$

where

E = volts (V)
I = amperes (A)

If the objective is to make a precise determination of the heat effects of arcs on the materials being welded, the net energy input, H_{net}, should be used:

$$H_{net} = \frac{f_1 EI}{V} \tag{2.3}$$

where f_1 is the heat transfer efficiency, the heat actually transferred to the workpiece divided by the total heat generated by the heat source. With most consumable electrode arcs, the distinction between H and H_{net} is not of great practical importance because the heat transfer efficiency, f_1, is generally greater than 0.8 and often close to 1.0.

The primary function of most heat sources is to melt metal. The quantity of metal which must be melted to produce a certain length of weld is dictated by the size and configuration of the joint, by the number of weld passes used, and by the welding process. Almost without exception, it is preferable, for metallurgical reasons, to accomplish the necessary melting with minimum energy input, an objective more easily realized the higher the intensity of the heat source.

In this connection it is useful to introduce the concept of melting efficiency, that fraction of the net energy input, H_{net}, which is used for melting metal. The bead-on-plate weld cross section shown schematically in Fig. 2.1 identifies three characteristic areas:

A_m = cross-sectional area of that portion of the weld metal bounded by the weld fusion line and the original top surface of the plate. This area times the unit length of weld is the volume of base metal which has been melted by the traveling heat source.
A_r = cross-sectional area of that portion of the weld metal sometimes referred to as the reinforcement. This area times the unit length of weld is the volume of filler metal added (in the molten condition).
A_z = cross-sectional area of the heat-affected zone; that portion of the surrounding solid metal which has undergone some significant change in structure or properties. (The basis for defining the outer extremity of the heat-affected zone must be established.)

The cross section of weld metal, A_w, is then:

$$A_w = A_m + A_r \tag{2.4}$$

Of course, if no filler metal is added, then

$$A_w = A_m$$

There is a specific theoretical quantity of heat, Q, required to melt a given volume of metal (from a cold start). The quantity, Q, is a property of a metal or alloy, and is obtained by adding (1) the heat required to elevate the temperature of the solid metal to its melting point, to (2) the heat of fusion, the heat required to convert solid to liquid at the melting point.

A reasonable approximation of Q is:

$$Q = \frac{(T_m + 273)^2}{300\ 000} \text{ J/mm}^3 \qquad (2.5)$$

where T_m equals the melting temperature, °C.

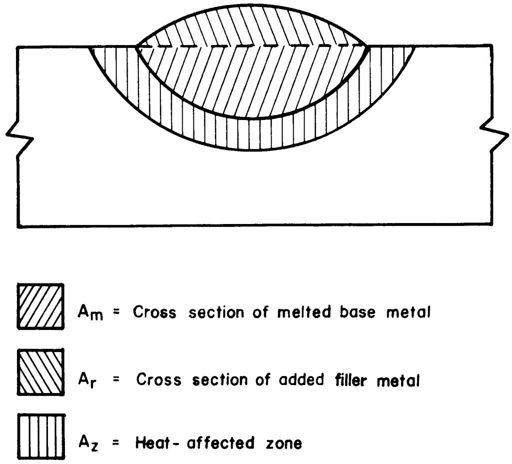

Fig. 2.1 — Bead-on-plate weld cross section.

The melting efficiency, f_2, characterizing a weld pass, can be determined by measuring the weld metal cross section and the net energy input. Specifically, f_2 is the theoretical minimum arc heat required for melting, divided by the net energy input:

$$f_2 = \frac{QA_w}{H_{net}} = \frac{QA_wV}{f_1P} = \frac{QA_wV}{f_1EI} \qquad (2.6)$$

The melting efficiency depends both on the process and the material being welded; it also depends on factors such as joint configuration and plate thickness. The higher the thermal conductivity of the metal being welded, the lower the melting efficiency because of the more rapid conduction of heat from the weld region.

The effect of thermal conductivity is more pronounced with a low intensity heat source. For example, when the oxyacetylene flame is used for welding aluminum, only about two percent of the heat delivered to the workpiece is used for melting metal; the rest is lost by conduction. (This fact helps explain why oxyfuel gas welding of aluminum is such a delicate art. By the time local melting occurs the entire weld region is very near the melting point, and, as anyone who has tried it can testify, there is great risk of melting a large portion of the workpiece.)

Very high intensity heat sources, such as the electron and laser beam, accomplish melting with virtually 100 percent efficiency; heat is delivered so locally and so rapidly that melting takes place before any significant thermal conduction occurs. An intensity of 10 kW/mm^2 (6.5 MW/in.^{2}) is close to the maximum which can be used in welding because, at higher intensities, boiling as well as melting occurs, and a cutting or erosive action results. Indeed high intensity devices such as laser beams are used for drilling and cutting.

The submerged arc is a remarkably efficient welding heat source. Its intensity and therefore its melting efficiency are higher than with any of the open arc processes.

There is a simple but important relationship between the weld metal cross section, A_w, and the energy input:

$$A_w = \frac{f_2H_{net}}{Q} = \frac{f_1f_2H}{Q} \qquad (2.7)$$

For any particular welding process, the efficiencies of heat transfer and melting, f_1 and f_2, do not vary greatly with changes in specific welding parameters, such as arc voltage, amperage, or travel speed. This means the cross section of a single weld pass is roughly proportional to the energy input. For example, when an arc weld pass is made on steel under the following conditions:

E = 20 V
I = 200 A
V = 5 mm/s
f_1 = 0.9
f_2 = 0.3
Q = 10 J/mm^3

then, the cross-sectional area of the weld pass can be estimated based on equation (2.7):

$$A_w = \frac{0.9(0.3)20(200)}{5(10)}$$

$$= 21.6 \text{ mm}^2 \ (0.03 \text{ in.}^2)$$

ENERGY SOURCES FOR WELDING

All welding processes require some form of energy. For many processes (such as the ones listed on p. 34), the energy source provides the heat necessary for melting and joining. However, there are welding processes that do not utilize heat, but nevertheless require some form of energy to produce a bond. The welding processes discussed in this section are grouped under these five categories of energy sources: electrical sources, chemical sources, optical sources, mechanical sources, and solid state sources.

While this section covers the most significant processes or process groups in each category, some important processes have been omitted. Flash welding, for instance, is not covered here, but it is nevertheless an important process which uses electrical resistance as its source of energy. A general discussion of the process can be found on p. 16 of Chapter 1.

Brazing and soldering, which are also omitted from the following discussion, cannot be categorized by their energy source (or heat source) because they can be performed using a variety of different energy sources. Their distinguishing feature is the temperature at which they are performed rather than their source of energy. For a general discussion of these processes, refer to p. 23 for brazing and p. 25 for soldering in Chapter 1 and p. 149 in Chapter 4.

ELECTRICAL SOURCES OF WELDING ENERGY

Arc Welding*

A large number of welding processes use the electric arc** as the source of heat for fusion because the heat of the arc may be effectively concentrated and controlled.

The physics of metal transfer through the arc has been studied extensively during recent years. The electric arc consists of a relatively high current discharge sustained through a thermally ionized gaseous column called a plasma.†

The power of an arc may be expressed in electrical units as the product of the current passing through the arc and the voltage drop across the arc. Given a typical value of 300 A and 25 V for current and voltage, the power dissipation of the arc would be 7500 watts.†† This power dissipation is equivalent to a heat generation of about 7.11 Btu/s. However, not all of the heat generated in the arc can be effectively utilized in arc welding processes. Values for the efficiency of heat utilization may vary from 20 to 85 percent in which convection, conduction, radiation, and spatter are responsible for heat losses. Efficiency of heat utilization is generally low for GTAW, intermediate for SMAW, and high for SAW.

The arc energy input parameter, already discussed, has been used in weldability studies for travel speeds within a narrow range for covered electrodes. However, with higher travel speeds, the efficiency of heat transfer in the fusion zone is increased, and for a constant arc energy input, the volume of the fused metal increases as the travel speed is increased. As a result, with automatic welding processes where higher speeds and higher currents are utilized, the use of the arc energy input parameter may not be adequate in making comparisons in weldability studies.

The use of a plasma torch or plasma arc torch as a heat source is a more recent development. The arc is directed through a nozzle through which a carrier gas flows. Instead of diverging into an open arc, the nozzle, located between the electrode and the work, constricts the arc into a small cross section.

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*Refer to Chapter 1 for a general discussion of arc welding processes, starting on p. 3.

**Due to the widespread use of arc welding methods and the importance of the electric arc, a separate section of this chapter is devoted to arc characteristics. See p. 52.

†The plasma is discussed in detail on p. 52.

††For dc, $W = EI$ but for ac, $W = EI \cos \theta$ where θ is the phase angle. In arc and resistance welding, $\cos \theta = 1$ for practical purposes since reactive losses may be assumed to be negligible. Cos θ is also called the "power factor."

This action greatly increases resistive heating of the arc so that both the arc temperature and voltage are raised. After passing through the nozzle, the arc exits in the form of a high velocity, column shaped, and intensely hot plasma jet. This plasma jet is referred to as a "plasma arc" and can be used as either a transferred arc or nontransferred arc.*

The plasma arc cutting of 25 mm (1 in.) thick aluminum plate at a speed of 20 mm/s (50 in./min) provides an example of the use of a transferred arc. A typical operation might require an arc using 170 V and 400 A with a gas flow of 70 litres/min (150 ft^3/h) through a 3 mm (1/8 in.) diam nozzle. The 68 kW of power would produce a power density in the nozzle of approximately 8.5 kW/mm^2 (5.5 $MW/in.^2$) and an average gas temperature of 9700 to 14 700 °C (17 500 to 26 500 °F). The resulting gas velocity approaches sonic velocity at these high temperatures. For arc welding operations, of course, the gas velocity is intentionally reduced in order to avoid spattering of the molten pool.

Resistance Welding**

The resistance welding processes employ a combination of force and heat to produce a weld between the workpieces. Resistance heating occurs as electrical (welding) current flows through the workpieces. The workpieces are generally in the secondary circuit of a transformer which converts the high voltage, low current commercial power into suitable high current, low voltage welding power.

The heat generated by current flow may be expressed by:

$$H = I^2Rt \qquad (2.8)$$

where

H = heat generated, in joules (watt • seconds)
I = current, in amperes
R = resistance, in ohms
t = time of current flow in seconds

The welding current and time can be easily measured, but the resistance is a complex factor and difficult to measure. The resistance that is important in resistance spot welding, for example, is composed of several parts:

(1) The contact resistances between the electrodes and the work.

(2) The contact resistance between the workpieces.

(3) The body resistance of the workpieces.

(4) The resistance of the electrodes.

Contact resistance is greatly affected by surface conditions such as cleanliness and freedom from oxides or other chemical compounds and by the toughness or smoothness of the surface. In addition, contact resistance is a direct function of the resistivities of the materials in contact and is inversely proportional to the welding force. With materials of uniform surface conditions, welding force becomes the major factor in the determination of contact resistance. Oxides, such as mill scale on steel, are of such nonuniform quality as to render uncertain the control of energy in resistance welding. It is therefore preferable to remove these oxides chemically or mechanically or to prevent their formation by cold rolling and controlled-atmosphere annealing.

Base metal resistance is proportional to the resistivity of the material and the length of the current path, and is inversely proportional to the area of the current path. For materials of high resistivity and heavier gages, the base metal resistance becomes more important, and the contact resistance becomes less important. For high conductivity materials, on the other hand, contact resistance is of the utmost importance. Differences in resistivity are reflected in the rather widely differing currents that are required to make the same size weld in various materials. In general, the magnitudes of the resistances involved are on the order of $100 \mu\Omega$. As a result, the currents are large, running into the thousands and tens of thou-

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*For an explanation of transferred and nontransferred arcs, refer to the discussion of plasma arc welding in Chapter 1, p. 11.

**Refer to Chapter 1, p. 14, for a general discussion of resistance welding.

sands of amperes. In the case of capacitor-discharge power supplies, the current may be as great as 200 000 A, but for a much briefer duration.

In the case of steel, contact resistance between the workpieces largely disappears during the first half cycle of the current flow. It might seem, therefore, that contact resistance would be of little importance. However, the greatly increased generation of heat during the first cycle, made possible by contact resistance, causes a significant increase in base metal resistance which rises with temperature. This rise in base metal resistance makes the remainder of the current more effective. The importance of contact resistance in materials of medium resistivity, such as steel, is borne out by the fact that higher welding forces, which reduce contact resistance, necessitate higher welding currents.

The quantity of heat (or energy) that is required to produce a given resistance weld is determined by several factors. The desired weld area (that is, heated volume), peak temperature, specific heat of the workpieces, and heat losses into the surrounding metal and electrodes are key factors. An increase in magnitude of one or more of these factors requires a corresponding increase in energy to produce the weld. The exact nature of a given resistance welded joint (service stresses, base metal, joint design, part dimensions, and so forth) has a significant effect on these key factors.

The particular resistance welding process and weld schedule selected are also significant in their effects on the above energy factors. For example, heat losses become significantly greater as the duration of current flow increases. Hence, long weld times require a corresponding increase in input energy to the weld to compensate for the heat losses.

As an example, it is possible to estimate the heat generated in the spot welding of two sheets of 1.0 mm (0.04 in.) thick steel that required a current of 10 000 A for 0.1 second. An effective resistance of $100 \mu\Omega$ will be assumed:

$$H = (10\,000)^2\ (0.0001)\ (0.1) = 1000\ \text{J}$$

Approximately 1381 J are required to heat and melt 1 g of steel (600 Btu/lb). Assuming that the fusion zone for the above weld is a cylinder of 5 mm (0.2 in.) diameter and 1.5 mm (0.06 in.) high, the fused metal would have a volume of approximately 31 mm^3 (1.89 $\times$ 10^{-3} in.^{3}), and a mass of 0.246 g (0.0005 lb).

To heat and melt this mass would require 339 joules. Additional heat would be utilized in raising the temperature of the surrounding metal and supplying the heat lost elsewhere.

By comparison, consider the use of a capacitor-discharge power supply in making a projection weld between two sheets of steel, each sheet also being 1.0 mm (0.04 in.) thick. The weld current pulse would have a typical effective value of 30 000 A and a flow time of 0.005 seconds.

$$H = (30\,000)^2\ (0.0001)\ (0.005) = 450\ \text{J}$$

The lesser quantity of heat, in this instance, is due to lower heat losses and the localizing of heat at the weld interface.

Electroslag Welding*

In electroslag welding (ESW), an electrode such as a wire is fed through an electrically conductive bath of molten slag. The resistance of the slag bath to the flow of current produces heat, the bulk of which is concentrated primarily in the slag area immediately surrounding the electrode tip. The quantity of heat, H, produced in the slag pool, can be expressed as $H = EIt$ (in joules), where t is time in seconds.

This heat melts the wire and base metal to form the weld. As the electrode wire or consumable nozzle and wire melt, weld metal is deposited through the molten slag which refines out some impurities and protects the weld metal from the atmosphere. The weld metal then solidifies upward as heat is extracted by the surrounding weldment, the containing shoes or dams, and the atmosphere.

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*Refer to Chapter 1, p. 12, for a general discussion of electroslag welding.

The manner in which the heat is transferred is complex. In a practical sense, however, the properties of the weldment can be determined, to a large extent, by controlling the pool shape. The pool shape is influenced by the nature and depth of the slag, the electrical parameters, the electrode and base metals and dimensions, and the geometry of the weldment.

While the slag is used primarily for converting electrical energy to thermal energy, its properties are important. The slag should be conductive and stable at reasonable operating temperatures; it should possess low volatility and provide the proper chemical reactivity required for producing suitable weld metal. The slag conductivity should vary as little as possible over the normal operating range.

For ESW to be stable, an essentially constant slag temperature should be maintained to provide a proper balance between heat generated and heat lost. The slag should have the proper viscosity so as to perform adequate refining without being so fluid that it leaks through shoe or backing bar openings too readily.

Generally, the best weld properties are obtained if the weld pool is shallow with a large radius of curvature. A shallow pool promotes vertical freezing with an acute angle between weld metal grains. Shallow pools are produced by high voltages and low current values. Deep and thus less desirable weld pools are produced by high current, high wire feed levels, and low voltages. The slag bath should also be relatively shallow since deep slag baths result in incomplete fusion.

ESW can be performed using either alternating or direct current (ac or dc). The choice of the current type is more significant for slag-metal reactions than for operating characteristics. Most ESW done in the United States uses direct current electrode positive (dcep). (This is also called direct current reverse polarity [dcrp].) Constant potential power sources and wire feeders are commonly used. Welding with ac usually produces more heat and the voltage is slightly higher than welding done with direct current.

CHEMICAL SOURCES OF WELDING ENERGY

Chemical energy stored in a wide variety of forms can be converted to useful heat. The temperature and rate of reaction are two major characteristics which determine the application of the various energy sources.

Oxyfuel Gas Welding*

The welding of steel with a fuel gas requires two flame characteristics: a high flame temperature capable of melting and controlling the weld metal and a neutral atmosphere surrounding the molten metal to prevent contamination before solidification. Most commonly used fuel gases achieve maximum flame temperatures over 2760 °C (5000 °F) when mixed with oxygen and burned in an open flame. At maximum temperature, the flames are oxidizing in nature and are therefore not suitable for welding due to the formation of oxides in the weld metal. Adjusting the flames to neutral by reducing the quantity of oxygen mixed with the fuels lowers most flame temperatures substantially as shown in Table 2.1.

Table 2.1 — Flame temperatures of oxyfuel gases

	Max temp.		Neutral flame temp.	
	°C	°F	°C	°F
Acetylene	3102	5615	3100	5612
MAPP†	2902	5255	2600	4712
Propylene	2857	5174	2500	4532
Hydrogen	2871	5200	2390	4334
Propane	2777	5030	2450	4442
Natural gas/methane	2742	4967	2350	4260

†Methylacetylene-propadiene (stabilized)

With the exception of the acetylene flame which is lowered by only 2 °C (3 °F), the flame intensities are reduced to the point where it is impossible to melt and control the weld puddle for other than thin sheet metal. Methylacetylene-propadiene (stabilized) can be used for welding providing special procedures are followed. The fuel-to-oxygen ratio must be adjusted to be slightly oxidizing so

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*Refer to Chapter 1, p. 17, for a general discussion of oxyfuel gas welding.

that the flame temperature is moderately increased, and a highly deoxidized filler metal must be used to produce sound weld metal.

The combustion of acetylene in oxygen at the orifice of a torch takes place in two steps. The first step is the burning of carbon to carbon monoxide, the hydrogen remaining unconsumed. This burning takes place in a small bluish white cone close to the torch in which the gases are mixed. This reaction provides the heat which is most effective for welding. In the second step, the burning of the carbon monoxide to carbon dioxide, and of the hydrogen to water vapor takes place in a large blue flame that surrounds the welding operation, but contributes only a preheating effect. The equations representing these two steps of combustion are as follows:

$$C_2H_2 + O_2 \rightarrow 2CO + H_2$$

$$2CO + H_2 + 1.5\ O_2 \rightarrow 2CO_2 + H_2O(g)$$

The first reaction generates heat by the breaking up of acetylene as well as by the formation of carbon monoxide. The dissociation of acetylene liberates 227 kJ/mol at 15 °C (59 °F). The combustion of carbon to form carbon monoxide liberates 221 kJ/mol. The total heat supplied by the first reaction is therefore 448 kJ/mol (501 Btu/ft^3) of acetylene.

The second reaction liberates 242 kJ/mol of water vapor by the burning of hydrogen. The combustion of carbon monoxide provides 285 kJ/mol or an additional 570 kJ/mol for the reaction. The total heat supplied by the second reaction is therefore 812 kJ/mol (907 Btu/ft^3).

Adding the heat supplied by the two reactions gives the total heat of combustion which is 1260 kJ/mol (1408 Btu/ft^3) of acetylene. The concentrated heat liberated by the first reaction in the small inner cone of the flame is 35.6 percent of the total heat. The remaining heat is developed in the large brush-like outer envelope of the flame, and is effective for preheating. It is this heat that reduces the thermal gradient and cooling rate for oxyacetylene welding (OAW).

One volume of oxygen is used in the first step of the combustion to burn one volume of acetylene. This oxygen must be supplied in the pure state through the torch. The one and one-half volumes of oxygen required in the second step are supplied from the atmosphere. When just enough oxygen is supplied to burn the carbon to carbon monoxide, as indicated in the first step, the resulting flame is said to be neutral. If less than enough oxygen is supplied to complete the combustion of the carbon, the flame is said to be a reducing or an excess acetylene flame. This flame has certain uses in welding and is discussed in other volumes of the *Handbook.** With more than enough oxygen for the first reaction, the flame is oxidizing.

The combustion of hydrogen is a simple reaction with oxygen to form water vapor. If sufficient pure oxygen were supplied to burn all of the hydrogen completely, the flame temperature would be approximately 2870 °C (5200 °F). However, this would not provide a protective outer envelope of reducing atmosphere and consequently would be impractical. If only enough pure oxygen to burn half of the hydrogen were provided, the concentrated heat would be 121 kJ/mol (135 Btu/ft^3). In the latter case, the flame temperature would drop to a little over 2480 °C (4500 °F).

An oxyhydrogen flame exhibits a temperature difference (above the melting point of steel) of about 930 °C (1700 °F) in contrast to about 1540 °C (2800 °F) for the oxyacetylene flame. Consequently, oxyhydrogen welding (OHW) is much slower for the welding of steel. It may be noted that by adjusting the amount of oxygen supplied, the relative proportions of concentrated heat and outer flame preheat may be varied. A similar control of the acetylene flame is not available since any attempt to reduce the relative amount of the outer envelope of heat results in an oxidizing flame, and a change in the other direction results in a carburizing flame.

Oxyacetylene torches of medium size are provided with a variety of orifices since acetylene flows from 0.9 to 142 litres/min (2 to 300 ft^3/h). Assuming a flow rate of 28

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*It is discussed in Section 3A of the *Welding Handbook*, Sixth Edition. In the Seventh Edition, it will tentatively be covered in Volume 2.

litres/min (60 ft^3/h), the total heat available would be 25 kJ/s (1408 Btu/min). However, remembering that approximately one-third of the heat is liberated in the small inner core of the flame, only 8.8 kJ/s (500 Btu/min) would be available at the torch tip. The efficiency of heat utilization is very low in most cases. Typically, heat transfer rates for oxyacetylene torches are on the order of 1.6 to 16 $J/mm^2 \cdot s$ (1 to 10 $Btu/in.^2 \cdot s$).

Thermit Welding

Thermit welding (TW) encompasses a group of processes which uses heat from exothermic reactions to perform welding and other operations. The process name is derived from "thermite," the generic name given to reactions between metal oxides and reducing agents. The usual oxides are those that have low heats of formation and the usual reducing agents are those which, when oxidized, have high heats of formation. The excess heats of formation of the products, as compared with the starting materials of the reaction, represent the heat produced by the reaction, hence the term "exothermic."

Typical thermit reactions, and their theoretical temperatures are as follows:

$$3Fe_3O_4 + 8A1 = 9Fe + 4A1_2O_3 + 3010\ \text{kJ/mol}\ (3088\ °C\ [5590\ °F])$$

$$3FeO + 2A1 = 3Fe + A1_2O_3 + 783\ \text{kJ/mol}\ (2500\ °C\ [4532\ °F])$$

$$Fe_2O_3 + 2A1 = 2Fe + A1_2O_3 + 759\ \text{kJ/mol}\ (2960\ °C\ [5360\ °F])$$

$$3CuO + 2A1 = 3Cu + A1_2O_3 + 1152\ \text{kJ/mol}\ (4866\ °C\ [8790\ °F])$$

$$3Cu_2O + 2A1 = 6Cu + A1_2O_3 + 1089\ \text{kJ/mol}\ (3138\ °C\ [5680\ °F])$$

$$3NiO + 2A1 = 3Ni + A1_2O_3 + 864\ \text{kJ/mol}\ (3171\ °C\ [5740\ °F])$$

$$Cr_2O_3 + 2A1 = 2Cr + A1_2 0_3 + 2287\ \text{kJ/mol}\ (2977\ °C\ [5390\ °F])$$

$$3MnO + 2A1 = 3Mn + A1_2O_3 + 1686\ \text{kJ/mol}\ (2427\ °C\ [4400\ °F])$$

$$3MnO_2 + 4A1 = 3Mn + 2A1_2O_3 + 4356\ \text{kJ/mol}\ (4993\ °C\ [9020\ °F])$$

In TW, the parts to be welded are aligned with a gap between them, and a mold, either built on the parts or formed on a pattern of the parts, is placed in position. The next step varies according to the size of the parts. If they are large, preheating within the mold cavity is necessary to bring the parts to welding temperature and to dry out the mold. If the parts are small, however, preheating is often eliminated. The superheated products of a thermit reaction are next allowed to flow into the gap between the parts with sufficient heat to melt both faces of the base metal. When the filler metal has cooled, all unwanted excess metal may be removed by oxygen cutting, machining, or grinding.

The first reaction in the preceding series of formulas is the one most commonly used as the basis in formulating thermit mixtures for welding. The proportions of such mixtures are usually about three parts of iron scale to one part of aluminum. The theoretical temperature resulting from such a reaction is 3088 °C (5590 °F). Radiant heat loss and losses to the reaction vessel or crucible, however, reduce this temperature to about 2540 °C (4600 °F). Other additions to the mixture to adjust the metal for chemistry and the slag for fluidity serve to further reduce the temperature. In practice, weld metal temperatures are designed for 400 to 550 °C (750 to 1020 °F) superheat. Approximately 35 kJ/kg (1500 Btu per hundred pounds) of base thermit are generated during the reaction. The reaction is not explosive and requires less than one minute to complete itself, regardless of size. No fire hazard is incurred under normal conditions of handling and storing thermit mixtures since an initial temperature of more than 1205 °C (2200 °F) is needed for ignition. To start the reaction, a special starting thermit incorporating peroxides, chlorates, or chromates as the oxidizing agent is required.

Thermit mixtures employed for welding generally contain materials in addition to iron oxide and aluminum. By using these additional materials, variables such as the time and temperature of reaction and the chemical analysis of the weld metal produced can be controlled. For example, additions either in the form of metal pieces which are melted during the reaction, or of secondary exothermic reactions chosen from the preceding list of equations make possible wide variations in weld metal to meet almost any of the standard AISI or SAE steel classifications. Similarly, physical properties of the weld metal can be varied over a wide range and as-welded tensile strengths between approximately 350 and 900 MPa (50 000 and 130 000 psi), with elongations of over 40 percent in 50 mm (2 in.) for the lower tensiles, are possible.

In designating the weight of thermit mixtures for welding, only the iron oxide and aluminum are considered. Additions for adjustment of analysis and temperature are not included in the given weight. Thus 45 kg (100 lb) of oxide and aluminum, to which have been added 14 kg (30 lb) of metals and alloys, are termed 45 kg of thermit.

The heat liberated is expressed only in terms of the basic oxide and aluminum in the mix. Temperatures, however, obviously are for all of the reaction products.

OPTICAL SOURCES OF WELDING ENERGY

Two sources of welding energy, the laser and electron beam, are focused beams that operate according to the laws of optics. In the case of the laser beam, focusing is accomplished by various lens arrangements. Electrostatic and magnetic means are employed to focus the electron beam. Consequently, high power densities can be achieved with these methods.

Lasers

A high degree of spectral purity and low divergence of the laser output beam permit focusing of laser radiation to extremely precise areas, resulting in power densities often greater than 10 kW/mm² (6.45 MW/in.²). The raw beam exiting from a laser source may be typically 1 to 10 mm (0.04 to 0.4 in.) in diameter and must be focused to be useful for laser beam welding (LBW)* applications. The focused spot size, d, of a laser beam is given by

$$d = f\theta \qquad (2.9)$$

where f is the focal length of the lens and θ is the full angle beam divergence.

The power density, PD, at the focal plane of the lens is given by

$$PD = \frac{4P_1}{\pi d^2} \qquad (2.10)$$

where P_1 is the input power, hence

$$PD = \frac{4P_1}{\pi (f\theta)^2} \qquad (2.11)$$

Therefore power density is determined by the laser power, P, and beam divergence, θ. For a laser beam operating in the fundamental mode where the energy distribution across the beam is gaussian, the beam divergence is

$$\theta \propto \frac{\lambda}{a} \qquad (2.12)$$

where a is a characteristic dimension of the laser beam and λ is the wavelength of laser radiation. Note that, according to equations (2.11) and (2.12), the power density is inversely proportional to the square of the wavelength of the laser radiation.

Lasers used for welding can be grouped conveniently as solid state lasers and gas lasers. The solid state lasers are ruby, Nd:Glass,** and Nd:YAG,** and the chief gas laser is the CO_2. Ruby and Nd:Glass are capable of high energy pulses, but are limited in maximum repetition rate. Nd:YAG and CO_2 lasers can be continuous wave or pulsed at very high repetition rates.

Most metallic surfaces reflect appreciable amounts of incidental laser radiation. In practice, however, sufficient energy is usually absorbed to initiate and sustain a continuous molten puddle. Ruby and Nd:Glass lasers, because of their high energy outputs per pulse, can overcome most metal welding reflectivity

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*Refer to Chapter 1, p. 21, for a general discussion of laser beam welding.

**Lasers in which glass (Nd:Glass) or single crystals of Yttrium-Aluminum-Garnet (Nd:YAG) are doped with Nd (neodymium) ions as the active medium.

Table 2.2 — Thermal time constants — laser beam welding seconds

Material	Time, in seconds		
	Thickness 0.13 mm (0.005 in.)	Thickness 0.64 mm (0.025 in.)	Thickness 2.5 mm (0.100 in.)
Copper	0.035	0.884	14.1
Brass	0.119	2.970	47.5
Aluminum	0.047	1.170	18.8
1% Carbon steel	0.333	8.330	133.3
Stainless steel	1.004	25.100	401.7
Nickel	0.260	6.500	104.1
Inconel	0.948	23.700	379.3
Titanium	0.593	14.800	237.3
Tungsten	0.060	1.509	34.1

problems. However, due to their inherently low pulse rates, typically 1 to 50 pulses per second, welding speeds in thin gage metals are extremely slow. In contrast, Nd:YAG and in particular CO_2, lasers are capable of very high continuous wave outputs or they can be pulsed at several thousand pulses per second, giving rise to high speed continuous welding.

Pulsed Laser Beam Welding

When a pulse of focused solid state type laser energy is incident on a metallic surface, the beam energy is absorbed within a very small area and may be dealt with as a surface heating phenomenon. Thermal response beneath the focused spot, therefore, depends on heat conduction. The depth to which the energy pulse is felt in time, t, is thus dependent on the thermal diffusivity of the metal, and is given approximately by $\sqrt{4kt}$ where k is the thermal diffusivity. This leads to the concept of a thermal time constant for a metal plate of thickness, x. The thermal time constant is equal to $x^2/4k$ which represents the pulse duration required for penetration.

For effective melting, the laser pulse should be approximately equal to the thermal time constant for the given metallic sample. For 0.13 to 0.25 mm (0.005 to 0.010 in.) thick metals, thermal time constants are comparable to pulse durations from normal solid state pulsed lasers. If the laser pulse is very short with respect to thermal diffusion time, the pulse energy is deposited primarily at the surface and rapid localized heating occurs with very little depth of penetration. This type of heating effect results in metal being vaporized from the surface. In laser beam welding, the lower surface of the metal must reach the melting point before the upper surface reaches the vaporization point. Consequently, thermal diffusivity and pulse duration control the depth to which successful porosity-free welds can be made. Typically, a solid state laser can be pulsed for an on period of ten milliseconds; this limits the depth of penetration to 1.0 mm (0.04 in.). (See Table 2.2.)

Continuous Wave Laser Beam Welding

Nd:YAG and CO_2 lasers are capable of making high speed continuous metal welds. Lasers in excess of 500 W output are capable of welding steel sheet 0.25 mm (0.010 in.) thick at several millimetres per second, while CO_2 lasers of 10 kW continuous wave output power can produce deep penetration welds in 13 mm (1/2 in.) thick steel at 25 mm/s (60 in./min).

When heating or melting a metal with a laser beam, the concept of energy absorbed per unit volume of metal becomes a controlling parameter. The energy absorbed can be written in dimensions of joules per cubic millimetre. This parameter becomes a measure of power density/welding speed. For example,

$$\mathrm{W/mm^2} \times \mathrm{s/mm} = \mathrm{J/mm^3}$$

Electron Beam Welding*

In electron beam welding (EBW), energy is impressed upon the workpiece by bombarding it with a focused beam of electrons. The power density in watts per unit area is given by

$$P = \frac{neE}{A} = \frac{EI}{A} \qquad (2.13)$$

where

n = total number of electrons per second in the beam

e = 1.602×10^{-19} (the charge of an individual electron in coulombs)

E = the accelerating voltage on the gun, in volts

I = the beam current in amperes

A = the area of the focused beam on the workpiece

Once the beam has been focused, depth of penetration is determined by the beam current, accelerating voltage, and relative speed of the welding.

Power concentrations of 1 to 100 kW/mm^2 (0.65 to 65 MW/in.^{2}) are routinely achieved, and 10 MW/mm^2 (65 000 MW/in.^{2}) can be obtained. The ability to obtain a high concentration of energies in the beam is voltage dependent. Electron beam welding is generally performed at voltages between 20 kV and 150 kV, with the higher voltages having higher power densities, but at the same time requiring more x-ray protection.

The advantages associated with the EBW process include a high depth-to-width ratio, high strength, and the ability to weld thick sections in a single pass with low heat input, low distortion, and minimum width of the heat-affected zone. These advantages result from the ability to focus large concentrations of electron beam power in a small spot.

Deep welding penetration is not the direct result of the ability of electrons to traverse solids, but is associated with the high power densities, achievable with electron beams, that cause practically instantaneous volatilization of metals. This produces a needlelike vapor-filled cavity or keyhole in the workpiece through which the beam can penetrate. (This cavity is held open by the pressure associated with the volatilization of the workpiece material.) As a result of the relative motion between the workpiece and the beam, surface tension and gravity act to cause molten metal to flow into the cavity.

Thus EBW can be viewed as resulting from the motion of a beam-created cavity through the section to be welded. Consequently, a melted zone with a high depth-to-width ratio is created. The limited ability of the beam to traverse matter is an extremely important aspect since the penetration can be accomplished only if the beam can be transmitted through the cavity.

There are three commercial variants of the EBW process, distinguished by the degree of vacuum used:

(1) Hard vacuum EBW, the pioneering process operational at a pressure of 0.013 Pa (10^{-4} torr) or lower.

(2) Commercial vacuum or soft vacuum EBW, operational at pressures of 13.0 Pa (10^{-1} torr).

(3) Nonvacuum EBW which operates at 100 kPa (1 atm). Each of these has different performance capabilities and has excelled in different application areas.

The hard vacuum process is the most powerful of all these and has the best depth-to-width performance capabilities, the highest purity of the fusion zone, and, consequently, produces the best properties when joining interstitial embrittlement-sensitive materials. It has the longest working distance (up to 750 mm [30 in.]) and the ability to weld the greatest thickness of metal. As a matter of fact, with this mode one can join virtually any metallic substance or combination of substances deemed weldable by accepted physical metallurgy and phase diagram criteria for weldability. This mode is capable of welding a wide range of thicknesses from a few thousand angstroms to over 150 mm (6 in.) and, in special cases, up to 225 mm (9 in.) with a single pass.

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*Refer to Chapter 1, p. 20, for a general discussion of electron beam welding.

This process is performed using electron guns with 30 kV to 150 kV acceleration, the bulk of the equipment being operational at 60 to 150 kV. The systems power level can be in the 1 to 25 kW range with higher power levels possible, but, to date, only limited requirements for a higher power system have been found. The welding is performed in a variety of systems with several prevailing varieties. One system has either stationary or movable guns, and observation of the workpiece is either coaxial to the gun (most preferred and best) or oblique.

Inasmuch as the workpiece is always confined in a vacuum chamber which determines the maximum size of object to be processed, a large variety of chamber sizes as well as shapes have been manufactured over the years. Rectangular chambers have been the most widely used though a number of cylindrical chambers for very long objects (nuclear fuel elements, for example) have been built.

Operation of the equipment is either manual or programmed with numerically controlled (NC) machines being the preferred choice in recent years. This welding mode which was discovered in connection with the needs of the nuclear industry continues to provide service to this industry. Today, aerospace, aircraft, automotive, and instrumentation industries also use the hard vacuum mode because of the substantial advantages it offers.

The soft vacuum mode follows the hard mode in terms of performance capabilities with working distance on the order of 300 mm (12 in.), the ability to join metal thicknesses up to 50 mm (2 in.), and virtually no penalty for contamination of the fused zone. For example, air at 5 Pa (3.8×10^{-2} torr) has a contaminant level comparable to 99.995 percent pure argon gas. The main advantage of the soft vacuum process is that the operational pressure required is obtained by simple mechanical pumping in contrast to the hard vacuum mode where a combination of mechanical and diffusion pumping is needed to reach the operational pressures for the process. The speed of operation, quality, and suitable fusion zone configuration at higher pressures makes this mode very attractive. The workpiece is also confined by a work chamber and utilizes the smallest possible chamber capable of fitting a part to be welded. As a matter of fact, this mode is readily adapted to use special chambers for each part to be welded. Since the beam must be generated at 0.13 mPa (10^{-6} torr), the beam reaches the workpiece after it passes through a high impedance orifice and before it is brought to the relatively higher pressure workpiece area of the vacuum chamber. This mode is carried out with machines in the 60 to 150 kV range and up to 15 kW of power.

The nonvacuum EBW process, also referred to by some as the inert atmosphere EBW, is the least versatile and powerful of the modes. However, it does have one major advantage over the other two process methods: It does not require a vacuum work chamber. Since the 0.13 mPa (10^{-6} torr) pressure is needed to generate the beam, as is the case in the other two modes, the beam is again so generated, but here it is brought onto the workpiece through two sets of differentially pumped chambers. These are interconnected with orifices the size of the beam to bring the beam in steps up to the nominal atmospheric pressure of the shielding gas at the work.

Unlike the other two modes, there is only about 25 mm (1 in.) of working distance because of the severe scattering of the beam by the air molecules which leads to substantial power loss. Also, the high depth-to-width ratio fusion zone which the other modes produce and which is considered the earmark of EBW cannot be obtained with inert atmosphere EBW nor can it weld metals sensitive to embrittlement by interstitials. The shielding from x-rays produced by EBW at the work, which is usually provided by the design of the vacuum chamber, must be provided externally in the nonvacuum process. Nevertheless, there are diverse manufacturing operations possible with this process, as for example, butt welding of seamless tubing, where the nonvacuum inert atmosphere process has met with considerable success and can perform quite competitively. The development of new applications, including some in the automotive field, is in progress.

MECHANICAL SOURCES OF WELDING ENERGY

The three processes discussed in this category—friction, ultrasonic, and explosion welding—are officially classified by AWS as solid state processes although some authorities consider them to involve localized melting. (According to the authors of the following text, localized melting does not occur with these processes.) Whether or not localized melting is a factor, these processes all involve some type of mechanical movement which produces the energy for welding. This feature distinguishes them from a solid state process such as diffusion welding which is characterized by lack of motion.

Friction Welding*

In friction welding (FRW), a bond is created between a stationary and a rotating member by utilizing the frictional heat generated between them while subjected to high normal forces on the interface. Application of this process requires that the rotating member be essentially symmetrical about the axis of rotation while the other member can be of any geometry that is within the clamping limitations of the welding machine.

Practical application of this welding heat source utilizes one of three approaches: (1) relatively slow speeds and high normal force, (2) high speed and lower normal force, or (3) a flywheel that is disengaged from the rotating power source before the start of welding. In the latter case, the rotational speed is continuously decreasing during the welding cycle. The first two approaches are referred to as conventional FRW while the latter, because of the use of the energy in the flywheel, is called inertia welding. Both make use of the frictional heating of the interface as the welding energy source.

Since frictional heat is related to speed and normal force, the time required to produce a bond is a function of both of these parameters. Also, the radial temperature distribution is nonuniform, being highest near the outer surface where the surface speed is highest.

Recent studies indicate that the average interface temperature is always below the melting point of either member being joined. Thus, the bond is metallurgically achieved by diffusion rather than fusion. Because of this, the process is admirably suited for joining dissimilar metals, particularly those that undergo undesirable phases when joined by melting processes. The width of the diffusion zone may vary from a line that cannot be accurately defined in width by present techniques to one readily detected by a relatively low power metallograph.

Ultrasonic Welding

Ultrasonic welds are produced by the introduction of high frequency vibratory energy into the weld zone of metals to be joined. Ultrasonic welding (USW) is generally used to produce spot, straight, and circular seam (ring) welds between members of which at least one is of sheet or foil thickness. The workpieces are clamped together between two tips or jaws, and the vibratory energy is transmitted through one or both tips which oscillate in a plane essentially parallel to the weld interface. This oscillating shear stress results in elastic hysteresis, localized slip, and plastic deformation at the contacting surfaces which disrupt surface films and permit metal-to-metal contact. The process thus produces a metallurgical bond between similar or dissimilar metals without melting. The elastic and plastic deformations induce a very localized, transient temperature rise at the weld interface. Under proper conditions of clamping force and vibratory power, the temperatures reached are usually in the range of 35 to 50 percent of the absolute melting point of the metals joined.

By means of a frequency converter, 60 Hz electrical power is transformed into high fre-

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*Refer to Chapter 1, p. 19, for a general discussion of FRW.

quency generally within the range of 15 000 to 75 000 Hz, although higher or lower frequencies may be used. The high frequency electrical power is converted into acoustical power at the same frequency by one or more transducers of either the magnetostrictive or piezoelectric ceramic types. Appropriate acoustical coupling members transmit the acoustical power from the transducer to the work-contacting tip and into the metal workpieces.

With recently developed solid state frequency converters, more than 90 percent of the line power is delivered electrically as high frequency power to the transducer. The electromechanical conversion efficiency of the transducers, that is, its efficiency in converting electrical power into acoustical power, is in the range of 25 to 35 percent for magnetostrictive nickel-stack transducers and is frequently in excess of 75 percent for piezoelectric transducers such as lead zirconate titanate ceramics. Thus, in the case of ceramic transducers, as much as 65 to 70 percent of the input electrical line power may be delivered to the weld metal as acoustical power.

The amount of acoustical energy required to weld a given material increases with material hardness and thickness. This relationship for ultrasonic spot welding can be expressed, as a first approximation, by the equation:

$$E_a = 63\, H^{3/2} t^{3/2} \qquad (2.14)$$

where

E_a = acoustical energy in joules

H = Vickers microindentation hardness number

t = thickness of the material adjacent to the ultrasonically active tip, in inches

This empirical equation is reasonably valid for common metals such as aluminum, steel, nickel, and copper in thicknesses up to at least 0.81 mm (0.032 in.). Some of the more exotic materials are less responsive to this relationship. Experimentation over a range of welding machine settings is usually recommended to establish precise settings that will produce satisfactory welds in a given material and material thickness.

Explosion Welding

In explosion welding (EXW), the detonation of an explosive is utilized to accelerate one of the components (called the flyer) to a high velocity before it collides with the stationary component. At the moment of impact, the kinetic energy of the flyer plate is released as a compressive stress wave on the surface of the two components. The pressure level of these stress waves is on the order of thousands of megapascals (millions of pounds per square inch). During explosive bonding, the collision progresses across the surface of the plates being welded so that an angle is formed between the two colliding components. The surface films are liquefied, scarfed off the colliding surfaces, and jetted out of the interface leaving perfectly clean, oxide-free surfaces. Under these conditions, the normal interatomic and intermolecular forces create a bond. The result of this process is a cold weld without a heat-affected zone.

The energy for the EXW process is provided by an explosive. The detonation velocity of the explosive must fall within limits to produce the necessary impact velocity and angle between the two components. The maximum velocity of the explosive detonation should not exceed the highest sonic velocity within the materials being bonded. The physical forms of the explosives utilized include plastic flexible sheet, cord, and pressed, cast, granulated, and liquid shapes. These explosives also vary in detonation velocity. They are usually detonated with a standard commercial blasting cap.

Most explosive bonding applications today use a low detonation velocity explosive, which is usually placed in direct contact with the flyer plate. Low velocity explosives develop relatively lower pressures than the high velocity explosives and can be used without causing shock damage. These explosives make it easier and more practical to achieve explosive bonding. The explosives used should have a detonation velocity of approximately 2400 to 3600 m/s (8000 to 12 000 ft/s). The detonation velocity depends on the thickness of the explosive layer and the packing density.

When the detonation velocity is less than the sonic velocity of the metal, the pressure generated in the metal by the expanding gases moves faster than the detonation and is spread out ahead of the detonation front. A shock wave is not produced. If the detonation velocity of the explosive is slightly greater than the sonic velocity in the metal, a detached shock wave may be created. In this case, the detonation velocity slightly exceeds the metal sonic velocity and a shock wave is formed which moves slightly ahead of the detonation. High velocity explosives are difficult to use for high quality bonding because they can cause considerable shock wave damage resulting in spalling along the edges and fissuring at the bond interface. When high velocity explosives are used, thick buffers are required between the explosive and the cladding plate.

The velocity of the flyer plate can be changed by changing the explosive charge per unit of area. If it is increased, several things can happen:

(1) The angle of incidence at which bond waviness begins increases.

(2) Larger waves are produced with the same angle of incidence.

(3) The range of angles within which waves are produced also increases.

(4) Tendency for the formation of intermetallic compounds in the weld interface increases.

Two components will not bond if the explosive charge per unit area is too low. This shows that there is a minimum flyer plate velocity.

The detonation velocity tends to be constant throughout the entire explosion. Since the energy release of most explosives depends on the thickness of the explosive and the degree of confinement, the detonation velocity may vary as these quantities are changed. The velocity may also be varied by selection of the explosive ingredients and by changing the packing density of the explosive.

SOLID STATE SOURCES OF WELDING ENERGY

Diffusion Principles and Mechanisms

Because diffusion plays an essential role in solid state welding, a short description of the theory and the mechanism of diffusion is in order.

The diffusion phenomenon is of prime importance from both the theoretical and practical aspects of metallurgy because of the many phase changes that take place in metal alloys involving a redistribution of the atoms present. These changes occur at rates that are dependent on the speed of the migrating atoms.

Diffusion in metal systems is usually categorized into three different processes depending on the path of the diffusing element. Each of these processes—volume diffusion, grain boundary diffusion, and surface diffusion—have different diffusivity constants. The specific rates for grain boundary and surface diffusion are higher than the rate for volume diffusion.

Fick's first law gives the basic equation for diffusion in metals as:

$$\frac{1}{A}\frac{dm}{dt} = -D\frac{\partial c}{\partial x} \qquad (2.15)$$

where

$\frac{dm}{dt}$ = rate of flow (g/s) of metal across a plane perpendicular to the direction of diffusion

D = diffusion coefficient whose values depend on the metallic system being considered (cm^2/s); minus sign expresses a negative concentration gradient

A = the area (cm^2) of the plane across which diffusion occurs

$\frac{\partial c}{\partial x}$ = the concentration gradient that exists at the plane in question (c is expressed in g/cm^3)

x = distance, cm

The diffusion coefficient, *D*, is not generally constant since it is a function of such dynamic variables as temperature, concentration, and crystal structure. Since at any one particular time these variables are assumed to have finite values, the coefficient *D* is a definite number.

Several mechanisms can account for the diffusion of atoms in metals. Two of these are the interstitial mechanism and the vacancy mechanism. The former is concerned with the movement of atoms having small atomic radii compared to the matrix atoms. These elements move from one location to another along the interstices of the crystal lattice, hence the name interstitial elements. These moves occur within the crystal without distorting or permanently displacing the matrix atoms.

The matrix or substitutional atoms use the vacancy mechanism for their mode of transportation. Because of their size, it is literally impossible for these atoms to migrate along the interstices. The only path open to them is the vacancy sites. Although the energy required to move a matrix atom is equal to that for an interstitial element, the rate is considerably slower due to the fewer vacant locations available to the atoms.

The pronounced effect that temperature has on diffusion may be evaluated by the rule of thumb that an 11 °C (20 °F) rise in temperature will double the diffusion constant. It has been found that the diffusion constant changes with variations in concentration. For example, the diffusion constant of carbon in iron at 930 °C (1700 °F) will show a three fold increase over a range of carbon from 0 to 1.4 percent. Crystal structure has also been found to influence the diffusion constant at a given temperature. Self-diffusion of iron occurs 100 times more rapidly in ferrite than in austenite. Directionality of a crystal also influences the diffusion constant. It has also been shown that crystal distortion due to plastic deformation usually increases with the rate of diffusion.

The Welding Process

Solid state welding as reported in the literature has often been referred to by a number of names: diffusion bonding, pressure bonding, self-welding, gas pressure bonding, eutectic brazing, eutectic bonding, and so forth. The one common denominator of all these techniques is a solid state bond between the base metals being joined. Each different name describes a specific technique used to secure the same resultant welded joint.

Perhaps because of the nature of the joining procedure, with diffusion playing a major role, the term diffusion welding (DFW)* should really be considered the parent subject. The techniques noted, including solid state bonding, are only variations of it. The following definition will be used here: Solid state welding is a joining technique in which time, temperature, and pressure produce, through diffusion, coalescence of the base metals at temperatures below their melting point or melting range.

The two key words in the definition are diffusion and coalescence. Diffusion depicts the mechanism by which actual joining occurs. Coalescence (growing or coming together into one) characterizes the final condition in the joint after the bonding process is completed.

Time, temperature, and pressure are the three essential ingredients of this process. The metal surfaces to be welded are prepared and placed in intimate contact with each other, and this union is maintained by applying external pressure. The assembly is then heated to a selected temperature and held at this temperature for a given time. (Actual times and temperatures vary from metal to metal.) While in intimate contact at the selected temperature, the atoms in the metal acquire increased energy due to the elevated temperature to which they are subjected. This energy causes the atoms to become more and more mobile and in time they migrate from one location to another. After a specified period of time, the transport of atoms across the original joint interface results in a solid state bond.

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*Refer to Chapter 1, p. 18, for a general discussion of diffusion welding.

ARC CHARACTERISTICS

DEFINITIONS

For all practical purposes, a welding arc can be thought of as a gaseous conductor which changes electrical energy into heat. The arc is the heat source for many important welding processes because it produces a high intensity of heat and is easy to control through electrical means. Some unexplained phenomena of arcs appear to require new concepts because known laws are not applicable in all cases.

Arcs are more than heat sources. They are sources of radiation as well. They may be used as sources of light, as in arc lamps, or sources of radiant energy, as in the testing of materials. When used in welding processes, the arc helps remove surface oxides in addition to supplying heat. The arc is also able to control the transfer of metal.

The welding arc can be defined as a particular group of electrical discharges that are formed and sustained by the development of a gaseous conduction medium. The current carriers for the gaseous medium are produced by thermal means and field emission. Many kinds of welding arcs have been conceived, each with a unique application in the field of metal joining. In some cases, the welding arc, an electrical discharge between two electrodes, is a steady state device, but more frequently it is intermittent, subject to interruptions by electrical short circuiting, or it is continuously nonsteady, being influenced by an alternating directional flow of current or by turbulent flow of the conducting gas medium.

THE PLASMA

The arc current is carried by the plasma, the ionized state of a gas composed of nearly equal numbers of electrons and ions. The electrons, which support most of the current conduction, flow out of a negative terminal (cathode) and move toward a positive terminal (anode). Mixed with the plasma are other states of matter, including molten metals, slags, vapors, neutral and excited gaseous atoms, and molecules. The establishment of the neutral plasma state by thermal means, that is, by collision processes, requires the attainment of equilibrium temperatures according to the ionization potential of the material from which the plasma is produced. The formation of plasma is governed by an extended concept of the Ideal Gas Law and the Law of Mass Action. A basic equation is:

$$\frac{n_e n_1}{n_o} = \frac{2 Z_i (2\pi m_e KT)^{3/2} e \quad -V_i}{Z_o h^3 \qquad\qquad KT} \qquad (2.16)$$

where

n_e, n_i, and n_o = particle densities (number per unit volume for electrons, ions, and neutral atoms, respectively).

V_i = the ionization potential

T = temperature in degrees absolute

Z_i and Z_o = partition functions for ions and neutral particles

h = Planck's constant

m_e = the electron mass

K = Boltzmann's constant

The particle densities of three kinds of particles can be determined by assuming equilibrium conditions, making the densities of electrons and ions equal.

$$n_e = n_i$$

The composition of heated argon calculated with equation (2.16) is shown in Fig. 2.2.

The expression of thermal equilibrium of the heated gas in an arc means that all kinetics and reactions of the particles in a microvolume may be represented by the same temperature. Thermal equilibrium in welding arcs is closely approached, but may be considered only approximate because of the influence of dominant processes of energy transport, including radiation, heat conduction, convection, and diffusion. The heated gas of the arc attains a maximum temperature of between 5000 and 50 000 K, depending on the kind of gas and the intensity of current carried by it. The degree of ionization is between 1 and 100 percent; complete ionization is based on all particles being at a temperature corresponding to the first ionization potential.

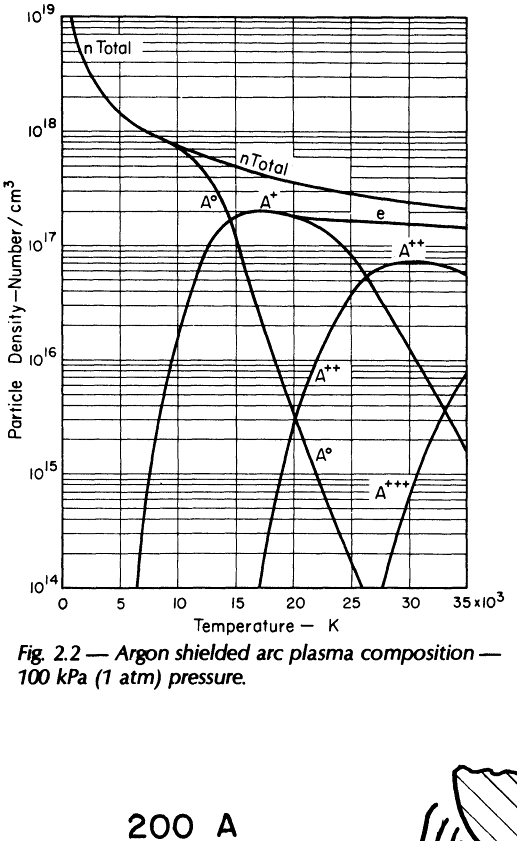


Fig. 2.2 — Argon shielded arc plasma composition — 100 kPa (1 atm) pressure.

The attainment of a very close approximation to thermal equilibrium is more questionable in the region very near to the arc terminals where current-conducting electrons are accelerated so suddenly by a high electric field that the required number of collisions does not occur. It is in the arc terminal regions that an explanation of current conduction based wholly on thermal ionization is insufficient and must be augmented by the theory of field emission or some other concept.

TEMPERATURE

Measured values of welding arc temperatures normally fall between 5000 and 30 000 K, depending on the nature of the plasma and the current conducted by it. Due to a high concentration of easily ionized materials such as sodium and potassium, which are incorporated in the coatings of covered welding electrodes, maximum arc temperatures are about 6000 K. In pure inert gas arcs, the axial temperature may rise to 30 000 K. Some special arcs of extreme power loading may attain an axial temperature of 50 000 K. In most cases the temperature of the arc is determined by measuring the spectral radiation emitted. An isothermal map of a 200 A arc in argon between a tungsten cathode and a watercooled copper anode is shown in Fig. 2.3.

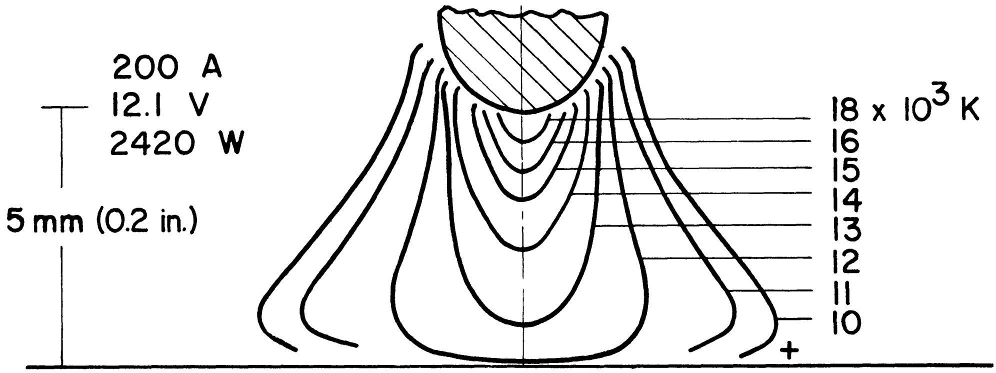


Fig. 2.3 — Isothermal map of an argon-tungsten arc.

The temperature attainable in arcs is limited by heat leakage rather than by a theoretical limit. The energy losses (due to heat conduction, diffusion, convection, and radiation) characteristic of the arc plasma composition and mass flows are in balance with the electrical power input. The energy losses from arcs vary in a complex way according to the magnitude of the temperatures and the influence of thermal conduction, convection, and radiation characteristics of the arc plasma on the thermal gradients. In the classical Elenbaas-Heller equation of energy balance, the radial loss due to thermal conduction in the cylindrical geometry of the arc plasma is expressed as follows:

$$\sigma E^2 = -\frac{1}{r}\frac{d}{dr}\left(r\,k\,\frac{dT}{dr}\right) \qquad (2.17)$$

where

σ = the electrical conductivity
E = the field strength
k = the thermal conductivity coefficient
r = the column radius
T = the temperature

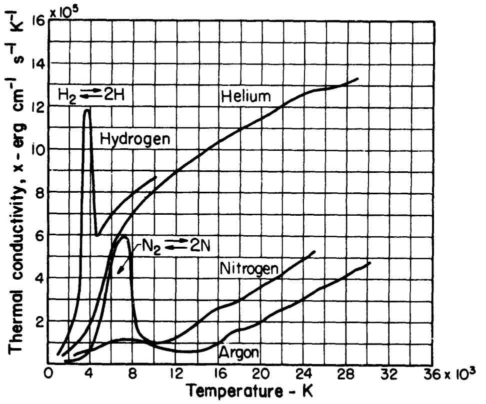
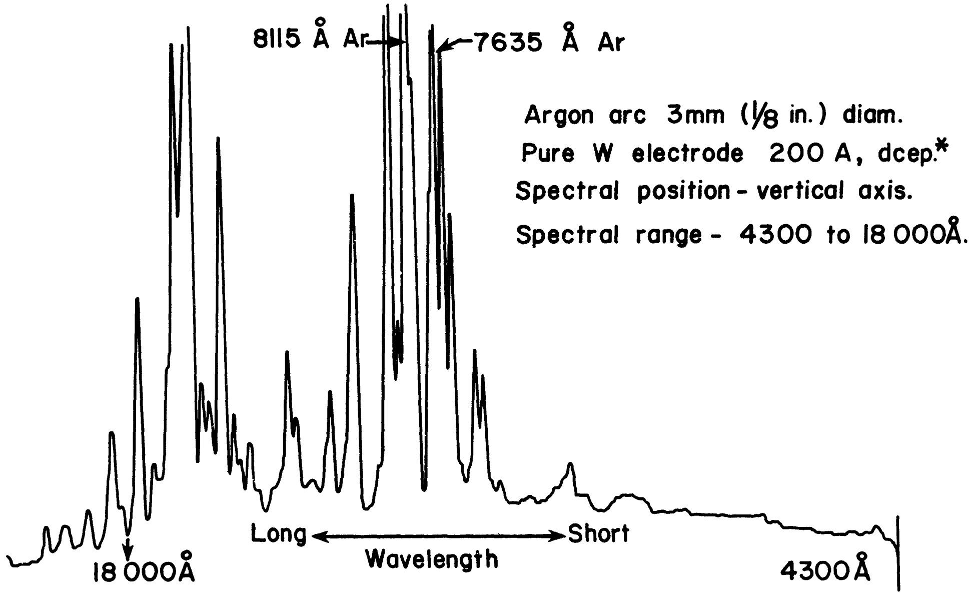


Fig. 2.4 — Thermal conductivity of some representative gases as a function of temperature (100 kPa [1 atm]) (1 erg cm^{-1} s^{-1} K^{-1} = W x 10^{-5}/m·K).



* direct current electrode positive

Fig. 2.5 — Spectrum of the argon shielded gas tungsten arc.

To include all loss mechanisms in the energy balance requires a more involved differential equation. The thermal conductivities, X, of several gases for one atmosphere pressure is shown in Fig. 2.4.

The curves shown for the molecular gases, hydrogen and nitrogen, show peaks due to the effect of thermal dissociation-association of the atomic forms of the gases.

RADIATION

The amount and character of radiation emitted by arcs depend fundamentally upon the atomic mass and chemical structure of the gas, the temperature, and the pressure. Spectral analysis of arc radiation may show bands, lines, and continua. The analysis of radiation from organic type covered electrodes shows molecular bands due to the existence of vibrational and rotational states as well as line and continuum emission from excited and ionized states. The inert gas arcs radiate predominantly by atomic excitation and ionization. As the energy input to arcs increases, higher states of ionization occur, giving radiation from higher energy levels.

Radiation loss of energy may be over 20 percent of the total input in the case of argon welding arcs, while in other welding gases the radiation loss is not more than about 10 percent. Intense radiation of the ultraviolet, visible, and infrared wavelengths is emitted by all exposed welding arcs. Ultraviolet radiation from argon shielded arcs is particularly strong because of mass effects and because little or no self-absorption occurs within the plasma volume. The visible spectrum and a portion of the infrared spectrum emanating from the argon shielded gas tungsten arc are shown in Fig. 2.5.

ELECTRICAL FEATURES

Every arc offers an impedance to the flow of current, as do all normal conductors of electricity. The specific impedance is inversely proportional to the density of the charge carriers and their mobility, with the total impedance depending on the radial and axial distribution of the carrier density. The plasma column impedance is calculable as a function of temperature, but generally not in the regions of the arc near its terminals. The electrical power dissipated in each of the three spaces or regions of the arc is the product of the current flowing and the potential across the region. The current and potential across each region are expressed according to:

$$\text{Watts} = I\,(E_a + E_c + E_p) \qquad (2.18)$$

where

E_a = anode voltage
E_c = cathode voltage
E_p = plasma voltage

The regions are referred to as the cathode fall space, the plasma column fall space, and the anode fall space. The schematic in Fig. 2.6 shows the potential distribution across the arc. In welding arcs and other types of arcs, however, there are intermediate regions taken up in expanding or contracting the cross section of the gaseous conductor to accommodate each main region. As a consequence, welding arcs assume bell or cone shapes, elliptical contours or some other noncylindrical configuration. Many factors may contribute to the various shapes, including the configuration of arc terminals, gravitational and magnetic forces, and interactions between the plasma and ambient pressures. The area over which

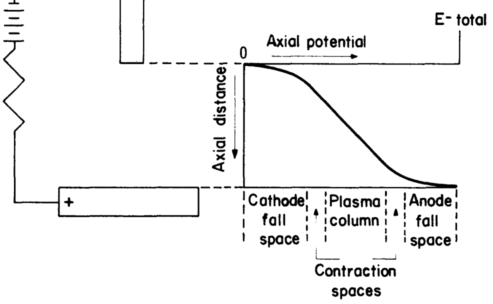


Fig. 2.6 — Arc potential (volts) distribution between electrode and work.

the current flows into the arc terminals (anode and cathode spots) has a strong effect on the arc configuration and on the flow of heat energy into these terminals. The current density at the workpiece terminal is of utmost importance to the size and shape of the fusion zone, and to the depth of fusion in a welded joint.

The total potential of an arc falls with increasing current and rises again with a further increase in current. Typical curves are shown in Fig. 2.7. The decrease in total arc potential with increasing current can be attributed to a growth of thermal ionization and thermally induced electron emission at the arc cathode. The total potential of arcs generally increases as the spacing between the arc terminals increases. Because the arc column is continually losing charge carriers by radial migration to the cool boundary of the arc, lengthening the arc exposes more of the arc column to the cool boundary, imposing a greater requirement on the charge carrier maintenance. This greater requirement causes the arc potential to rise.

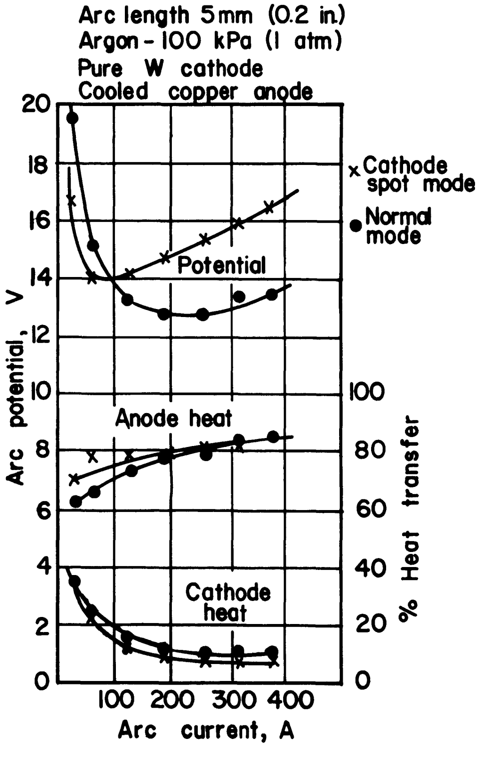


Fig. 2.7 — Typical volt-ampere and percent heat transfer characteristics of an argon shielded tungsten arc.

Much of the foregoing concerned the plasma column which is best understood. Although the mechanisms effective at the arc terminals have even more importance in welding arcs, they are less understood. The arc terminal materials must in most cases provide the means for achieving a continuity of conduction across the plasma column.

It is essential that the cathode material provide electrons by emission of sufficient density to carry the current. In the GTAW process, the tungsten electrode is chosen because it emits sufficient electrons when only a portion of the electrode tip is molten. Other cathode materials that are melted and transferred through the arc must also provide sufficient density of electrons to carry the arc current. In the case of consumable electrodes, additives in the form of coatings may be used to insure stable or spatter-free transfer.

INFLUENCE OF MAGNETIC FIELDS ON ARCS

Magnetism has interesting effects on welding arcs: some are detrimental, others beneficial. Magnetic fields, whether induced or permanent, interact with the arc current to produce force fields that cause arc deflection commonly called arc blow.* Arc blow, plasma streaming, and metal transfer are some of the welding arc characteristics strongly influenced by the presence of magnetic fields. Magnetic flux may be self-induced and associated with the arc current, or it may be produced by residual magnetism in the material being welded or by a permanent or generated external source.

Like gravity and electricity, magnetism is a field phenomenon, defined by vectorial measures of flux density. Since a welding arc always has its own associated magnetic field, any effects of external magnetic fields come as

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*See the following section on arc blow, p. 58.

a consequence of interaction with the self-field.

The effect of external magnetic fields on welding arcs is determined by the Lorentz force which is proportional to the vector product of the external field strength and the arc current. The usual effect of external magnetic fields on arcs is to cause arc deflection. In a macroscopic sense and within the limits of stable deflection, the arc behaves as a flexible conductor having an elastic stiffness that resists the overall Lorentz force. The arc deflects in a smooth curve from a fixed point at the electrode to the base metal. The magnitude of arc deflection is proportional to the applied field strength.

The direction of the Lorentz force, and subsequently arc deflection, is determined by Fleming's left-hand rule for arc deflection, illustrated in Fig. 2.8. Arc deflection may be understood intuitively if one thinks of the flux lines encircling a conductor, adding vectorially to the applied field lines on one side and canceling the applied field lines on the other side. The arc will seek the path of least resistance and deflect towards the weak flux side.

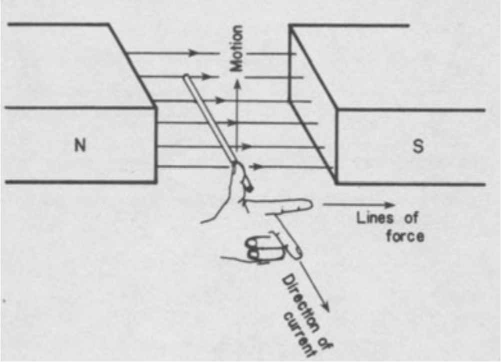

Fig. 2.8 — Fleming's left-hand rule for arc deflection.

Forward arc deflection in the direction of travel results in a more uniform weld that may be wider with less penetration. The controlled shallow penetration has application for welding thin sections. A more significant benefit, namely a considerable increase in weld travel speed before undercutting occurs, is associated with the wider bead. The use of forward arc deflection to reduce undercut is illustrated in Fig. 2.9.

Arc deflection can also be affected by the proximity of multiple arcs. A two- or three-wire submerged arc utilizes the magnetic fields of neighboring arcs to obtain higher travel speeds without undercut. The heavy undercutting and extensive reinforcement associated with backward arc deflections have little use in practical welding. Alternating fields, however, cause the arc to oscillate back and forth across the weld axis with a frequency equal to that of the applied field. This phenomenon is used to advantage in the GTAW hot wire process.

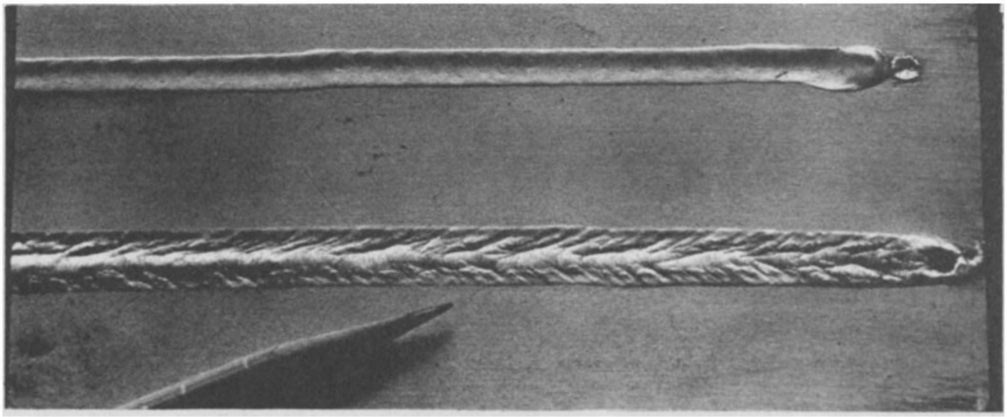

Fig. 2.9 — Appearance of gas tungsten arc bead on aluminum alloy 6061, using 300 A dcen, 18 V at 10.6 mm/s (25 in./min). Bead on bottom without magnetic field; weld on top subjected to transverse magnetic field of about 50 gauss.

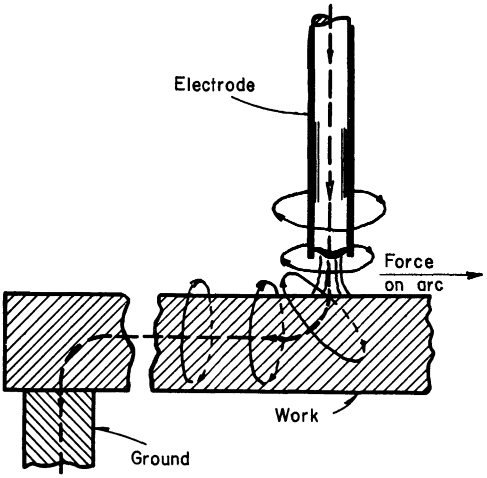

Fig. 2.10 — Distortion of induced magnetic field caused by location of ground.

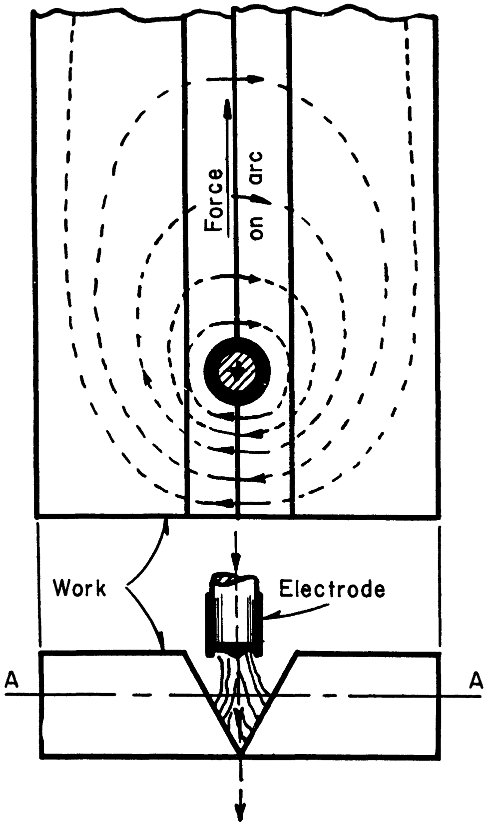

Fig. 2.11 — Distortion of induced magnetic field caused by asymmetric location.

Arc Blow

Under certain conditions the arc has a tendency to be forcibly directed away from the point of welding, thereby making it difficult to produce a satisfactory weld. This phenomenon, called arc blow, is the result of magnetic disturbances surrounding the welding arc. In general, arc blow is the result of two basic factors:

(1) The change in direction of current flow as it enters the work and is conducted away toward the ground connection.

(2) The asymmetric arrangement of magnetic material around the arc, a condition that normally exists when welding is done on ferrous materials.

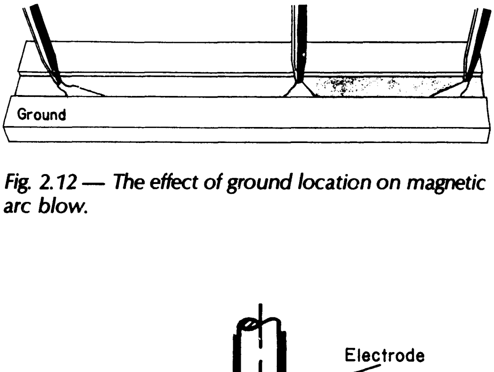

Fig. 2.12 — The effect of ground location on magnetic arc blow.

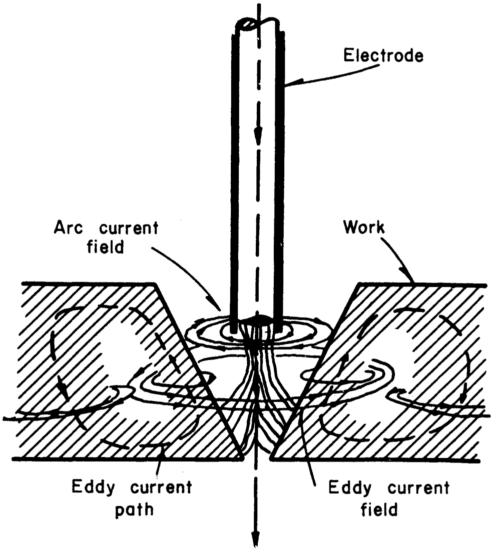

Fig. 2.13 — Effect of eddy currents in neutralizing field induced by ac current.

Although arc blow cannot always be eliminated, it can be controlled or reduced to an acceptable level through knowledge of these two factors.

The first factor is illustrated in Fig. 2.10. The heavy dotted line traces the path of the current through the electrode and the work to the ground. The magnetic lines of force surround the current path. The lines of force are shown here schematically as circles concentric with the current path. They are bunched together on the inside of the bend in the current path and are spread thin on the outside curve. Consequently, the magnetic field is much stronger on the side of the arc toward the ground connection than on the other side and, according to Fleming's left-hand rule, this force is always in a direction away from the ground.

The second factor is illustrated in Fig. 2.11. Since it is much easier for flux to pass through a magnetic material than through air, the majority of the lines follow the steel and take the shortest air distance, which is between the beveled edges of the seam. Because the arc is nearer one end of the seam than the other, the lines are crowded together at the short end and allowed to spread out over the longer end of the seam. The resulting force is shown in Fig. 2.12.

As a rule, the force on the arc due to the magnetic material around the arc acts toward the best magnetic path. When welding, the total force tending to cause the arc to blow is nearly always a combination of the two forces illustrated in Figs. 2.10 and 2.11. In welding with ac, their effect on the arc is lessened by eddy currents induced in the work (see Fig. 2.13).

METAL TRANSFER

The consumable electrode arc welding processes are used extensively since filler metal is deposited more efficiently and at higher rates with these processes than is possible with other methods. To be most effective, the metal needs to be transferred from the electrode with negligible losses due to spatter. Furthermore, uncontrolled short circuits between the electrode and work should be avoided; otherwise, the welder or welding operator will have difficulty controlling the process. In the case of the GMAW process, arc instability caused by erratic transfer generates pressure fluctuations that pump air into the vicinity of the arc.

The different types of transfer have been studied with motion pictures and by analysis of the short circuit oscillograms. Transfer through the arc stream of covered electrodes can be characterized as globular (massive drops) or as a showery spray (large number of small drops). These modes are rarely found alone; more generally, material is transferred in some combination of both. Transfer with the GMAW process varies greatly when used with argon shielding; when the current is above the transition level, the transfer mechanism can be best described as an axial spray. With it, short circuits are nonexistent. However, when active gases or helium is used for shielding, the transfer is globular and some short circuiting is unavoidable. Going a step further, the GMAW-short circuiting arc process has been intentionally adapted to use only short circuits for the transfer of metal to the pool.

The physics of metal transfer in arc welding is not well understood. The arcs are too small and their temperatures are too high for easy study, and the metal transfers at high rates. Because of the difficulty involved in establishing the mechanisms that regulate the process, a great number have been suggested. These forces have been considered:

(1) Pressure generated by the evolution of gas at the electrode tip.

(2) The electrostatic attraction between the electrodes.

(3) Gravity.

(4) The "pinch effect" caused by a mo-

mentary necking of the liquid drop that is conducting current.

(5) Explosive evaporation of the necked filament between the drop and electrode due to the very high density of the conducting current.

(6) Electromagnetic action produced by a divergence of current in the plasma around the drop.

(7) Friction effects of the plasma jet.

In all probability, a combination of these forces functions to detach the liquid drop against the force of gravity.

EFFECT OF POLARITY ON METAL TRANSFER IN ARGON

Electrode Positive

At low welding currents in argon, liquid metal from the electrode is transferred in the form of drops having a diameter greater than that of the electrode. With electrode positive, the drop size is roughly inversely proportional to the current, and the drops are released at the rate of a few per second. With a sufficiently long arc to minimize short circuits, drop transfer is reasonably stable and associated with a relative absence of spatter. Above a critical current level, however, the characteristics of this transfer change to the axial spray mode. In axial spray transfer, the tip of the electrode becomes pointed and, from it, minute drops are transferred at the rate of hundreds per second. The current at which this occurs is called the transition current. Often, as in the case of steel, this change is very abrupt.

The axial spray transfer is unique not only because of its stability but because of the absence of spatter. Furthermore, the drops are transferred in line with the electrode rather than along the shortest path between the electrode and workpiece. The metal, therefore, can be directed where needed for making fillet, vertical, or overhead welds.

The key to spray transfer is the so-called "pinch effect" which automatically squeezes the drops off the electrode. This occurs as a result of the electromagnetic effects of the current. (See Fig. 2.14.)

The transition current is not fixed, but is dependent on a number of parameters including the electrode composition, diameter, and stickout or extension (distance between the point of current pickup and the arc). A great difference in transition current is found with

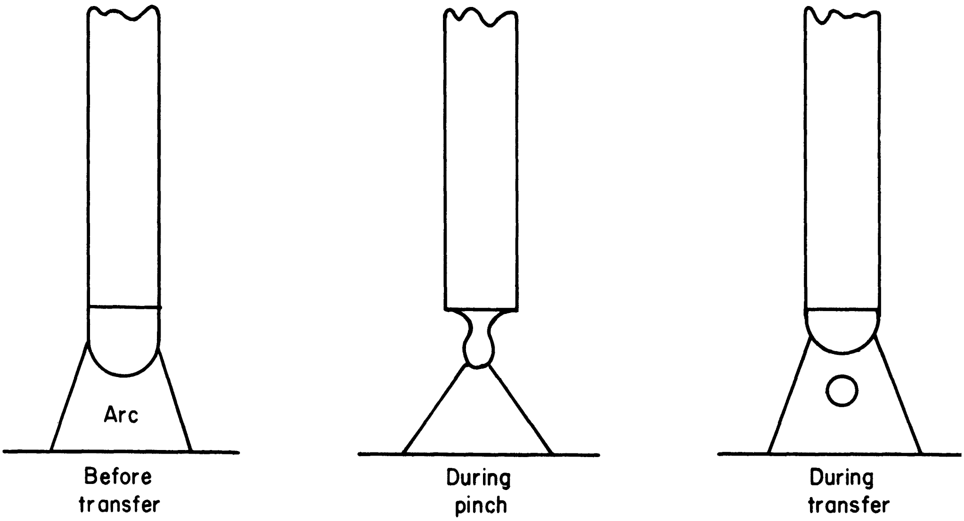

Fig. 2.14 — Example of individual particle generation in spray transfer.
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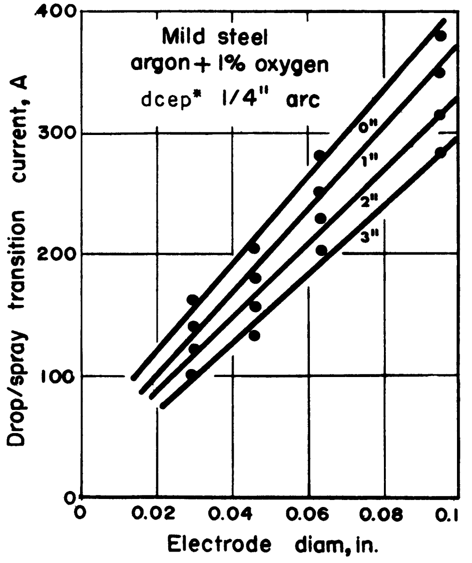
various metal systems. For example, using equivalent conditions and 1.6 mm or 1/16 in. diameter electrodes, the transition current for aluminum is approximately 170 A and for steel is approximately 275 amperes. Additional transition current data are shown in Table 2.3.

Table 2.3 — Approximate arc currents for transition from drop to spray metal transfer*

Electrode diam	Steel Ar +2% 0_2	Aluminum Argon
0.030 in.	155±5	90±5
0.035 in.	170±10	95±5
0.045 in.	220±10	120±10
0.0625 (1/16) in.	275±20	170±15
0.094 (3/32) in.	370±25	----
0.8 mm	160±5	90±5
1.0 mm	185±10	100±5
1.2 mm	220±10	120±10
1.4 mm	235±15	130±10
1.6 mm	275±20	170±15
2.0 mm	310±20	----
2.4 mm	370±25	----

*The current varies with electrode extension, alloy content, shielding gas, etc.



*direct current electrode positive

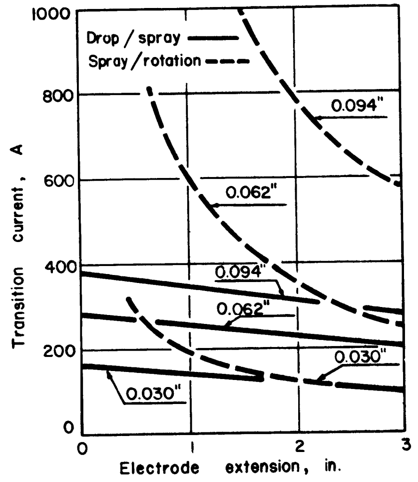
mm	0.5	1.0	1.5	2.0	2.5	6	25	50	75
in.	0.02	0.04	0.06	0.08	0.1	1/4	1	2	3

Fig. 2.15 — The influence of electrode diameter and extension on drop-to-spray transition current.

The transition current is almost directly proportional to the diameter of the electrode, rather than to its cross-sectional area. Hence it is not dependent on some critical current density. Figure 2.15 illustrates this and also shows the influence of another less significant variable, the electrode extension. An increase in the extension allows a slight decrease in the current at which spray transfer develops. (In practical welding operations, electrode extension is usually 13 to 25 mm [1/2 to 1 in.]).

With argon shielding, the GMAW process is used with spray transfer in most cases. The transition current defines the lower limit of useful current, and low current spray arcs are obtained with small diameter electrodes.

The useful upper limit of welding current is defined by the initiation of a spatter-forming rotation of the arc and globules on the electrode tip; this has been termed "jet rotation." As with the development of the axial spray arc at a lower current, the current at which axial spray disappears is proportional to the electrode diameter and varies inversely with electrode extension. The significance of these parameters is illustrated in Fig. 2.16.



mm	0.76	1.57	2.38	25	50	75
in.	0.030	0.062	0.094	1	2	3

Fig. 2.16 — Effect of electrode extension and diameter on transition current.

Spray transfer can be achieved at average current levels below the transition current by using pulsed current. Drops are transferred at the frequency of current pulses. This technique increases the useful operating range of a given electrode size.

Jet rotation at high currents is minimized by using electrodes having as large a diameter and as short an extension as possible. As with the lower level of transition current, the electrode composition has a strong influence on the jet rotation; although jet rotation forms easily with steel electrodes, the magnitude of current required to cause rotation with aluminum electrodes is so great that other problems (such as porosity in the weld) become important at current levels below those where rotation can be initiated.

Electrode Negative

The GMAW process was developed largely as a technique to be used with electrode positive since the arc becomes very unstable and spattery when electrode negative is used. The drop size with electrode negative (cathode electrode) is very large and, due to arc forces, the drops are propelled away from the workpiece as spatter. This appears to be caused by the concentration of current on the cold cathode spot. A sufficiently thermionic cathode,* however, develops a spot diameter which reduces the drop size, and the arc becomes equivalent with those typical of reverse polarity.

A number of methods have been developed to increase the thermionic properties of an electrode. The earliest method used oxygen additions to argon to form thermionic iron oxides on the surfaces of steel wires. Although this solution was helpful for ferrous metals, it was completely ineffective for aluminum alloys. Wash coatings on steel wires of oxide mixtures containing calcium and titanium have also been used. With these coatings, the metal transfer and stability become equivalent to those that had been associated only with reverse polarity but, again, the coatings are useful only on steels. However, monatomic films of alkaki metals have been proven universally effective for improving the transfer of cold cathode metals. By depositing small quantities of cesium and rubidium compounds on the wire surface, metal transfer is improved. These compounds may also stabilize the alternating current arc.

Although several parameters are involved in promoting spray transfer, the arc plasma developed through the choice of arc shielding gas is of primary importance.

Spray transfer is observed in the argon shielded consumable electrode arc while with some other gases, this type of metal transfer is not generally obtained. Not all gas consumable electrode welding arcs exhibit axial metal spray transfer. It appears that only a gas shield composed predominantly of argon provides the unique plasma properties with the self-magnetic force to develop axial spray transfer through the arc. Only in argon does current conduction occur over the whole metal droplet surface, through the bell-shaped plasma (there are exceptions for special conditions, however.) If current is conducted out of the underside of the molten metal drop, through the plasma, magnetic forces are developed that may oppose metal transfer through the arc, thus preventing axial spray transfer. It is suggested that the plasma properties of argon (thermal conductivity, mobility, etc.) develop gaseous conduction which promotes the vectorial magnetic force field conducive to axial spray transfer.

Alternating Current Arcs

Although, in general, all mechanisms governing dc arcs may be applied to the understanding of ac arcs, the dynamic rather than static characteristics of ac arcs are the important feature. The dynamic characteristic depends greatly on the rate of current change. For finite cases, a hysteresis occurs (Fig. 2.17) due to the thermal behavior of the electrodes and arc plasma.

With an alternating flow of current, the arc is extinguished during each half cycle as

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*For an explanation of thermionic, refer to p. 67.

the current reduces to zero requiring reignition as the voltage rises again. After reigniting, it passes, with increasing current, through the usual falling V/A characteristic. As the current decreases again, the arc potential is lower because the temperature and degree of ionization of the arc path correspond to the heated condition of the plasma, anode, and cathode during the time of increasing current.

The greater the arc length, the less the arc gas will be heated by the hot electrode terminals, and a higher reignition potential will be required. As a result, the hysteresis will be more sharply defined. Depending on the thermal inertia of the hot electrode terminals and plasma, the cathode emitter may cool sufficiently, during the fall of the current to zero, to stop the arc completely.

When the electrode and welding work have different thermal inertia and ability to emit electrons, the current will flow by different amounts during each half cycle, thus causing rectification to a lesser or greater degree. Complete rectification of one half cycle has been experienced in arcs with a hot tungsten electrode and a cold copper opposing terminal. Partial rectification of one half cycle is common when using the GTAW process with ac power.

EFFECT OF OTHER GASES ON METAL TRANSFER

Although helium is inert, it is unlike argon for shielding a welding arc because it does not usually produce an axial spray arc. Instead, the transfer is globular at all current levels and with both polarities. Helium shielded arcs are useful, nevertheless, because they provide deep penetration. Spray transfer is produced in helium by mixing relatively small quantities of argon with it. Using dilute mixtures, the deep penetration is not adversely changed. Although 20 percent argon in helium is sufficient to achieve these results, the normal commercial mixtures contain 25 percent argon as a safety factor.

Active gases such as carbon dioxide and nitrogen are much like helium in their effects on the arc. Spray transfer cannot be achieved without treatment of the wire surface; in addition, greater instabilities in the arc and chemical reactions between the gas and superheated metal drops cause considerable spatter. The difficulty with spatter can be minimized by burying the arc below the plate surface to trap the spatter in the deep arc crater. This technique is common when carbon dioxide is used to shield arcs in mild steels, when nitrogen is used to shield copper, and when nitrogen is mixed with argon to shield aluminum alloys. The amount of spatter, massiveness of the drops, and instability of transfer generally are greater when the electrode is negative.

Although the control of these arcs is more difficult than those in argon, some modification of the cathode is possible to improve the transfer; the anode is not amenable to such changes. Arcs shielded with carbon dioxide have been improved greatly with the addition of alkali metal compounds (such as cesium and sodium) to the steel wire surface, and spray transfer has been achieved. However, spray transfer is possible only with direct current electrode negative (dcen).

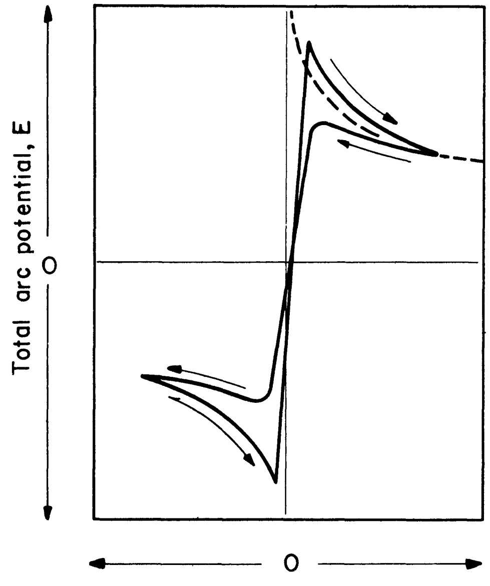


Fig. 2.17 — Alternating current arc characteristics showing hysteresis due to plasma thermal behavior.

SHORT CIRCUITING TRANSFER

Short circuits (of the electrode to the work) for the transfer of metal from the electrode tip have also been used to advantage. Metal deposited in this way is less fluid and less penetrating than that formed with the spray arc. It is free of spatter, very easily handled by the welder in all positions, and is particularly useful for joining thin materials. The spatter normally associated with short circuits is minimized by using electrical reactance to control the rate of current rise when the wire and pool are in contact. As a result, the peak value of current at short circuit is relatively low. The average current is kept low by using relatively small diameter electrodes.

With the proper adjustment of equipment, the rate of short circuiting is high (on the order of hundreds of drops per second) and since little time is available to fuse the electrode, the drops formed on the tip are very small. They are transferred to the weld by surface tension when the electrode tip and weld pool come in contact.

A schematic of the changes in current that characterize one form of such transfer is shown in Fig. 2.18. When the wire contacts the weld pool, the current surges to a level high enough to cause the interface between the solid wire and liquid pool to vaporize. An arc is formed and, because of its relatively high current, it develops a plasma pressure sufficiently great to depress the liquid pool. The high current also causes the electrode to melt. However, immediately after the arc is established, the current decreases rapidly from its short circuit peak. The depression in the weld pool fills and the wire advances toward it. Eventually, the current is too low to maintain a cavity; a short circuit redevelops and the cycle repeats itself.

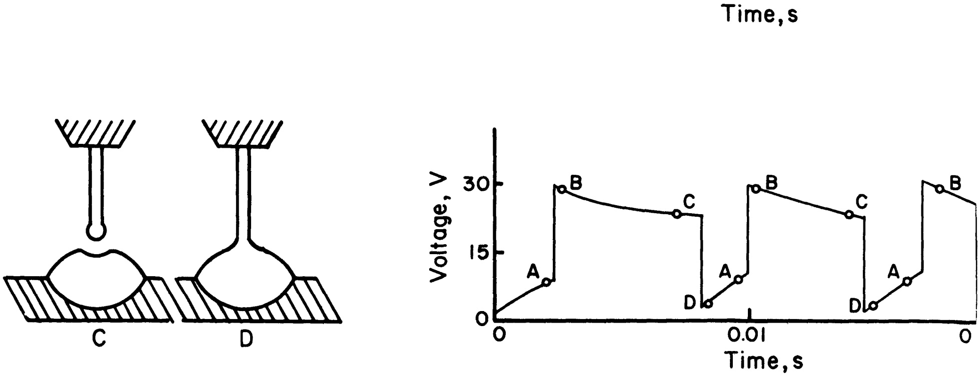


Fig. 2.18 — Schematic representation of short circuiting metal transfer.

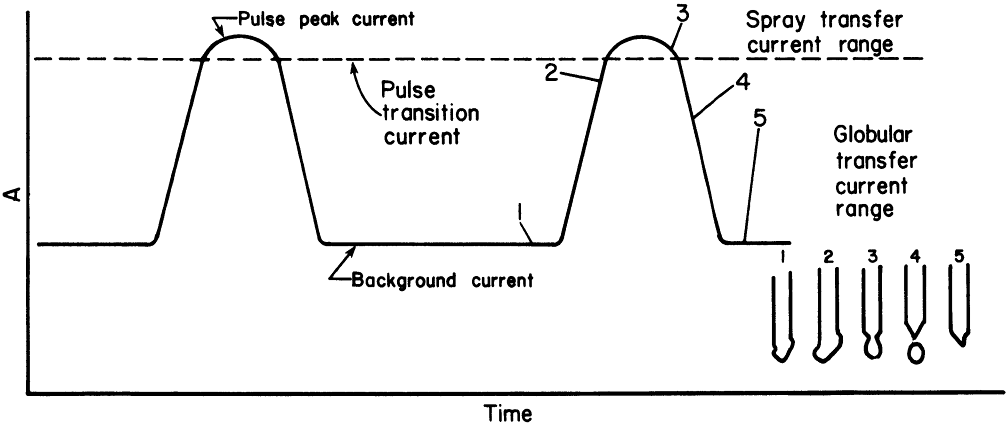


Fig. 2.19 — Illustration of the output current wave form of the pulsed current power supply; the metal transfer sequence is also shown.

PULSED CURRENT CONSUMABLE ELECTRODE TRANSFER

Pulsed current transfer is achieved by pulsing the current back and forth between the globular and spray transfer current ranges. To suppress globular transfer, the time period between consecutive pulses must be less than that required for transfer by the globular mode. The time period between pulses produced by positive half cycles from a 60 Hz power supply is short enough to suppress globular transfer at all current levels. Conversely, the pulse duration is long enough to ensure that transfer by the spray mode will occur at an appropriate current in the spray transfer range. The pulsed current mode of transfer differs from normal spray transfer in that droplets are ejected from the electrode tip at a regular frequency corresponding to the frequency of current pulses supplied from a special power source.

There are many ways of generating the modulated dc current for the pulsed current transfer. The current is comprised of a background and a pulse current. The pulsating current is illustrated in Fig. 2.19 which also shows the metal transfer sequence. With a pulsed arc, currents and deposition rates can be decreased so that welding speed can be reduced to cope more easily with awkward shapes and unsupported butt welds in thicknesses down to approximately 1.0 mm (0.04 in.) or even thinner with mechanized welding.

SUBMERGED ARC TRANSFER

Direct observation of metal transfer in the SAW process is impossible because the arc is completely obscured by a flux blanket. Investigators have reported that the submerged arc plasma is essentially a slightly ionized vapor column with a core temperature of about 6273 K. This central core is surrounded by thin concentric zones at lower temperatures with a steep radial temperature gradient. This gradient terminates at an indefinite vapor liquid phase boundary at the boiling temperature of the flux components. Oscillographic studies indicate that the current may be carried simultaneously through the ionized vapor and liquid phases; the major portion of the current, in commercial fluxes, is through the vapor phase. The transfer of the metal from the electrode to the crater undoubtedly is in the form of globules and fine droplets, depending upon the current.

Several investigators have used x-ray radiographic techniques for studying the spatial relations in SAW. In the SAW process, as in open arc processes, separation of the electrode and crater increases with voltage.

COVERED ELECTRODE TRANSFER

The mechanism of metal transfer with covered electrodes is difficult to establish since the arc is partially obscured by fume and particles of slag. Also, in many cases, a deep cavity formed by the covering hides the tip of the electrode from view. In general, the metal during transfer consists of globules that short circuit the arc, at one extreme, or a fine, showery spray of metal and slag particles that, because of their small size, are unable to create a short circuit. The showery spray transfer is desirable. In some cases, however, the showery spray cannot be used because it is associated with great quantities of spatter. Since covered electrodes are fed manually and used with considerable manipulation, the stability includes the regularity of transfer, ease of sustaining a long arc, and other subtle points difficult to define.

Bare electrodes rarely are used for welding because the weld becomes contaminated and the arc is difficult to sustain. A considerable increase in stability is achieved by making the electrode more thermionic with direct current electrode negative. Bare electrodes are not used with reverse polarity (electrode positive) and provide little protection from the atmosphere.

Most electrodes contain cellulose or metal carbonates that dissociate in the arc, forming a gas shield to protect the weld from atmospheric contamination. This shield consists primarily of the active gases carbon dioxide, carbon monoxide, hydrogen, and oxygen. Similar to their effect on gas metal arcs, these gases do not develop a highly conductive arc plasma; the current distribution is such that the liquid metal is forced away from the arc and weld pool as massive drops and spatter. Because these reactions are more intense when the electrode is negative, reverse polarity is generally used with the covered electrodes that do not contain cathode stabilizers (E6010, E7015).

Coverings are intended to make the electrode thermionic. Rutile, lime, and iron oxide are generally used in combination for this purpose. Such electrodes produce a more stable arc, less spatter, and form smaller drops with direct current electrode negative. Included in this type are the E6012, E6020, and the high iron powder varieties.

The stability of arcs with ac is dependent upon reignition of the arc during the interval when polarity is changed and the current has been reduced to zero. Stability frequently is achieved by substituting potassium silicate for the sodium silicate binder. The potassium forms a lower ionization path between the electrode and work and increases the cathode emissivity to permit an easy reignition. Electrodes containing large quantities of rutile or lime are also thermionic and do not require a substitution of potassium containing binders when stability with ac is necessary.

MELTING RATES

GENERAL CONTROLLING PARAMETERS

As discussed earlier, heat in an arc is generated by electrical reactions at the anode and cathode regions and within the plasma. Portions of this energy will melt the electrodes which support the arc unless they are adequately cooled. The greatest portion of the arc energy used for melting is obtained from cathode or anode reactions, but substantially more heating can be released from the cathode. Furthermore, when the electrode is the cathode terminal, considerable control of the energy release is possible. Little can be done to modify the release of energy at the anode; it is related mostly to the current magnitude and less to composition and other factors.

Most structural metals and their alloys form what is called a cold cathode, its area is rather small, but great quantities of energy are generated to release the electrons needed to support an arc. However, metals having very high melting points easily supply electrons to sustain the arc due to their temperature; these metals are called *thermionic*. Included in this category are molybdenum and tungsten. The cold cathode, low melting point metals can be made to supply electrons more easily by coating them with compounds that reduce the surface work function. They then become thermionic at low temperatures. In some cases, the mechanism of electron release depends on surface oxide emission; in others, it is due to the formation of an atomic film of an alkali metal on the surface. The degree of change is regulated by the selection of the oxides or metals and their quantities. In general, the change from cold cathode to thermionic emission is accompanied by a lowering of the heating energy, and therefore, a reduction in the melting rate. Also, in general, any improvement in the mode of metal transfer with dcen or arc stability with ac is associated with a reduction in melting rate.

The arc plasma may or may not supply heat by radiation for melting the electrode. When it does, the effect is relatively small by comparison with other sources. Therefore, those parameters affecting the plasma, such as the shielding gas or flux or the arc length, do not directly affect melting rate by changing the radiation energy. If such a change in melting rate is demonstrated, it is more likely to be caused by a modification of some other factor such as current or cathode heating.

In addition to the energy supplied by the welding arc, electrical resistance heating of the electrode by welding current affects the electrode's melting rate. This effect is particularly significant in welding processes that use small diameter electrodes. Since this heating is caused by the resistance of the electrode to the flow of current, it is usually dependent upon Ohm's law and will be greater with small electrode diameters, long electrode extensions, and high electrical resistivity metals and alloys. This dependence upon Ohm's law has been proven true for all practical purposes.

The relationship of all the aforementioned parameters on electrode melting rate can be written simply as follows:

$$MR = aI + bLI^2 \qquad (2.19)$$

where

MR = the electrode melting rate
a = the constant of proportionality for anode or cathode heating. Its magnitude is dependent upon polarity, composition, and, with direct current electrode negative, the emissivity of the cathode
b = the constant of proportionality for electrical resistance heating and includes the electrode resistivity
L = the electrode extension or stickout
I = the welding current

Arc power is not a term in this equation, nor is it essential since the plasma drop and voltage drop at the workpiece are not part of the relationships affecting melting rate.

Table 2.4 — Relative magnitude of heating coefficients in the melting rate of 1.6 mm (1/16 in.) diam wire electrode

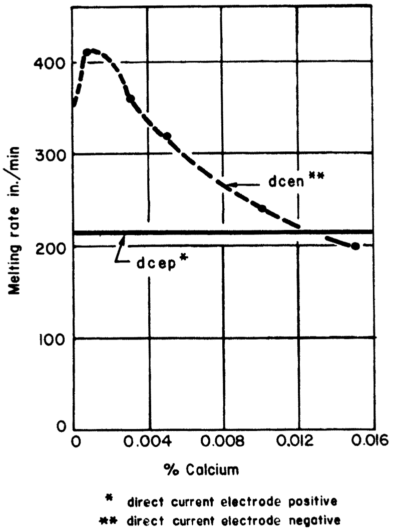
	a*		b*	
	kg/h·A	lb/h·A	kg/h A^2·mm	lb/h A^2·in.
Aluminum (dcep)	5.4×10^{-3}	1.2×10^{-2}	4.4×10^{-6}	9.7×10^{-6}
Mild steel (dcep)	8.6×10^{-3}	1.9×10^{-2}	2.5×10^{-5}	54.7×10^{-6}
Mild steel (dcen)	1.8×10^{-2}	4.0×10^{-2}	2.5×10^{-5}	54.7×10^{-6}

*Values given are for *a* and *b* in equation (2.19) when the electrode diam is 1.6 mm (1/16 in.).

MELTING RATES IN GMAW

The melting rate with the GMAW processes is controlled by the electrode diameter and extension and cathode or anode heating, depending on the polarity of welding current as well as the magnitude of the welding current. Neither the shielding gas nor the arc length nor, therefore, the arc voltage has been shown to exercise a significant effect on melting rate except, with some alloys, when the arc is very short. Shielding gas composition is also an exception when the electrode is negative because oxidizing gas additives such as carbon dioxide and oxygen form oxides on the wire surface that may affect the electrode thermionic properties.

Equation (2.19) for melting rate can be used to calculate melting rates with electrode positive. Problems develop with dcen because the cathode heating value is so sensitive to the presence of oxides and alkali and alkaline-earth compounds.



mm/s	42	85	127	169
in./min	100	200	300	400

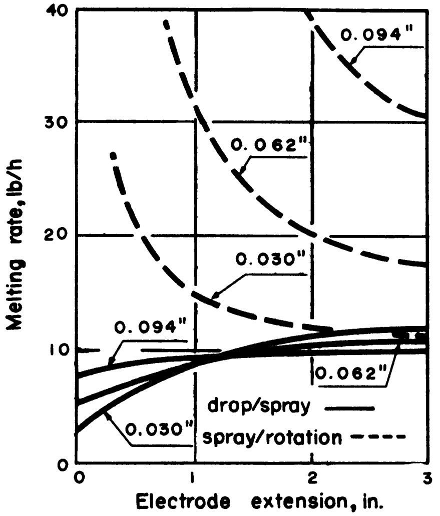
Fig. 2.20 — Effect of percent calcium in compound additive on melting rate of 1.6 mm (1/16 in.) diam mild steel electrode.

The first term of the equation is more significant at low currents and with short extensions of the electrode. The influence of the second term becomes progressively greater as the electrode diameter is reduced and its extension or resistivity is increased and the current is raised. The relative magnitude of the heating coefficients with 1.6 mm (1/16 in.) diam wires is shown in Table 2.4.

The values of these terms are dependent to a great extent on the particular alloy as well as the metal being welded. For example, the first term is of greater significance with aluminum since the resistivity component is low. It is also more important when the electrode is negative since the use of any additive that affects the cathode emissivity will also reduce the magnitude of *a*.

An example of the effect of an additive on melting rate is shown in Fig. 2.20. The electrode can be made sufficiently thermionic to reduce the heating effect represented by the term *a* for straight polarity below that of direct current electrode positive. Direct current electrode negative arcs have great appeal because their melting rates can be so high. Unfortunately, as mentioned earlier, when melting rates are high, the transfer of metal is invariably globular and spattery, and the improvements in transfer gained by making the cathode more thermionic are accompanied by a reduction in melting rate. When ac is used, the magnitude of *a* is an average of the values obtained at direct current with electrode negative and electrode positive.

The range of melting rate is limited by a number of undesirable effects. When argon shields are used, the lower limits of melting rates are defined by the current at which drop transfer begins. This varies with the electrode diameter since lower currents can be used with smaller wire diameters. Very often, however, the melting rate is not reduced significantly by this expedient since the resistivity increase compensates somewhat for the current decrease. The upper limit is defined by the formation of jet rotation and, since this term increases with the electrode diameter, high current arcs generally are sustained with the large



mm	0.76	1.57	2.38	25	50	75
in.	0.030	0.062	0.094	1	2	3
kg/h	4.5	9	13.5	18		
lb/h	10	20	30	40		

Fig. 2.21 — Effect of electrode diameter and extension on melting rate of mild steel electrode.

diameter electrodes. The extent of these ranges is shown in Fig. 2.21 for steel. This factor is particularly important with steel, but is of little significance with aluminum. The upper current with aluminum is limited by the formation of a very rough weld surface.

The current limits of arcs in active gas shields are not determined on the basis of metal transfer since the transfer is always globular. Here the lower level is established by random short circuiting, absence of wetting, and other parameters that are reflected in poor weld quality. The upper limit of current is determined in substantially the same way — spatter, poor bead appearance, and porosity. Generally, however, the diameter requirements are related to the welding current to be used. Very small diameters (0.8 mm [0.03 in.] or less) and large diameters (2.3 mm [0.092 in.] and greater) are difficult to feed with conventional equipment. The smaller diameter wires are expensive. However, when very low melting rates are necessary, the short circuit technique is used frequently.

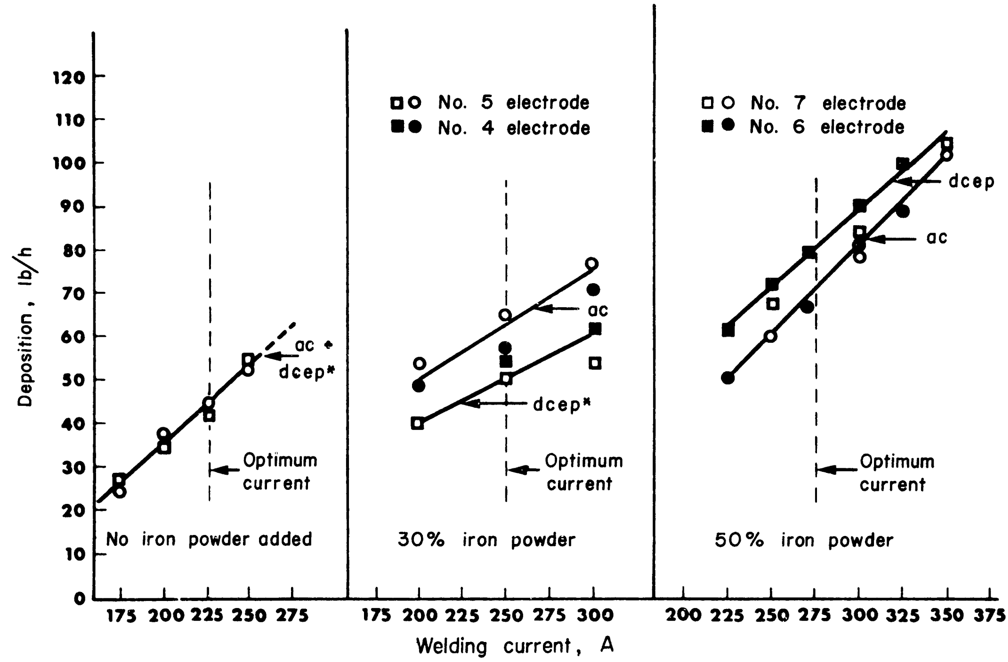
MELTING RATES IN SAW

Generally speaking, the preceding comments for GMAW apply to the SAW process. The melting rate of the electrode increases as the current increases. Changes in the anode or cathode voltages produced by changes in flux composition or changes in voltage level, travel speed, or in electrode preheat will influence the exact melting rates. The melting rate for the SAW process is often reported as 13.5 kg/h•kA (30 lb/h•kA) and will range from approximately 11 to over 16 kg/h•kA (24 to over 36 lb/h•kA) depending upon polarity and composition.

MELTING RATES WITH SMAW

The SMAW process is the least efficient of the three in converting electrical energy to useful weld heat. This inefficiency is due in part to the need for melting a flux along with the core wire. More important, however, is the absence of extensive electrical resistance heating. The diameters of the electrodes are so large that anode or cathode heating is the primary source of energy. Control of melting rate, therefore, is achieved largely by adjusting current. The range of current that can be used with covered electrodes is more limited than with the GMAW or SAW processes; and as the current requirements increase, the electrode diameter must increase proportionally.

The lower limit of current is defined by incomplete fusion, high viscosity of the flux, or an unstable globular transfer. The upper limit is caused by a cumulative rise in temperature of the steel electrode due to electrical resistance heating that does damage to the electrode covering. This heating of some materials in the covering, such as cellulose materials and carbonates, will cause these constituents to break down before reaching the arc where the products of dissociation are needed for shielding. Overheating may also cause the covering to spall. Some coverings are more susceptible to damage by overheating than others. For example, the cellulose containing E6010 electrode of 6 mm (1/4 in.) diam is



* direct current electrode positive

kg/h	4.5	9	13.5	18	22.5	27	31.5	36	40.5	45	50	54
lb/h	10	20	30	40	50	60	70	80	90	100	110	120

Fig. 2.22 — The effect of an increase in iron powder on deposition rate for covered electrodes.

useful in the range between 200 and 300 A, while for the same diameter, the rutile-base E6012 that does not rely on gas formers has a useful range between 200 and 400 amperes.

Iron powder electrodes were introduced to provide even higher melting rates and better material transfer than was possible with the conventional mineral coverings. Because iron is contained in the flux, the melting rate for a given current is higher. However, the optimum current needed to obtain the same quality weld appearance with the iron powder electrodes is also higher. This increase in current is proportional to the amount of iron contained in the covering. Therefore, higher melting rates for a given electrode diameter are achieved by a combination of increased efficiency and higher current. The results of these effects are shown in Fig. 2.22.

PHYSICAL PROPERTIES OF METALS AND SHIELDING GASES

As previously stated, the physical properties of the metals or alloys being joined influence either the efficiency or applicability of the various joining processes. Further, the nature and properties of the shielding gases generally employed, and of contaminants from the atmosphere, may have a pronounced effect upon achieving the desired final result. The shielding gases may be generated either by the decomposition of fluxing materials or by their direct introduction into the arc stream and the area surrounding the arc plasma.

It has been pointed out that both thermal conductivity and thermal expansion have a direct effect on distortion. Yield strengths of the materials being joined also influence the extent of permanent yielding of welded structures. Further, it has been shown that electrical resistivity and thermal conductivity have a pronounced effect on the application of both resistance and arc welding to the various metals. In the case of resistance welding, resistivity of the metals being joined, as well as their thermal conductivity and specific heat, influence the power requirements.

In the case of arc welding, arc starting and arc stability are greatly influenced by the ionization potentials of the metal and flux vapors as well as the various electronic transitions that occur in the shielding gases under the extreme temperature conditions that exist in the arc. The thermionic work function of the electrode material, and to a lesser extent, that of the materials being welded, have a direct bearing upon the efficiency of the energy transferred by a welding arc. Electrical resistivity also plays an important role in these processes due to I^2R heating of the wire between the contact tube or electrode holder and the work, which may be an important contribution to the total energy input to the weld zone.

Weld bead shape is dependent to varying degrees upon the interfacial energy between the surrounding atmosphere and the molten metal. The surrounding atmosphere may consist either of a gas or a liquid flux. Elements in the surrounding medium may control the shape of the bead.

Another important material property that should be considered when determining the relative weldability of alloys is the rate of oxidation of the base metal or of any of the alloy additions that are present in significant quantity. This rate is critically important in determining the degree of shielding required. A corollary to this is the relative stability of oxides that may be present.

Both the "heat" of the arc and the degree of shielding are influenced by the specific heat and density of the shielding gases. Surface tension and the solubility of gases are discussed in Chapter 4, p. 139. The role played by various other properties is discussed in greater detail in the following sections.

Electrical Resistivity

The importance of electrical resistivity to many welding processes cannot be overemphasized. Its role in resistance welding is obvious since the resistance of the materials

Table 2.5—Physical properties of selected metals (at 20 °C [68 °F])

Metal	Melting Temperature* °F	Melting Temperature* °C	Melting Temperature* K	Resistivity 10^{-8} Ωm	Thermal Conductivity W/cm^{-1}·K^{-1}	Coefficient of Expansion 10^{-6} K^{-1}	Density g·cm^{-3}
Aluminum							
99.9+ pure	1220.67	660.37	933.52	2.65	2.37	23.1	2.70
Wrought alloys	1170-1200	630-650	900-920	2.8-6.7	1.2-2.1	22-23	2.6-2.8
Casting alloys	930-1200	500-650	770-920	3.0-7.0	1.2-1.8	22-23	2.6-3.0
Cobalt							
99.9+ pure	2721	1494	1767	4.3	1.01	13.0	8.86
Co-Cr-W alloys	2400-2500	1320-1370	1590-1640	8.5-17.6	0.12-0.25	11.2	8.0-9.0
Copper							
99.9+ pure	1983.9	1084.4	1357.6	1.68	4.01	16.5	8.93
90 Cu, 10 Al (alum. bronze)	1920-1960	1050-1070	1320-1340	12-14	1.60	17	8.34
90 Cu, 10 Zn (commercial bronze)	1920-1960	1050-1070	1320-1340	3.92	1.92	18	8.92
Iron							
99.9+ pure	2800	1538	1811	9.69	0.808	11.8	7.87
Low alloy steel	2610-2730	1430-1500	1700-1770	10-20	0.32-0.66	11.4	7.8-8.0
Martensitic stainless steel	2700-2800	1480-1540	1750-1810	54-69	0.25	9-10	7.6-7.8
Austenitic stainless steel	2500-2650	1370-1450	1640-1730	71-79	0.15	14-15	7.8-8.0
Magnesium							
99.9+ pure	1200	649	922	4.30	1.56	24.8	1.74
Wrought alloys	930-1200	500-650	770-920	4.5-12.5	0.60-1.4	25-28	1.8
Cast alloys	840-1200	450-650	720-920	4.5-16	0.46-1.4	25-28	1.8-1.9
Molybdenum	4750	2621	2894	5.09	1.38	4.8	10.24
Nickel							
99.95 Ni + Co	2651	1455	1728	7.47	0.915	13.4	8.9
60 Ni, 33 Cu, 6.5 Fe	2370-2460	1300-1350	1570-1620	48	0.26	13	8.4
Ni-Cr-Mo-Fe alloys (Hastelloy alloy series)	2050-2460	1120-1350	1390-1620	110-140	0.10-0.20	11-12	7.8-9.1
Tantalum	5468	3020	3293	12.8	0.575	6.3	16.6
Titanium alloys	2780-3040	1530-1670	1800-1940	43-230	0.024-0.24	7-9	4.4-4.8
Tungsten	6129	3387	3360	5.42	1.75	4.5	19.3

*Based on the International Practical Temperature Scale of 1968; melting temperature may indicate a single temperature or a range of temperatures.

Note: Table 2.5 was prepared by the Thermophysical Properties Research Center, Purdue University, for the Office of Standard Reference Data of the National Bureau of Standards, Washington, DC 20234.

Table 2.6—Ionization potentials of vapors

Element	eV	Element	eV
Aluminum	5.986	Potassium	4.341
Barium	5.212	Lithium	5.392
Boron	8.298	Magnesium	7.646
Carbon	11.260	Molybdenum	7.099
Calcium	6.113	Nickel	7.635
Cobalt	7.86	Silicon	8.151
Chromium	6.766	Sodium	5.139
Cesium	3.894	Titanium	6.82
Copper	7.726	Tungsten	7.98
Iron	7.870		

Note: Table 2.6 was prepared by the Atomic Energy Levels Data Center, National Bureau of Standards, Washington, DC 20234.

being welded is directly related to the heat generated for a given current input. As mentioned previously, it also contributes to preheating the welding wire or electrode in both GMAW and manual processes. The resistivities of a number of the metals and alloy classes of interest in welding are listed in Table 2.5. (Alloy additions increase the resistivity.)

The values shown in the table were determined at room temperature, but in all cases the resistivity to a first approximation increases almost linearly as the temperature increases. Although the rate of increase is different for different materials, the room temperature resistivity is a useful guide in determining the relative values for various materials at elevated temperatures.

THERMAL CONDUCTIVITY

Thermal conductivity is also dependent on temperature, and again, the values given in Table 2.5 represent room temperature properties. Thermal conductivity decreases as the working temperature is increased in a manner analogous to the electrical conductivity values. Similarly, pure metals have the highest conductivity, and the addition of alloying elements tends to decrease the values of this property.

Table 2.7—Ionization potentials of gases

Element or Compound	Symbol	eV
Argon	Ar	15.760 (11.548)
Hydrogen	H_2	15.43
	H	13.598
Helium	He	24.5876 (20.96430) (19.8198)
Nitrogen	N_2	15.58
	N	14.534
Oxygen	O_2	12.07
	O	13.618
Carbon Dioxide	CO_2	13.77
Carbon Monoxide	CO	14.1

Note: Table 2.7 was prepared by the Atomic Energy Levels Data Center, National Bureau of Standards, Washington, DC 20234.

COEFFICIENT OF EXPANSION

The thermal coefficient of expansion of the materials being welded is critically important in analyzing the distortion problems involved in welded assemblies. Values of this coefficient are listed for the various types of materials in Table 2.5. Again, these vary with temperature, and the values given are those at or near room temperature. The same general considerations previously described for thermal conductivity and electrical resistivity are applicable for these values.

Table 2.8—Electron thermionic work functions—probable ranges, eV

Element	Range, eV	Element	Range, eV
aluminum (Al)	3.8 to 4.3	magnesium (Mg)	3.1 to 3.7
barium (Ba)	4.1 to 4.4	manganese (Mn) (α, β, or γ)	3.8 to 4.4
barium oxide (BaO)	4.9 to 5.2	molybdenum (Mo)	4.0 to 4.8
cerium (Ce)	1.7 to 2.6	neodymium (Nd)	4.1 to 4.5
cesium (Cs)	1.0 to 1.6	nickel (Ni)	2.9 to 3.5
cesium film or W	2.7 to 3.1	palladium (Pd)	4.5 to 5.3
chromium (Cr)	4.4 to 5.1	platinum (Pt)	4.9 to 5.7
cobalt (Co)	3.9 to 4.7	samarium (Sm)	5.2 to 5.9
columbium (Cb)*	1.8 to 2.1	scandium (Sc)	3.3 to 3.7
copper (Cu)	1.1 to 1.7	silver (Ag)	2.4 to 3.0
europium (Eu)	4.4 to 4.7	strontium (Sr)	2.1 to 2.7
gadolinium (Gd)	2.2 to 2.8	titanium (Ti)	3.8 to 4.5
gold (Au)	4.2 to 4.7	vanadium (V)	4.1 to 4.4
hafnium (Hf)	2.9 to 3.3	wolfram (W)	4.3 to 5.3
iron (Fe) (α or γ)	3.5 to 4.0	yttrium (Y)	2.9 to 3.3
lanthanum (La)	3.3 to 3.7	zirconium (Zr)	3.9 to 4.2

*Now renamed niobium (Nb)

Note: Table 2.8 was prepared by the Alloy Data Center, National Bureau of Standards, Washington, DC 20234.

Table 2.9—Metal oxides

Relative Stability (No. 1 is most stable and No. 10 is the least stable)	Oxidation Rate (No. 1 is the most reactive and No. 9 is the least reactive)
1. CaO	1. aluminum
2. MgO	2. magnesium
3. Al_2O_3	3. cobalt and titanium
4. TiO_2	4. tungsten
5. SiO_2	5. manganese
6. V_2O_3	6. vanadium
7. MnO	7. molybdenum
8. Cr_2O_3	8. iron
9. WO_2 and MoO_2	9. chromium
10. Fe_2O_3	

IONIZATION POTENTIALS

In the case of arc welding, both the ease of arc initiation and the subsequent stability of the arc are critically related to the minimum ionization potential of the elements in the arc atmosphere. This atmosphere consists of flux materials and metals in the vapor phase as well as gases introduced externally for shielding purposes. It is believed that, in the cases of helium and argon, the stability is achieved through the transitions from the metastable excited stages to the ionized state. The ionization potentials for a number of vapors and gases are shown in Tables 2.6 and 2.7

THERMIONIC WORK FUNCTION

The thermionic work function is the energy that must be imparted to an electron near the Fermi level* of a solid to get the electron out of the solid into a cavity. Since the ease of starting and maintaining an arc is exponentially related to the thermionic work function, representative values for a number of the elements are listed in Table 2.8. Generally the values do not differ very widely, with two or three exceptions. However, lowering this value by even one electron volt makes a very great difference in arc characteristics.

METAL OXIDES

The difficulty of transferring some alloying elements across the arc, as well as the susceptibility of oxide inclusions in the weld metal, is a direct function of the oxidation rate

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*The Fermi level of a solid is the maximum energy that electrons in a solid may reach, even at absolute zero, because of the crowding of electrons.

and the refractory stability of the metal oxides formed during welding. Table 2.9 demonstrates the comparative ease with which the various elements oxidize, and the refractory nature of the oxides formed. Thus it is possible to obtain some information as to the relative degree of shielding required when welding various materials or alloys.

SPECIFIC HEAT

Specific heats of the common gases are given in Table 2.10 and critical values are shown for most metals of interest in Table 2.11. These values are a measure of the amount of heat required to raise the temperature of a unit weight of material one degree. They are expressed in units of joules per kilogram•kelvin. It may be regarded as a measure of the ability of a body or gas to absorb or store heat. Thus it may be seen from Table 2.10 that much more energy is required to raise helium than argon to a given temperature. For dilute alloys such as plain carbon or low alloy steels, the values of the base metal given in Table 2.11 may be used with reasonable accuracy. In the case of higher alloys, Kopp's law of the additivity of heat capacity may be used except in temperature regions of anomalies such as the Curie temperatures for iron and nickel, or when an allotropic phase change occurs.

Table 2.10—Physical properties of shielding gases

Name of Gas	N_2	A	He	H_2	CO_2
Molecular weight	28.0134	39.948	4.0026	2.01594	44.011
Normal boiling point					
K	77.347	87.280	4.224	20.268	194.65
°C	−195.81	−185.88	−268.94	−252.89	−78.51
°F	−320.44	−302.57	−452.07	−423.19	−109.3
Density at 21.1 °C (70 °F), 1 atm:					
kg/m^3	1.161	1.656	0.1667	0.0841	1.833
lb/ft^3	0.07249	0.1034	0.01041	0.00525	0.1144
Specific volume at 21.1 °C (70 °F), 1 atm:					
m^3/kg	0.8613	0.6039	5.999	11.89	0.5455
ft^3/lb	13.79	9.671	96.06	190.5	8.741
Specific gravity at 21.1 °C (70 °F), 1 atm: (air = 1)	0.9676	1.380	0.1389	0.0700	1.527
Specific heat-const. pressure at 21.1 °C (70 °F), 1 atm:					
J/kg • K	1041	521.3	5192	1490	846.9
Btu/lb • °F	0.2487	0.1246	1.241	3.561	0.2024
Specific heat-const. volume at 21.1 °C (70 °F), 1 atm:					
J/kg • K	742.2	312.1	3861	1077	653.4
Btu/lb • °F	0.1774	0.0746	0.7448	2.575	0.1562

Note: Table 2.10 was prepared by the Cryogenic Data Center, National Bureau of Standards, Institute for Basic Standards, Boulder, Colorado 80302.

Table 2.11—Specific heats of selected elements

Element	Symbol	Atomic Weight	Temperature*			Specific Heat
			°F	°C	K	10^3 J/kg^{-1} • K^{-1}
Aluminum	Al	26.98154	68	20	293	0.898
			212	100	373	0.937
			1220.67**	660.37**	933.52**	1.250
Carbon (gas)	C	12.011	68	20	293	1.735
			932	500	773	1.731
			1832	1000	1273	1.731
			3632	2000	2273	1.756
			5432	3000	3273	1.822
Cobalt	Co	58.9332	68	20	293	0.419
			783	417	690	0.524 (α)
			783	417	690	0.517 (β)
			2052†	1122†	1395†	0.936
			2721**	1494**	1767**	0.640
Chromium	Cr	51.996	68	20	293	0.483
			1832	1000	1273	0.705
			2732	1500	1773	0.870
			3380**	1860**	2133**	0.974
Columbium (Niobium)	Cb (Nb)	92.9064	68	20	293	0.273
			932	500	773	0.290
			1832	1000	1273	0.313
			3632	2000	2273	0.358
			4480**	2471**	2744**	0.381
Iron	Fe	55.847	68	20	293	0.444
			1416†	769†	1043†	1.498
			1672	911	1185	0.742 (α)
			1672	911	1185	0.608 (γ)
			2541	1394	1667	0.679 (γ)
			2541	1394	1667	0.737 (δ)
			2800**	1538**	1811**	0.763
Magnesium	Mg	24.305	68	20	293	1.019
			212	100	373	1.102
			932	500	773	1.253
			1200**	649**	922**	1.327
Molybdenum	Mo	95.94	68	20	293	0.259
			1832	1000	1273	0.313
			3632	2000	2273	0.419
			4750**	2621**	2894	0.546
Nickel	Ni	58.71	68	20	293	0.440
			1168†	358†	631†	0.663
			1832	1000	1273	0.604
			2651**	1455**	1728**	0.616
Tantalum	Ta	180.9479	68	20	293	0.140
			1832	1000	1273	0.156
			3632	2000	2273	0.181
			5468**	3020**	3293**	0.243
Titanium	Ti	47.90	68	20	293	0.519
			1621	883	1156	0.707 (α)
			1621	883	1156	0.611 (β)
			3043**	1673**	1946**	0.782
Tungsten	W	183.85	68	20	293	0.426
			1832	1000	1273	0.479
			3632	2000	2273	0.537
			6129	3387	3660	0.617

*Based on the International Practical Temperature Scale of 1968.

**Melting point.

†Curie temperature.

Note: Table 2.11 was prepared by the Thermophysical Properties Research Center, Purdue University, for the Office of Standard Reference Data of the National Bureau of Standards, Washington, DC 20234.

SUPPLEMENTARY READING LIST

Albom, M. J. 1964. Solid state bonding. *Welding Journal* 43 (6): 491-504.

Anderson, J. E. and Jackson, C. E. 1965. Theory and application of pulsed laser welding. *Welding Journal* 44 (12): 1018-1026.

Bakish, R. and White, S. S. *Handbook of Electron Beam Welding*. New York: J. Wiley & Sons, 1964.

Bunshaw, F. F. High power electron beams. *International Science and Technology*, April 1962.

Campbell, H. C. 1970. Electroslag, electrogas, and related welding processes. *Welding Research Council Bulletin* 154.

Chase, T. F. and Savage, W. F. 1971. Effect of anode composition on tungsten arc characteristics. *Welding Journal* 50 (11): 467s-473s.

D'Annessa, A. T. 1964. The solid-state bonding of refractory metals. *Welding Journal* 43 (5): 232s-240s.

Duvall, D. S., Owczarski, W. A., Paulonis, D. F., and King, W. H. 1972. Methods for diffusion welding superalloy Udimet 700. *Welding Journal* 51 (2): 41s-49s.

Gottlieb, M. B. The fourth state of matter. *International Science and Technology*, August 1965, pp. 42-47.

Hicken, G. Ken and Jackson, C. E. 1966. The effects of applied magnetic fields on welding arcs. *Welding Journal* 45 (11): 515s-524s.

Holtzman, A. H. and Cowan, G. R. 1965. Bonding of metals with explosives. *Welding Research Council Bulletin* 104.

Jackson, C. E. 1960. The science of arc welding. *Welding Journal* 39 (4-6): 129s-140s, 177s-190s, 225s-230s.

Jones, J. B., Maropis, N., Thomas, J. G., and Bancroft, D. 1961. Phenomenological considerations in ultrasonic welding. *Welding Journal* 40 (7): 289s-305s.

Jones, W. and March, N. H. *Theoretical Solid State Physics*, vol. 2. London: Wiley-Interscience, 1973.

Locke, E., Hoag, E., and Hella, R. 1972. Deep penetration welding with high power CO_2 lasers. *Welding Journal* 51 (5): 245s-249s.

Manz, A. F. *The Welding Power Handbook*. Tarrytown, NY: Union Carbide Corporation, 1973.

Needham, J. C. and Carter, A. W. 1965. Material transfer characteristics with pulsed current. *British Welding Journal* 12: 229-241.

Nestor, O. H. 1962. High intensity and current distributions at the anode of high current, inert gas arcs. *Journal of Applied Physics* 33: 1638-1648.

O'Brien, R. L. *Plasma Arc Metalworking Process*. New York: American Welding Society, 1967.

The Oxy-Acetylene Handbook. 2d ed. New York: Union Carbide Corporation, 1960.

Quigley, M. B. C. and Webster, J. M. 1971. Observations of exploding droplets in pulsed-arc GMA welding. *Welding Journal* 50: 461s-466s.

Rager, D. D. 1971. Direct current, straight polarity gas tungsten-arc welding of aluminum. *Welding Journal* 50 (5): 332-341.

Reed, T. B. Plasma torches. *International Science and Technology*, June 1962, pp. 42-48.

Shifrin, E. G. and Rich, M. I. 1973. Effect of heat source width in local heat treatment of piping. *Welding Journal* 52 (12): 792-799.

Stoeckinger, G. R. 1973. Pulsed dc high frequency GTA welding of aluminum plate. *Welding Journal* 52 (12): 558s-567s.

Tseng, Chao-Fang and Savage, W. F. 1971. Effect of arc oscillation. *Welding Journal* 50 (11): 777-786.

Vill, V. I. *Friction Welding of Metals*. Translated from the Russian. New York: American Welding Society, 1962.

Wood, F. W. and Beall, R. A. 1965. Studies of high-current metallic ores. *Bureau of Mines Bulletin* 625.

Woods, R. A. and Milner, D. R. 1971. Motion in the weld pool in arc welding. *Welding Journal* 50 (4): 163s-173s.

Woollard, K. F. and Gugdel, L. L. 1966. Welding and brazing developments utilizing stabilized methylacetylene propadiene. *Welding Journal* 45 (2): 123-129.

3

Heat Flow in Welding

Prepared by:

C. M. ADAMS, JR. *Chairman*
University of Cincinnati

Chapter Reviewer:

C. E. JACKSON
Ohio State University

3

Heat Flow in Welding

INTRODUCTION

In order to control metallurgical events in welding, the thermal conditions in and near the weld metal must be established. Of particular interest in this connection are: (1) the distribution of maximum or peak temperatures in the weld heat-affected zone, (2) cooling rates in the weld metal and in the heat-affected zone, and (3) the solidification rate of the weld metal. These factors will be considered in the order stated and will be followed by a description of typical weld thermal cycles.

Although the following discussions deal largely with manual arc welding, certain general statements can be applied to all welding processes. By applying these generalities in choosing a welding process and selecting welding variables, the welding engineer can often alter the nature and the extent of the metallurgical changes in the heat-affected zone to produce a more satisfactory joint. However, consideration must also be given to the metallurgical behavior of the material.

PEAK TEMPERATURES

PEAK TEMPERATURE EQUATION

Predicting or interpreting metallurgical transformations at a point in the solid metal near a weld requires some knowledge of the maximum or peak temperature reached at a specific location. For a single pass, full penetration butt weld in sheet or plate, for example, the distribution of peak temperatures in the base metal adjacent to the weld is given by:

$$\frac{1}{T_p - T_o} = \frac{4.13\,\rho C t Y}{H_{net}} + \frac{1}{T_m - T_o} \qquad (3.1)^*$$

where

T_p = the peak or maximum temperature, °C, at a distance, Y (mm), from the weld fusion boundary. (The peak temperature equation does not apply at points within the weld

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Note: The SI (metric) and U.S. customary values given in this chapter are not, in most cases, exact equivalents. The SI values are the primary measurements used in this and all Volume 1 chapters. The secondary U.S. measurements (given parenthetically in text) are rounded off conversions from the SI values. For a further explanation of the system of measurements used in Volume 1, refer to the Foreward on p. xi.

*C.M. Adams, Jr., "Cooling Rates and Peak Temperatures," pp. 210s-215s. (See Supplementary Reading List for the complete bibliographical entry.)

metal, but only in the adjacent heat-affected zone.)

T_o = initial uniform temperature of the sheet or plate, °C

T_m = melting temperature, °C (specifically, liquidus temperature of the metal being welded)

H_{net} = net energy input = $\frac{f_1 EI}{V}$

(E = volts; I = amperage; f_1 = heat transfer efficiency; V = travel velocity of heat source)*

ρ = density of material, g/mm^3

C = specific heat of solid metal, J/g • °C

ρC = volumetric specific heat, J/mm^3 • °C

t = thickness of sheet or plate, mm

(See Table 3.1 for a guide to all the mathematical symbols used in this chapter.)

The thermal properties for some metals are given in Table 2.5, Chapter 2, p. 72. The density and specific heat always occur as the product, ρC, the volumetric specific heat. This property is of fundamental importance in problems on heat conduction.

The peak temperature equation can be used for several purposes including: (1) the determination of peak temperatures at specific locations in the heat-affected zone, (2) estimating the width of the heat-affected zone, and (3) showing the effect of preheat on the width of the heat-affected zone.

For example, a single full penetration weld pass is made on steel using the following parameters:

E = 20 V
I = 200 A
V = 5 mm/s
T_o = 25 °C
T_m = 1510 °C
ρC = 0.0044 J/mm^3 • °C
t = 5 mm
f_1 = 0.9**
H_{net} = 720 J/mm

The peak temperatures calculated at distances of 1.5 and 3.0 mm from the weld fusion boundary are shown below.

at Y = 1.5 mm (0.06 in.):

$$\frac{1}{T_p - 25} = \frac{4.13\,(0.0044)\,5\,(1.5)}{720} + \frac{1}{1510 - 25}$$

T_p = 1184 °C (2163 °F)

at Y = 3.0 mm (0.12 in.):

$$\frac{1}{T_p - 25} = \frac{4.13\,(0.0044)\,5\,(3)}{720} + \frac{1}{1510 - 25}$$

T_p = 976 °C (1789 °F)

As would be expected, the peak temperature decreases with increasing distance from the weld. Moreover, at $Y = 0$, the equation shows that $T_p = T_m$. This result is consistent with the requirement that the peak temperature at the weld fusion boundary equal the melting temperature.

CALCULATING WIDTH OF HEAT-AFFECTED ZONE

One of the more interesting uses of the peak temperature equation is in calculating the width of the weld heat-affected zone. However, to calculate the width accurately the outer extremity of the heat-affected zone must be clearly identified with a specific peak temperature which in turn is associated with some characteristic change in structure or properties. For example, for most plain carbon or low alloy steels, there is a distinct etching boundary (as observed on the polished and etched weld cross section), corresponding to a peak temperature of 730 °C (1346 °F). Assuming this etching boundary defines the outer extremity, the width of the heat-affected zone for the preceding example can be calculated. Here the problem is to determine that value of Y at which T_p = 730 °C:

$$\frac{1}{730 - 25} = \frac{4.13\,(0.0044)\,5\,Y_z}{720} + \frac{1}{1510 - 25}$$

Y_z = the width of the heat-affected zone = 5.9 mm (0.23 in.)

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*Refer to Chapter 2, p. 36, for a discussion of H and H_{net}.

**Approximate value assumed as 0.9 for purposes of calculation.

Table 3.1—Guide to mathematical symbols in Chapter 3

Symbol	Definition	Unit of Measurement	Equation(s) where used
T_p Y Y_z	The peak or maximum temperature at a particular distance, Y, from the weld fusion boundary; Y_z is the width of the heat-affected zone	T_p = °C Y, Y_z = mm	3.1 3.1 Y_z referred to in calculations only
T_o	The uniform initial temperature of the sheet or plate	°C	3.1, 3.2, 3.3, 3.4, 3.5
T_m	Melting temperature (specifically, liquidus temperature of the metal being welded)	°C	3.1, 3.5
ρ	Density of material	g/mm³	3.1, 3.3, 3.4, 3.5
C	Specific heat of solid metal	J/g· °C	3.1, 3.3, 3.4, 3.5
ρC	Volumetric specific heat	J/mm³· °C	3.1, 3.3, 3.4, 3.5
t	Thickness of sheet or plate	mm	3.1, 3.3, 3.4
$H_{net} = \frac{f_1 EI}{V}$ f_1 E I V	Net energy input Heat transfer efficiency Volts Amperage Travel velocity of heat source	J/mm — V A mm/s	3.1, 3.2, 3.3, 3.4, 3.5
R T_c	The cooling rate at a point on the weld center line at just that moment when the point is cooling past the temperature of interest, T_c	R = °C/s T_c = °C	3.2, 3.3 3.2, 3.3, 3.4
k	Thermal conductivity of the metal	J/mm · s °C	3.2, 3.3, 3.5
τ	Relative plate thickness	Dimensionless	3.4
S_t	Solidification time, the time lapse from beginning to end of solidification at a fixed point in the weld metal	s	3.5
L	Heat of fusion	J/mm³	3.5

Thus, it is predicted that the 730 °C (1346 °F) characteristic etching boundary will be located 5.9 mm from the fusion boundary, or that a region 5.9 mm wide, adjacent to the weld, will be structurally changed; that is, it may be affected by the heat of welding.

If, however, this had been a quenched and tempered steel, tempered at 430 °C (806 °F), then any region heated above 430 °C will, in theory, have been "over-tempered," and may exhibit modified properties. It would then be reasonable to consider the modified zone as "heat-affected," with its outer extremity located where $T_p = 430$ °C:

$$\frac{1}{430 - 25} = \frac{4.13\,(0.0044)\,5\,Y_z}{720} + \frac{1}{1510 - 25}$$

$$Y_z = 14.2 \text{ mm } (0.56 \text{ in.})$$

Steels which respond to a quench-and-temper heat treatment are frequently preheated prior to welding. This treatment has the side effect of widening the heat-affected zone. Referring to the preceding example, suppose the preheat temperature is $T_o = 200$ °C (390 °F):

$$\frac{1}{430 - 200} = \frac{4.13\,(0.0044)\,5\,Y_z}{720} + \frac{1}{1510 - 200}$$

$$Y_z = 28.4 \text{ mm } (1.12 \text{ in.})$$

Thus, preheat has doubled the width of the heat-affected zone.

Finally, one of the simplest and most important conclusions to be drawn from the peak temperature equation, is that the width of the heat-affected zone is directly proportional to the net energy input. Again using the preceding example (but without preheat), suppose the net energy input is increased 50 percent to 1080 J/mm (27 432 J/in.):

$$\frac{1}{430 - 25} = \frac{4.13\,(0.0044)\,5\,Y_z}{1080} + \frac{1}{1510 - 25}$$

$$Y_z = 21.3 \text{ mm } (0.84 \text{ in.})$$

The width of the heat-affected zone is also increased 50 percent.

Although the peak temperature equation can be very instructive and useful, it is important to recognize certain restrictions in its application. The most important of these is that the equation is derived for the so-called "thin-plate" condition in which heat conduction takes place along paths which are parallel to the plane of the plate. The equation thus applies to any single pass full penetration (welding or thermal cutting) process, regardless of plate thickness. In fact, it applies to any full penetration arc weld which is accomplished with fewer than four passes. The equation must be applied on a per pass basis; however, the interpass temperature (that temperature to which the weld region cools between passes) may be inserted as an accurate value for T_o in the peak temperature equation.

When heat flow is essentially planar, the volume of heat-affected metal per unit length of weld is $2tY$; this value is also the total area (both sides of the weld) of the heat-affected zone as observed in a transverse cross section of the weld. Thus, for any given material and definition of the heat-affected zone, this area (or volume per unit length) is simply proportional to the net energy input, a concept which can be used to extend application of the peak temperature equation to other geometrics (such as multipass welding of thick plates).

When heat transfer and melting efficiencies are taken into account, the quantity of weld metal divided by the quantity of heat-affected metal is a parameter which depends on and increases with the intensity of the heat source. As was discussed in Chapter 2, p. 36, the quantity of heat required to produce a weld having a specific cross section is determined by the theoretical heat requirement for melting divided by the melting efficiency. This net heat input, in turn, determines the size of the heat-affected zone. It follows that small heat-affected zones are associated with higher intensity processes. The high intensity electron beam heat source provides a double benefit in this respect: less metal must be melted (by comparison with an arc source) to produce a given joint, and a small amount of metal is melted with very high efficiency. The result is that electron beam welds require very low energy inputs and contain correspondingly small heat-affected zones.

In arc welding, there frequently exists the option of producing a given joint with a few large or many small passes. There are technical and economic factors favoring both courses of action. The objective of minimizing the heat-affected zone is best served by exercising the second option (many low energy passes), especially if there is ample time for cooling between passes, so that the interpass temperature is kept moderately low.

COOLING RATES

The next important aspect of heat flow to be considered is the cooling rate of the weld. After a point in or near the weld has reached its peak temperature, the rate at which it cools may have a significant effect on the metallurgical structure, the properties, or even the soundness of the base metal. It is principally in connection with the heat treatable steels that cooling rate is of interest. These metals are somewhat unique because their cooling rates, which are critical to structure and properties, are commensurate with those likely to be encountered in welding. In general, this condition is not true of other metals. For example, in welding aluminum, the cooling rates developed are almost always much higher than any which might be regarded as metallurgically "critical;" therefore, calculation of cooling rates actually contributes very little to the understanding of aluminum welding metallurgy.

THICK AND THIN PLATE COOLING RATE EQUATIONS

Calculation and comparison of cooling rates require careful specification of conditions. Reference to simply "the cooling rate" of a weld is inadequate because the cooling rate varies with position and time. The most useful method is to determine the cooling rate on the center line of the weld at the instant the metal is passing through a particular temperature of interest, T_c. At temperatures well below melting, the cooling rate in the weld and in its immediate heat-affected zone is substantially independent of position.

With carbon and low alloy steels, the temperature of interest is best taken near the pearlite "nose" temperature on the time-temperature-transformation (TTT) diagram.* The exact temperature is not critical, but should be the same for all calculations and comparisons. A value of T_c = 550 °C (1022 °F) is quite satisfactory for most steels.

The major practical use of cooling rate equations is in the calculation of preheat requirements. For instance, consider a single weld pass in making a butt weld between two plates of equal thickness. If the plates are relatively "thick," requiring several passes (more than six) to complete the joint, the cooling rate, R, is given by:

$$R = \frac{2\pi k(T_c - T_0)^2}{H_{net}} \qquad (3.2)^{**}$$

where

R = the cooling rate at a point on the weld center line, °C/s, at just that moment when the point is cooling past the temperature of interest, T_c

k = thermal conductivity of the metal, J/mm•s °C

Strictly speaking, the cooling rate is a maximum on the weld center line, and it is this

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*TTT diagrams are discussed in Chapter 4, p. 111 and in Chapter 64, Section 4 of the *Welding Handbook*, Sixth Edition.

**C. M. Adams, Jr., "Cooling Rates and Peak Temperatures," pp. 210s-215s. (See Supplementary Reading List for the complete bibliographical entry.)

maximum which is given by the equation. However, the cooling rate near the weld fusion boundary is only a few percent lower than on the center line. Accordingly, the cooling rate equation applies to the entire weld and the immediate heat-affected zone.

If the plates are relatively thin, requiring fewer than four passes:

$$R = 2\pi k\rho C \left(\frac{t}{H_{net}}\right)^2 \quad (T_c - T_o)^3 \qquad (3.3)^*$$

The distinction between thick and thin requires some explanation. The thick plate equation is used when heat flow is three-dimensional, downward as well as lateral from the weld. The thick plate equation would apply, for example, to a small bead-on-plate weld pass deposited on thick material. The thin plate equation would apply to any single pass, full penetration welding (or thermal cutting) process. Sometimes, it is not obvious whether the plate is thick or thin because the terms have no absolute meaning. For this reason, it is helpful to define a dimensionless quantity called "the relative plate thickness,"τ:

$$\tau = t\sqrt{\frac{\rho C(T_c - T_o)}{H_{net}}} \qquad (3.4)$$

The thick plate equation applies when τ is greater than 0.9, and the thin plate equation when τ is less than 0.6. When τ falls between 0.6 and 0.09, the thick plate equation gives a cooling rate which is too high, and the thin plate equation gives one which is too low. However, if an arbitrary division is made at τ =0.75, larger values being regarded as thick and smaller as thin, the maximum error may not exceed 15 percent in a cooling rate calculation, and, as will be seen, the error in applying the equations to the calculation of preheat requirements is minor. As an example of the ambiguity in the qualitative terms thick and thin, the cooling of an electroslag weld joining 300 mm (11.8 in.) thick plates would be calculated using the thin plate equation.

PREHEAT TEMPERATURE AND CRITICAL COOLING RATE

As can be seen from the cooling rate equations, increasing the initial uniform temperature, T_o, of the base metal being welded has the effect of reducing the cooling rate. Preheat is often used for this purpose in welding the hardenable steels. For each steel composition, there exists a critical cooling rate; if the actual cooling rate in the weld metal exceeds this critical value, hard martensitic structures may develop in the heat-affected zone, and there is great risk of cracking under the influence of thermal stresses in the presence of hydrogen. The cooling rate equation can be used (1) to determine the critical cooling rate (under welding conditions), and (2) to calculate preheat temperatures.

When welding hardenable steel, the first problem is to determine the critical cooling rate. The simplest and most direct way of doing this is to make a series of bead-on-plate weld passes in which all parameters, except the arc travel speed, are held constant. Suppose, for example:

E = 25 V
I = 300 A
t = 6 mm
f_1 = 0.9**
T_o = 25 °C
T_c = 550 °C

The bead-on-plate weld passes are deposited at 6, 7, 8, 9, and 10 mm/s (14, 17, 19, 21, and 24 in./min). Hardness tests are performed on the weld cross sections, and it is found that structures having high hardnesses have developed in the heat-affected zones of the welds deposited at 9 and 10 mm/s, but not in the others. The conclusion is the critical cooling rate was encountered at some travel speed above 8 mm/s. More to the point, the pass deposited at 8 mm/s experienced a cooling rate

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*P. Jhaveri, W.G. Moffatt, and C.M. Adams, Jr., "The Effect of Plate Thickness and Radiation on Heat Flow in Welding and Cutting," pp. 12s-16s. (See Supplementary Reading List for the complete bibliographical entry.)

**Approximate value assumed as 0.9 for purposes of calculation.

which is a maximum "safe" value. In this circumstance, the net energy input is:

$$H_{net} = \frac{25\ (300)\ 0.9}{8}$$

$$= 843.75 \text{ J/mm } (21\ 431 \text{ J/in.})$$

In this example, the relative plate thickness is:

$$\tau = 6\sqrt{\frac{0.0044\ (550 - 25)}{843.75}} = 0.31$$

Therefore, the thin plate equation (3.3) applies, and

$$\frac{R}{2\pi k} = 0.0044\left(\frac{6}{843.75}\right)^2 (550 - 25)^3 = 32.2$$

$$R = 2\pi\ (0.028)\ 32.2$$

$$= 5.7\ °\text{C/s}\ (10.26\ °\text{F/s})$$

This result means that approximately 6 °C/s (10.8 °F/s) is the maximum safe cooling rate for this steel, under welding conditions, and the actual cooling rate should not exceed this value. Preheat can be used in actual welding operations to reduce the cooling rate to 6 °C/s or less.

For example, if the following conditions prevail:

$E = 25$ V
$I = 250$ A
$V = 7$ mm/s
$t = 9$ mm
$f_1 = 0.9$

assuming the thin plate equation (3.3) applies,

$$\left(\frac{R}{2\pi k}\right)_{\max} = 32.2$$

$$= 0.0044\left(\frac{9}{804}\right)^2 (550 - T_o)^3$$

where

$$H_{net} = \frac{25\ (250)\ 0.9}{7}$$

$$= 804 \text{ J/mm } (20\ 422 \text{ J/in.})$$

then

$$T_o = 162\ °\text{C}\ (324\ °\text{F})$$

The relative plate thickness is:

$$\tau = 9\sqrt{\frac{0.0044\ (550 - 162)}{804}} = 0.41$$

and the thin plate equation does apply.

If the initial plate temperature is raised to or above 162 °C (324 °F) the cooling rate will not exceed 6 °C/s (10.8 °F/s), and brittle material will not form in the heat-affected zone. Next, if a weld pass of the same energy input is deposited on a 25 mm (1 in.) plate, the plate, in this situation, is neither thick nor thin. Using the thin plate equation (3.3):

$$32.2 = 0.0044\left(\frac{25}{804}\right)^2 (550 - T_o)^3$$

$$T_o = 354\ °\text{C}\ (669\ °\text{F})$$

$$\tau = 25\sqrt{\frac{0.0044\ (550 - 354)}{804}} = 0.82$$

The thick plate equation gives a similar result:

$$32.2 = \frac{(550 - T_o)^2}{804}$$

$$T_o = 389\ °\text{C}\ (732\ °\text{F})$$

$$\tau = 25\sqrt{\frac{0.0044\ (550 - 389)}{804}} = 0.74$$

Neither of the two calculated preheat values is exactly correct. (In fact, one is too low and one too high.) However, the difference is not of practical importance. In this case, selecting the higher preheat temperature is prudent.

Repeating the exercise for a 50 mm (2 in.) plate, but with the same energy input, the thick plate equation (3.2) applies, and again:

$$T_o = 389\ °\text{C}\ (732\ °\text{F})$$

Sometimes, it is not necessary to reduce the cooling rate through the use of preheat. If a weld of the same energy input were deposited on a 5 mm (0.2 in.) plate:

$$32.2 = 0.0044\left(\frac{5}{804}\right)^2 (550 - T_o)^3$$

$$T_o = -24\ °\text{C}\ (-11\ °\text{F})$$

The very low value determined for T_o has no practical meaning, except to show that preheat (for cooling rate control) is not necessary. Certainly, there would be no point in refrigerating the plate before welding. In actual practice, even when cooling rate considerations do not so dictate, a modest preheat is frequently used with the hardenable steels to remove condensed moisture on the work surfaces.

The cooling of a weld depends on the available paths for conducting heat into the surrounding cold base metal. It is sometimes necessary to modify the cooling rate equations for butt or for bead-on-plate welds. The following equation is for a T-fillet weld joining 9 mm (0.4 in.) plates, where:

$$H_{net} = 804 \text{ J/mm } (20\ 422 \text{ J/in.})$$

Here, there are three "legs" instead of two, conducting heat from the weld. The cooling rate equation, accordingly, is modified by reducing the effective energy input by a factor of two-thirds:

$$H_{net} = \tfrac{2}{3}(804) = 536 \text{ J/mm } (13\ 614 \text{ J/in.})$$

$$32.2 = 0.0044\left(\frac{9}{536}\right)^2 (550 - T_o)^3$$

$$T_o = 254\,^\circ\text{C } (489\,^\circ\text{F})$$

$$\tau = 9\sqrt{\frac{0.0044\,(550 - 254)}{536}}$$

$$= 0.44 \text{ ("thin")}$$

Because of the enhanced cooling, a higher preheat temperature is required than for a butt weld. A similar situation can arise in fillet welding very thick plate. If the same weld pass (H_{net} = 804 J/mm [20 422 J/in.]) is deposited at the 90 degree intersection between two 50 mm (2 in.) plates, the weld will be more completely "surrounded" by cold metal than if it were deposited on a flat 50 mm plate. As in the preceding example, this situation is accommodated by reducing the effective arc energy input, because the heat flows into three rather than two "quadrants" of cold metal:

$$H_{net} = \frac{2}{3}(804) = 536 \text{ J/mm}$$

$$32.2 = \frac{(550 - T_o)^2}{536}$$

$$T_o = 419\,^\circ\text{C } (786\,^\circ\text{F})$$

The variables, other than material properties which affect cooling rate and peak temperature distribution, are the initial temperature and thickness of the plate and the energy input. In using preheat to control cooling rate, the temperature required may vary widely with conditions, and very high levels of preheat are indicated for relatively low energy weld passes on thick plate, especially in fillet weld configurations. At the other extreme, when the energy input divided by the square of the plate thickness is relatively large, no preheat may be required (except, for example, to insure dryness).

In welding the hardenable steels, the critical cooling rate is a property of the steel and should be determined under welding conditions. Although TTT diagrams have been published for all of the important low alloy steels, these have been determined under conditions which relate to conventional heat treatment, not to those special circumstances prevailing in the weld heat-affected zone. In general, the heat-affected zone acts more hardenable (that is, it exhibits a lower critical cooling rate) than does the same steel subjected to a typical austenitize-and-quench sequence. This difference is due to the temperatures in the heat-affected zone which exceed by several hundred degrees the maximum which would ever be used in normal heat treatment; as a consequence, the dissolution and homogenization of alloy elements and carbides are much more complete in the heat-affected zone, in spite of the short exposure time to high temperature. An indirect effect of very high temperature excursions is that coarse local grain size develops, further reducing the critical cooling rate.

Selecting preheat temperatures should be guided by experience as well as by calculation whenever possible. The optimum preheat temperature is one that maintains the cooling rate somewhat below the critical temperature (allowing for a margin of safety). Excessive preheat not only adds unnecessarily to the discomfort of the welder, but, as has been pointed out, increases the extent of the heat-affected zone. Unfortunately, preheat temperature commonly has been regarded as a fixed property of the steel being welded. For example, it may be stated that 200 °C (390 °F) is the proper preheat temperature for arc welding hardenable steel; this assumption is dangerously misleading since 200 °C may be too high or too low. It is not the preheat temperature but rather the critical cooling rate which is a property of the steel.

SOLIDIFICATION RATES

The rate at which weld metal solidifies can have a profound effect on its metallurgical structure, properties, response to heat treatment, and soundness. The solidification time, S_t (in seconds), of weld metal depends on the net energy input:

$$S_t = \frac{L\,H_{net}}{2\pi k\rho C(T_m - T_o)^2} \qquad (3.5)$$

where

S_t = solidification time, the time lapse from beginning to end of solidification at a fixed point in the weld metal, s

L = heat of fusion, J/mm^3

The solidification time is a function of the energy input and the initial temperature of the metal. If, for example, a weld pass of 800 J/mm (20 300 J/in.) net energy input is deposited on a steel plate, with initial temperature, 25 °C (77 °F):

$$S_t = \frac{2\,(800)}{2\pi 0.028(0.0044)\ (1510 - 25)^2}$$

$$= 0.94\ \text{s}$$

By comparison with any casting process, weld metal solidification is extremely rapid. In even a severely chilled ingot or casting, the solidification time is several seconds, while, for many castings, solidification time is over a minute. For this reason, it is misleading to describe weld metal as having a "cast" structure; welding involves a unique solidification process. A principal reason weld metal freezes so much more rapidly than a casting is that, in a weld deposit, the weld metal is in good contact with the surrounding metal (that is, the surrounding cold metal, which acts as a "mold").

EFFECT OF DENDRITE SPACING

The solidification equation (3.5) shows that solidification time is proportional to energy input. Solidification time directly affects the structure of weld metal. Most alloys of technical importance freeze dendritically, and an important structural feature of weld metal is the dendrite spacing* (more exactly, dendrite arm spacing). The dendrite spacing is proportional to the square root of the solidification time. For example, in comparing two weld passes, one having four times the energy input of the other, the dendrite spacing will be twice as great in the larger deposit. In other words, the larger energy input will produce a coarser structure, and the dendrite structure directly influences the properties and responsiveness to heat treatment of weld metal. (In this connection, dendrite spacing should not be confused with grain size**, an entirely separate structural feature and one

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*For an explanation of dendrite structure, refer to Chapter 4, p. 125.

**For an explanation of grain size, refer to Chapter 4, p. 101.

which does not depend systematically on solidification time.)

With most metals, strength, ductility, and toughness all improve with finer dendrite spacing. Furthermore, fine dendrite structure favors rapid response to heat treatment.

EFFECT OF ENERGY INPUT

The dominant factor governing all significant thermal events in welding is the energy input which affects peak temperature distribution, cooling rate, and solidification time. There is also a direct, if somewhat inexact, relationship between energy input and the size of a weld pass (weld metal cross section per pass). Changes in individual parameters such as voltage, current, or travel speed have effect only in so far as energy input is changed. Two weld passes deposited under the following conditions will emphasize this point:

		Weld No. 1	Weld No. 2
E	=	25 V	25 V
I	=	250 A	500 A
V	=	7 mm/s	14 mm/s
f_1	=	0.9*	0.9*
t	=	9 mm	9 mm
T_o	=	162 °C	162 °C
H_{net}	=	804 J/mm	804 J/mm

Between these two weld passes, there will be no important differences in peak temperature distribution, cooling rate, or dendrite structure. There will be substantial differences in penetration and perhaps other important features such as weld contour, the presence or absence of undercut, and soundness. In other words, energy input is not the sole factor governing weld quality, but is a unique determinant of thermal events.

Metallurgical considerations generally favor low arc energy input; the extent of the heat-affected zone is minimized and weld metal properties are enhanced through production of fine dendrite structure. Ignoring other factors, this reasoning would favor the use of many small rather than a few large passes to produce a weld. Expressed in practical terms, there are definite metallurgical benefits to be gained from the selection of the "stringer-bead" technique.**

Simple economics favor the use of large weld passes (high energy input) because they are associated with high deposition and production rates and reduction of time lost performing interpass chipping and cleaning operations. However, there can also be metallurgical benefit from reduced cooling rates in the welding of hardenable ferrous base metals. An extreme example is the oxyacetylene welding of cast iron, where, because the melting efficiency is very low, the energy input is enormous and cooling rates are low enough to avoid brittle structures.

In summary, the significance of the all-important parameter, energy input, cannot be overemphasized, and limitations on energy input are frequently included in process specifications, especially in handling sensitive alloys.

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*Approximate value assumed as 0.9 for purposes of calculation.

**Stringer bead is defined on p. 318 of Appendix A.

TYPICAL WELD THERMAL CYCLES

Figure 3.1 shows typical members of the family of thermal cycles produced in 13 mm (1/2 in.) steel plate by an arc weld made using an energy input of 3940 J/mm (100 000 J/in.) with an initial plate temperature of 27 °C (80 °F). The uppermost curve represents the thermal cycle with a peak temperature of 1365 °C (2490 °F) experienced by a point located 10 mm (0.39 in.) from the weld center line. The lowest curve corresponds to the thermal cycle with a peak temperature of 515 °C (960 °F) experienced by a point 25 mm (1 in.) from the weld center line. The intermediate curves summarize the thermal cycles corresponding to distances of 11, 14, and 18 mm (0.45, 0.55, and 0.70 in.) from the weld center line, as labeled. The shapes of the five curves shown in Fig. 3.1 reflect a pattern typical of all arc welds. The following three characteristics are thus illustrated:

(1) The peak temperature decreases rapidly with increasing distance from the weld center line.

(2) The time required to reach peak temperature increases with increasing distance from the weld center line.

(3) The rate of heating and the rate of cooling both decrease with increasing distance from the weld center line.

EFFECTS OF ENERGY INPUT AND PREHEAT TEMPERATURE

Figure 3.2 illustrates the effects of energy input and preheat temperature on peak temperature distribution in the weld heat-affected zone. The specimen represented is a shielded metal arc welded steel plate, 13 mm (1/2 in.) thick. The upper two curves compare the distribution of peak temperatures produced with an energy input of 3940 J/mm (100 000 J/in.), using preheat temperatures of 27 °C (80 °F) and 500 °F (260 °C). The lower two curves present similar data for an energy input of 1970 J/mm (50 000 J/in.). Figure 3.2 shows that:

(1) Decreasing either the energy input or the preheat temperature provides a steeper distribution of peak temperatures in the weld heat-affected zone.

(2) Increasing the energy input causes a significant increase in the distance from the weld center line to a point experiencing a particular peak temperature for all values of peak temperature.

(3) Increasing the preheat temperature increases the distance from the weld center line to a point experiencing a particular peak temperature by an amount that varies inversely with the value of the peak temperature. For example, consider the distance from the weld center line to a point just heated to the upper critical temperature (Ac_3) for the four curves shown. The data for these curves, shown in the fourth column of Table 3.2 should be compared with the distance to the points just heated to the lower critical temperature (Ac_1) shown in the fifth column of Table 3.2.

In each case the readily visible heat-affected zone in steel extends from the location experiencing a peak temperature equal to the liquidus outward to the location just heated to the lower critical temperature (Ac_1). Thus, the heat-affected zones for the four conditions summarized would be 6.1, 11.2, 2.0, and 3.3 mm (0.24, 0.44, 0.08, and 0.13 in.) wide reading from top to bottom in Table 3.2. (These are the differences between the liquidus and the Ac_1 distances.)

Figure 3.3 summarizes the effects of energy input and preheat temperature on the shape of the actual weld thermal cycles. The heat-affected zones of arc welds in 13 mm (1/2 in.) plate using covered electrodes are illustrated. The four thermal cycles shown, giving comparisons for 3940 and 1970 J/mm

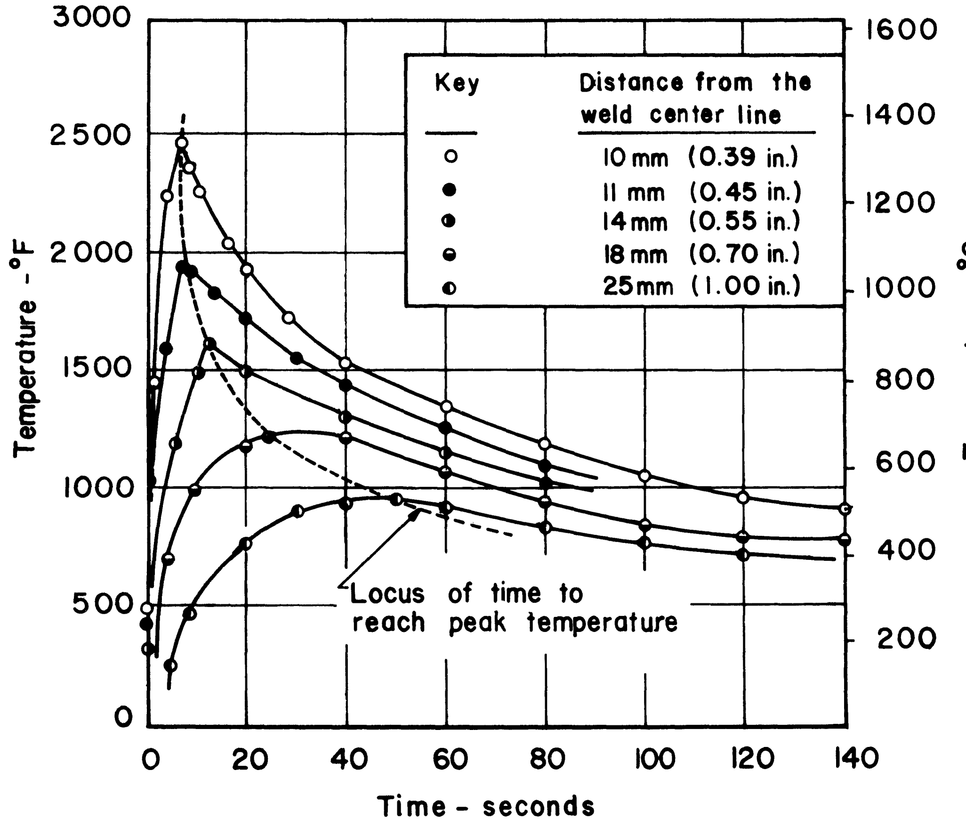


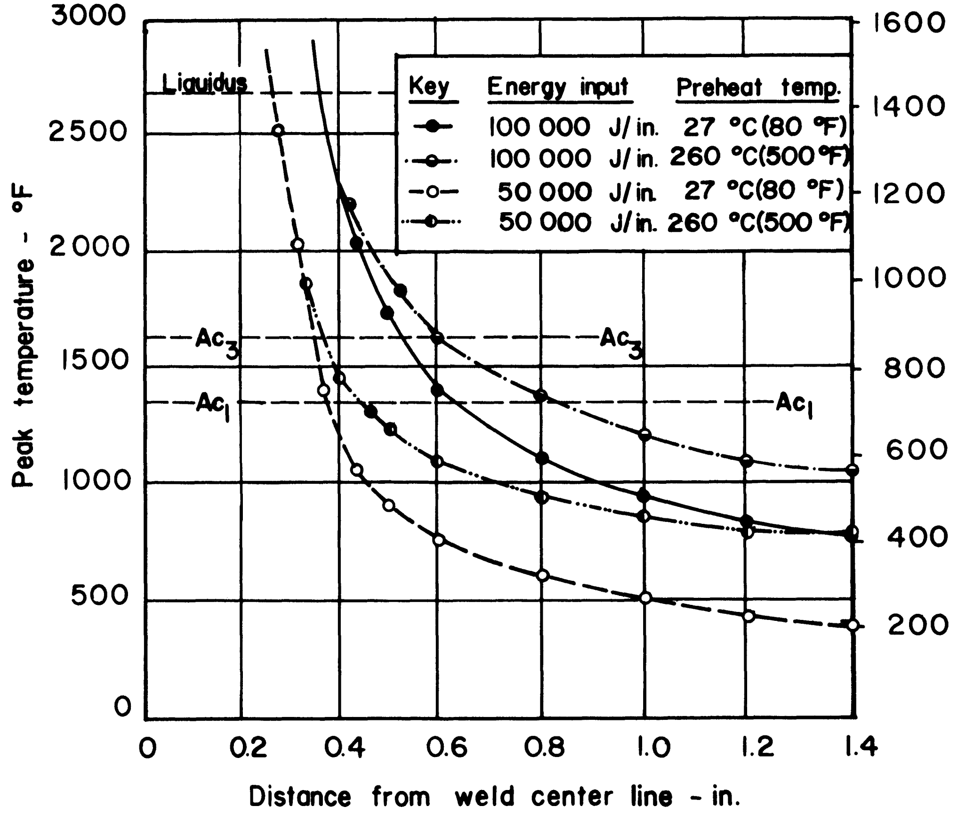
Fig. 3.1—Thermal cycles experienced by indicated locations in the heat-affected zone of an arc weld.

(100 000 and 50 000 J/in.) energy inputs, were chosen to have a peak temperature of 1365 °C (2490 °F) in each case. Consequently the corresponding locations are at different distances from the weld center line. The following is true of peak temperatures near the liquidus:

(1) For a given preheat temperature, increasing the energy input causes an increase in the time of exposure to temperatures near the peak temperature and causes a decrease in the cooling rate.

(2) For a given energy input, increasing the preheat temperature decreases the cooling rate, but does not significantly influence the time of exposure to temperatures near the peak temperature.

Table 3.3 compiled from Fig. 3.3, summarizes the time of exposure to temperatures above 1095 °C (2000 °F) and the cooling rate at 650 °C (1200 °F) for the four thermal cycles shown. Note that for a preheat temperature of 27 °C (80 °F), doubling the input from 1970 to 3940 J/mm (50 000 to 100 000 J/in.) increases the time above 1095 °C (2000 °F) from 5 to 16.5 s and decreases the cooling rate at 650 °C (1200 °F) from 14 to 4.4 °C/s (25 to 8 °F/s). On the other hand, if the energy input is held constant at about 1970 J/mm, increasing the preheat temperature from 27 °C to 260 °C (500 °F) decreases the cooling rate at 650 °C from 14 to 4.4 °C/s without measurably changing the time of exposure to temperatures above 1095 °C. Thus, by manipulating the energy input and the preheat temperature, the welding engineer can control the time at temperature and the cooling rate for the material in the weld heat-affected zone, in addition to



mm	5	10	15	20	25	30	36	**J/mm**	1970	3940
in.	0.2	0.4	0.6	0.8	1.0	1.2	1.4	**J/in.**	50 000	100 000

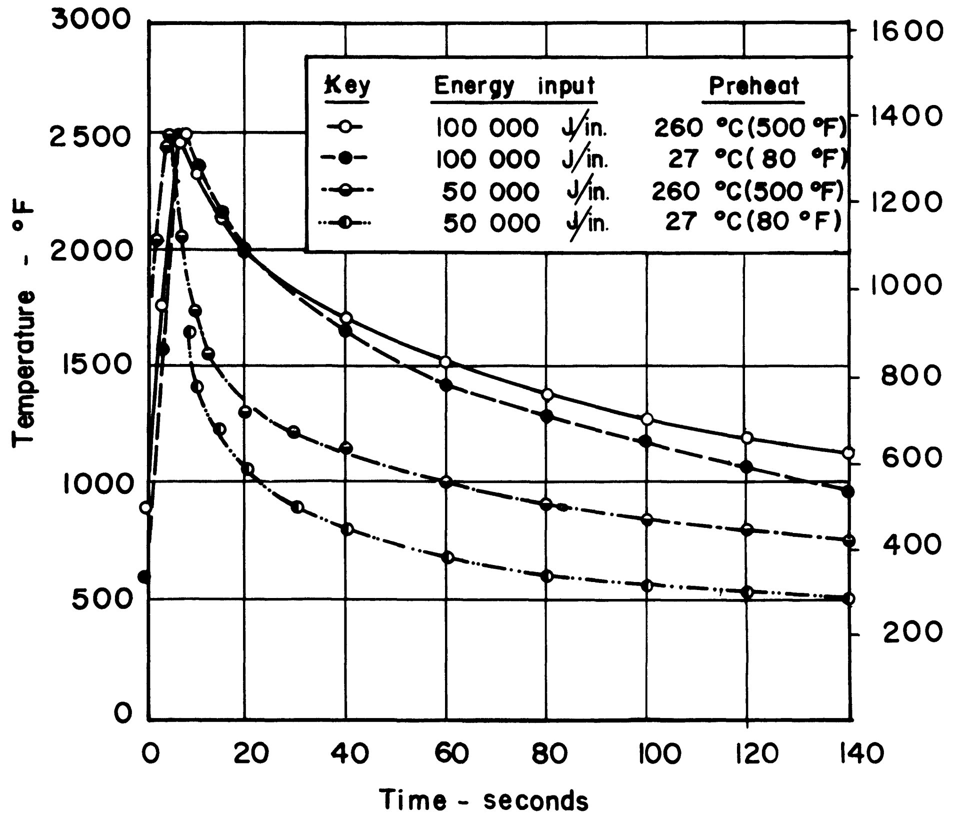
Fig. 3.2—Effect of energy input and preheat temperature on peak temperature distribution. A_{c_1} and A_{c_3} represent critical temperatures.

controlling the width of the heat-affected zone.

Figure 3.4 shows the effect of energy input on the temperature isotherms as measured at the surface of a 13 mm (1/2 in.) steel plate. Imagine that an arc weld has progressed along the horizontal center line of the figure from right to left until the arc is operating at the location labeled "O" distance behind the arc center line. The isotherms in the upper portion of Fig. 3.4 show the temperature distribution for a weld made at 1.3 mm/s (3 in./min) with an energy input of 3940 J/mm (100 000 J/in.) for an initial plate temperature of 27 °C (80 °F). The isotherms in the lower portion show similar data for a weld made with an energy input of 1970 J/mm (50 000 J/in.) using 2.5 mm/s (6 in./min) travel speed with the same arc current, arc voltage, and preheat temperature. The width of the heat-affected zone is reduced by decreasing the energy input, and the volume of metal heated above some temperature, say 815 ° C (1500 °F), is considerably less at any instant of time. This effect becomes much more pronounced with speeds greater than 5 mm/s (11.8 in./min) such as are

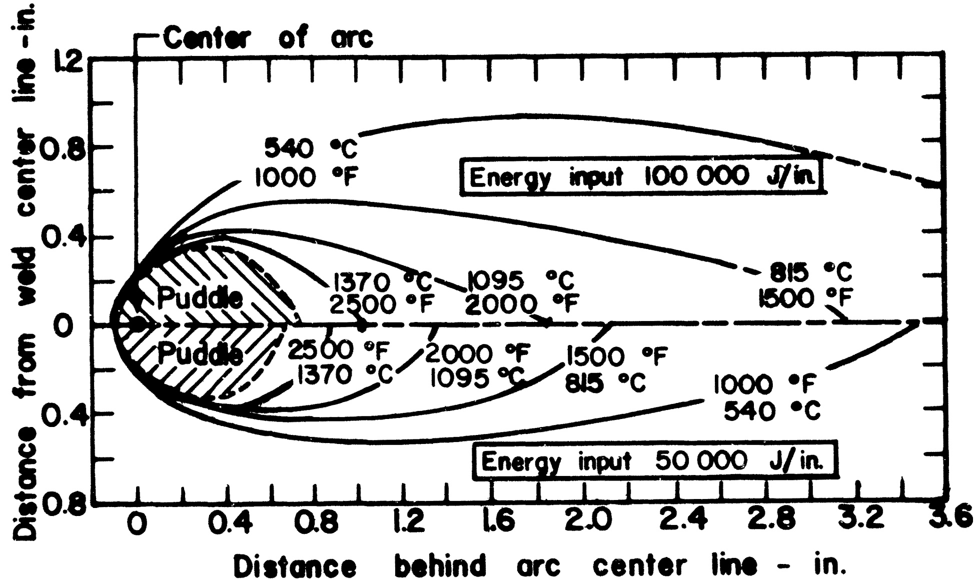
Table 3.2—Relation between temperature and distance from center line

Welding Conditions Energy Input		Preheat Temperature		Distance from weld center line to point heated to:					
				1480 °C 2700 °F (liquidus)		870 °C 1600 °F (Ac_3)		705 °C 1300 °F (Ac_1)	
J/mm	J/in.	°C	°F	mm	in.	mm	in.	mm	in.
3940	100 000	27	80	9.4	0.37	13.2	0.52	15.5	0.61
3940	100 000	260	500	9.4 +	0.37 +	15.2	0.60	20.6	0.81
1970	50 000	27	80	7.4	0.29	9.1	0.36	9.4	0.37
1970	50 000	260	500	7.4 +	0.29 +	9.4	0.37	10.7	0.42



J/mm	1970	3940
J/in.	50 000	100 000

Fig. 3.3—Effect of initial plate temperature on thermal cycles in the heat-affected zone of arc welds.



mm	10	20	30	40	50	60	70	80	90
in.	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6

Fig. 3.4—Effect of energy input on temperature isotherms at the surface of a steel plate. Upper portion: 3940 J/mm (100 000 J/in.), 24 V, 208 A, 1.3 mm/s (3 in./min). Lower portion: 1970 J/mm (50 000 J/in.), 24 V, 208 A, 2.5 mm/s (6 in./min).

Table 3.3—Time of exposure and cooling rate

Welding Conditions Energy Input J/mm	J/in.	Preheat Temperature °C	°F	Peak Temperature °C	°F	Time above 1095 °C (2000 °F) s	Cooling rate at 650 °C (1200 °F) °C/s	°F/s
3940	100 000	27	80	1365	2490	16.5	4.4	8
3940	100 000	260	500	1365	2490	17	1.4	2.5
1970	50 000	27	80	1365	2490	5	14	25
1970	50 000	260	500	1365	2490	5	4.4	8

Table 3.4—Typical cooling rates

Welding Conditions Energy Input J/mm	J/in.	Preheat Temperature °C	°F	Cooling Rate at 650 °C (1200 °F) For butt welds in 13 mm (1/2 in.) plate °C/s	°F/s	For fillet welds °C/s	°F/s
1970	50 000	22	72	11	20	44	79
1970	50 000	120	250	7	13	34	61
1970	50 000	205	400	5	9	20	36
3940	100 000	22	72	4	~ 7	10	18
3940	100 000	205	400	1.7	~ 3	5	9

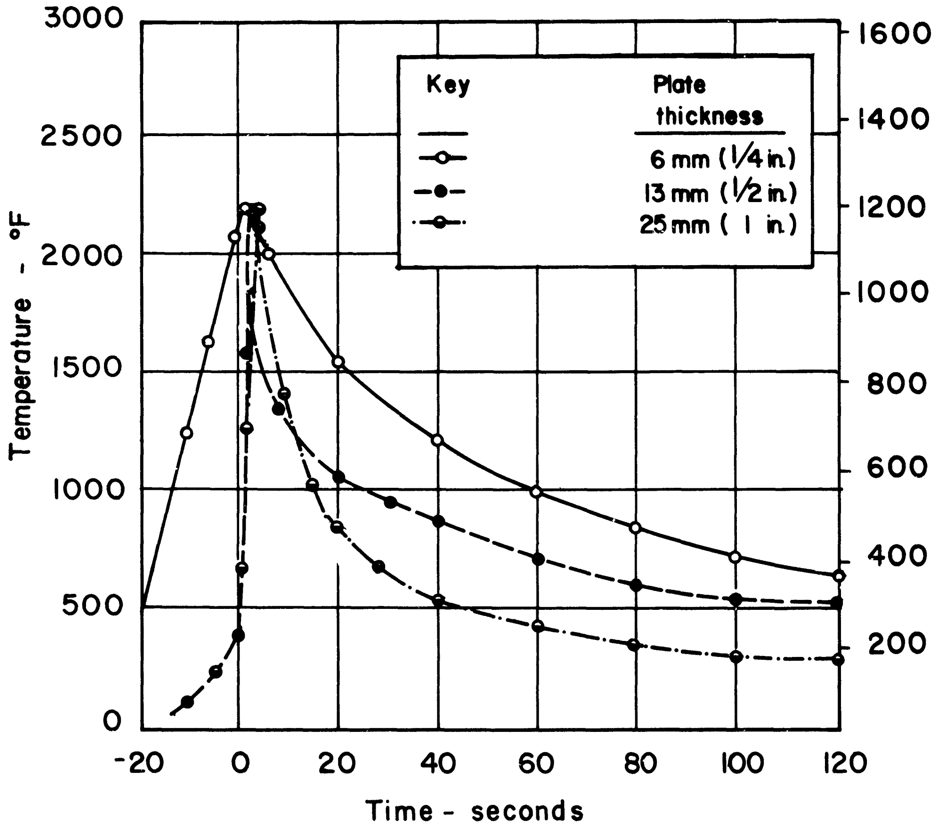


Fig. 3.5—*Effect of plate thickness on the thermal cycles in the weld heat-affected zone of manual shielded metal arc welds in steel plate. Energy input: 1850 J/mm (47 000 J/in.). Initial plate temperature: 27 °C (80 °F).*

often encountered with automated welding processes. In fact, the steepness of the temperature gradients normal to the direction of welding increases at an exponential rate with increase in the travel speed above 5 mm/s.

EFFECT OF PLATE THICKNESS AND WELD GEOMETRY

The effect of plate thickness on weld thermal cycles is illustrated in Fig. 3.5. The data shown compare the thermal cycles having a peak temperature of 1205 °C (2200 °F) for butt welds made with an energy input of 1850 J/mm (47 000 J/in.) on 6, 13, and 25 mm (1/4, 1/2, and 1 in.) thick plate. The cooling rate tends to increase with an increase in plate thickness, while the time at elevated temperature tends to decrease with an increase in plate thickness.

The effect of plate thickness is complex because the heat flow pattern changes markedly between thin plates and thick plates. In thin plates, the temperature isotherms shown in Fig. 3.4 tend to extend vertically downward into the plate and form curved surfaces roughly perpendicular to the plate surface. On the other hand, with very thick plates, the isotherms approximate surfaces of revolution about the longitudinal axis of the weld. Thus the heat flow pattern changes from a two-dimensional flow for very thin plates to a three-dimensional flow for very thick plates. This change explains in a qualitative fashion

Table 3.5—Peak temperature gradients

Process	Methods for increasing the steepness of the distribution of peak temperatures
Electron beam welding (EBW)	Decrease the effective diameter of the beam or increase the beam power and the welding speed.
Plasma arc welding (PAW)	Use smaller orifice or increase power and speed
Resistance spot welding (RSW)	Decrease the weld time with an appropriate increase in weld current or employ electrodes of higher conductivity.
Resistance seam welding (RSEW)	Decrease the on-time with an appropriate increase in weld current or flush cool the work.
Flash welding (FW)	Increase the rate of acceleration of the platens during flashing, decrease the clamping distance or, in some cases, increase the upset distance to extrude more of the heat-affected material from the weld region.
Upset welding (UW)	Decrease the heating time by an appropriate increase in heating current or decrease the clamping distance.
Arc welding (AW)	Decrease the energy input by increasing welding speed, use stringer beads, or use lower preheat temperatures.
Oxyacetylene welding (OAW)	Use a larger torch and a faster welding speed.

the influence of plate thickness on cooling rates. The same effect is present, although to a lesser degree, in fillet welds where the additional dimension of heat flow becomes effective for thinner plate due to the geometry of the joint.

Table 3.4 summarizes some typical cooling rates. The cooling rates for fillet welds average three to four times those for butt welds in 13 mm (1/2 in.) plate. The difference becomes less pronounced, however, for thicker plates and for last pass fillet welds.

EFFECT OF THERMAL CHARACTERISTICS

No quantitative data are presently available showing the effect of the thermal characteristics of material. However, the following general conclusions can be drawn:

(1) The lower the thermal diffusivity of the material, the steeper will be the distribution of peak temperatures.

(2) The higher the thermal diffusivity, the faster will be the cooling rate for a thermal cycle with a given peak temperature.

(3) The higher the thermal diffusivity, the shorter will be the time at elevated temperature for a thermal cycle with a given peak temperature.

The peak temperatures in the heat-affected zone of any weld involving fusion range from the melting temperature downward. The peak temperatures in the heat-affected zone of a fusion weld in copper would range from 1080 °C (1981 °F) at the edge of the fusion zone to the initial plate temperature at a considerable distance from the weld. By comparison, the heat-affected zone of a fusion weld in uranium would experience peak temperatures ranging from 1130 °C (2065 °F) to the initial plate temperature. However, the distance from the edge of the weld to a point experiencing a peak temperature of say 540 °C (1000 °F) would be much less for uranium than for copper, since the thermal diffusivity of uranium is only about eleven percent that of copper.

CONTROL OF THE WIDTH OF THE HEAT-AFFECTED ZONE

The width of the heat-affected zone in a given material may be controlled by altering the distribution of peak temperatures. In general, the distribution of peak temperatures is steeper the more concentrated the heat source.* Thus, electron beam welding with power concentrations as high as 10 MW/mm^2 (65 000 MW/in.^{2}) is capable of producing welds with such steep distribution of peak temperatures that the heat-affected zone almost disappears. On the other hand, oxyacetylene welding flames provide a diffuse heat source at a comparatively low temperature, causing the production of a relatively flat distribution of peak temperatures and consequently a wide heat-affected zone. Table 3.5 lists a number of common welding processes in approximate order of decreasing steepness of the peak temperature gradient. Included in the table are suggested techniques for altering the distribution of peak temperatures with each process.

In general, conditions which provide a steep distribution of peak temperatures tend to produce rapid cooling rates in the weld heat-affected zone. Therefore, if it is desirable to decrease the cooling rate in the weld heat-affected zone, the welding variables listed in Table 3.5 should be reversed. If sufficiently slow cooling rates are not obtainable within the practical range of welding variables, then consideration should be given to using a process providing inherently lower cooling rates.

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*Refer to Chapter 2, pp. 34-37, for a discussion of heat source intensities.

SUPPLEMENTARY READING LIST

Adams, C. M., Jr. 1958. Cooling rates and peak temperatures in fusion welding. *Welding Journal* 37 (5): 210s-215s.

Christensen, N., and Davies, V. 1959. Distribution of heat around finite moving sources. The Engineering Research Foundation, University of Norway, U.S. Department of Army European Research Office: Contract DA-91-508-EUC-378.

Christensen, N., Davies, L., and Gjermundsen, K. 1965. Distribution of temperatures in arc welding. *British Welding Journal* 2: 54-75.

Hess, W. F., Merrill, L. L., Nippes, E. F., and Bunk, A. P. 1943. The measurement of cooling rates associated with arc welding and their application to the selection of optimum welding conditions. *Welding Journal* 22 (9): 377s-422s.

Jhaveri, P., Moffatt, W. G., and Adams, C. M., Jr. 1962. The effect of plate thickness and radiation on heat flow in welding and cutting. *Welding Journal* 41 (1): 12s-16s.

Malmuth, N. D., Hall, W. F., Davis, B. I., and Rosen, C. D. Transient thermal phenomena and weld geometry in GTAW. *Welding Journal* 53 (9): 388s-400s.

Meyers, P. S., Uyehara, O. A., and Borman, G. L. 1967. Fundamentals of heat flow in welding. *Welding Research Council Bulletin* 123.

Niles, R. W. and Jackson, C. E. 1975. Weld thermal efficiency of the GTAW process. *Welding Journal* 54 (1): 25s-32s.

Nippes, E. F., Merrill, L. L., and Savage, W. F. 1949. Cooling rates in arc welds in 1/2 in. plate. *Welding Journal* 28 (11): 556s-564s.

Nippes, E. F. and Nelson, E. C. 1958. Predictions of weld heat-affected zone microstructures from continuous cooling transformation data. *Welding Journal* 37 (7): 289s-294s.

Nippes, E. F., Savage, W. F., and Allio, R. J. 1947. Studies of the weld heat affected zone of T-1 steel. *Welding Journal* 36 (12): 531s-540s.

Roest, C. A. and Rager, D. 1974. Resistance welding parameter profile for spot welding aluminum. *Welding Journal* 53 (12): 529s-536s.

Rosenthal, D. 1941. Mathematical theory of heat distribution during welding and cutting. *Welding Journal* 20 (5): 220s-234s.

Rosenthal, D. 1946. The theory of moving sources of heat and its application to metal treatment. *Transactions ASME* 68: 819-866.

Rykalin, N. N. *Calculation of Heat Flow in Welding*. Translated by Zvi Paley and C. M. Adams, Jr. Document 212-350-74, 1974. Contract No. UC-19-066-001-C-3817. London: International Institute of Welding.

Rykalin, N. N. 1948. Effectiveness of the metal-fusion process during arc welding. *Doklady Akademii Nauk SSSR* 63 (11): 131-134.

Wang, K. K. and Lin, W. 1974. Flywheel friction welding research. *Welding Journal* 53 (6): 233s-241s.

Wells, A. A. 1952. Heat flow in welding. *Welding Journal* 31 (5): 263s-267s.

Westby, Ola. *Temperature Distribution in the Work-Piece by Welding*. Document 212-144-68, 1968. Institutt for Mekanisk Teknologi, Ved Norges Tekniske Hogskole-Trondheim. London: International Institute of Welding (distributed in the United States by the American Welding Society).

4

Welding Metallurgy

Prepared by a committee consisting of:

A. W. PENSE, *Chairman*
Lehigh University
C. M. ADAMS, JR.
University of Cincinnati
R. E. BEAL
Illinois Institute of Technology
T. PROFT
Koehring Company
S. D. REYNOLDS, JR.
Westinghouse Electric Corp.
M. SUESS
Koehring Company
R. T. TELFORD
Union Carbide Corporation
S. WEISS
University of Wisconsin—Milwaukee
W. L. WILCOX
Gilbert Associates, Inc.

4

Welding Metallurgy

INTRODUCTION

Welding involves many metallurgical phenomena. The welding operation itself is somewhat akin to making a casting in a foundry. Electrode coverings and submerged arc fluxes produce slags which are similar to those used in steelmaking. Moreover, the heat of welding imposes thermal cycles on the base metal that are not unlike those used in heat treating steel and other base metals.

Although welding metallurgy differs from conventional metallurgy in certain important respects, an understanding of welding metallurgy requires a broad knowledge of general metallurgy. For this reason, the first part of this chapter deals with general metallurgy while the middle and latter sections cover the specific aspects of welding metallurgy. The survey of general metallurgy is by no means exhaustive, and one who wishes to increase his knowledge of the discipline is referred to the Supplementary Reading List which follows the chapter. Nevertheless, the reader without an extensive background in general metallurgy should find the opening discussion sufficient to enable him to follow the rest of the chapter.

GENERAL METALLURGY

STRUCTURE OF METALS

Solid metals have a crystalline structure in which the atoms of each crystal are arranged in a specific geometric pattern. This orderly arrangement of the atoms is responsible for many of the properties of the metal. The most common crystalline structures found in metals are listed in Table 4.1 and their atomic arrangements are illustrated in Fig. 4.1. In the liquid state, the atoms composing metals have no orderly arrangement, but when the liquid approaches the solidification temperature, solid particles called nuclei begin to form at preferred sites as shown in Fig. 4.2a. As solidification proceeds the individual nuclei grow into larger solid particles called grains (Fig. 4.2b). As the amount of solid metal increases, of course, the amount of liquid metal decreases proportionately, and the grains grow larger and larger until they ultimately meet.

Note: The SI (metric) and U.S. customary values given in this chapter are not, in most cases, exact equivalents. The SI values are the primary measurements used in this and all Volume 1 chapters. The secondary U.S. measurements (given parenthetically in text) are rounded off conversions from the SI values. For a further explanation of the system of measurement used in Volume 1, refer to the Foreword on p. xi.

Where the grains meet produces a disarrayed arrangement of atoms called a grain boundary (Fig. 4.2c) which is quite naturally irregular. Figure 4.2 shows the grain boundaries of an ingot which has been cast in a cylindrical mold. The situation is much the same in a weld, and because of the similarity in the shape of its grains, a fusion weld can be viewed as a tiny casting. At the same time, it should be pointed out that the thermal conditions which exist in making fusion welds produce cast structures with characteristics unique to welding. These characteristics are complex and not yet thoroughly understood. They will be discussed later in this chapter.

Each grain in a particular pure metal, examined at any particular temperature, has the same crystalline structure and the same atomic spacing as all of the other grains. However, since each grain grows independently of every other grain, the orientation of the grain lattice differs from one grain to another. Therefore, the grain boundaries are regions where the periodic and orderly arrangement of the atoms is disrupted. Because of this grain boundary disorder, there often are differences in the behavior of the metal at these locations.

Up to this point we have been considering pure metals. However, most common engineering metals are alloys which are combinations of metals or combinations of metals and nonmetals. Alloys provide engineering properties that, for specific applications, usually are superior to those of the unalloyed metals. The atomic arrangement of the alloy, the purity of the alloying elements, and the thermal and mechanical history which the alloy has experienced all have an influence on the engineering properties of an alloy.

Alloying elements are incorporated into the parent metal in one of two ways: The atoms of the alloying element may replace some of the parent metal atoms, or, if the atoms of the alloying element are small enough, they may fit into the spaces between the atoms of the parent metal. These two processes are described further as follows:

(1) *Direct Substitution.* If alloying atoms are similar in size and chemical behavior to the atoms in the original unalloyed metal, the alloying atoms may directly replace some of the parent metal atoms, as shown in Fig. 4.3a. Thus, the new atoms are dissolved or substituted in the parent metal and are known as the solute. The remaining old atoms are the solvent atoms, and with the new atoms, form an alloy known as a solid solution. Examples of solid solutions are gold dissolved in silver or copper dissolved in nickel.

(2) *Interstitial alloying.* When the alloying atoms are small in relation to the parent atoms, they can locate (or dissolve) in the spaces between the parent metal atoms without actually displacing any of those atoms. This is called interstitial alloying, and is illustrated in Fig. 4.3b. Very small amounts of carbon, for example, may alloy interstitially in iron. (Carbon is the most influential interstitial element in the steelmaking process.)

Very frequently, however, the alloying atoms cannot dissolve completely, either interstitially or subtitutionally. The result, in such cases, is the formation of mixed atomic groupings (different crystalline structures) within a single alloy. Each different crystalline structure is referred to as a phase, and the alloy is called a multiphase alloy. The individual phases may be distinguished, one from another, if the alloy is suitably polished and etched and then examined under a microscope at magnifications of 50 to 2000. (See Figs. 4.4a and b.) The process of polishing, etching, and examining metals at some magnification is called metallography. Metallographic examination is one way of studying the many characteristics of metals and alloys.

All engineering alloys consist of the primary or basic element and smaller amounts of one or more alloying elements. Alloys display one or more of the phases that are characteristic for the alloy. Each phase will have its own characteristic crystalline structure.

The overall arrangement of the grains, grain boundaries, and phases present in a metal alloy is called the microstructure of the alloy which is largely responsible for the physical and mechanical properties of the

Table 4.1 — Crystal structures of common metals

Crystal structure	Metals with this structure
Body Centered Cubic (BCC)	Fe (at room temperature and again near its melting point), Cr, Cb, W, V, Ti (at high temperatures), Mo
Face Centered Cubic (FCC)	Fe (at intermediate temperature), Cu, Au, Pb, Ni, Ag, Al
Hexagonal Close Packed (HCP)	Co, Mg, Sn, Ti, (at room temperature), Zn, Zr

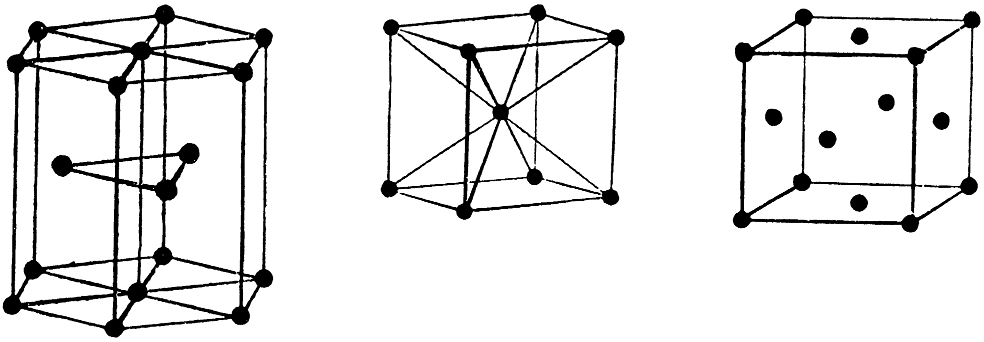

Fig. 4.1 — The three most common crystal structures in metals and alloys. Left: face centered cubic (FCC); center: body centered cubic (BCC); right: hexagonal close packed (HCP).

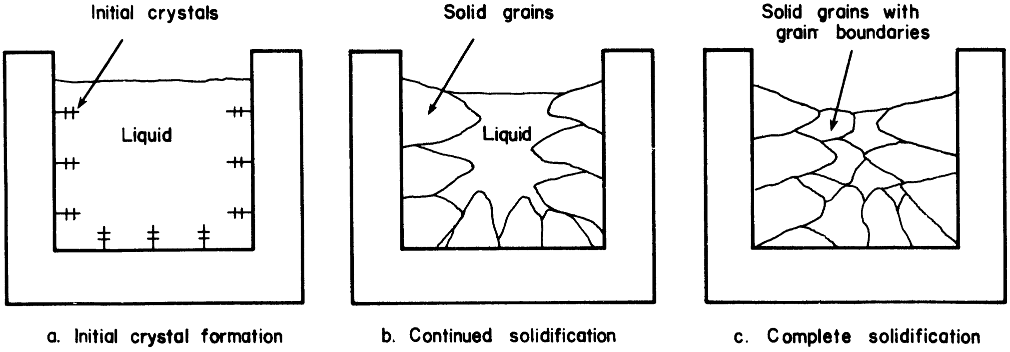

Fig. 4.2 — Solidification of a metal.

alloy. The microstructure is affected by the composition of the alloy and by hot or cold working and heat treatment. The microstructure is greatly affected by welding which, in turn, also influences the properties of the alloy.

Many unique phenomena that profoundly affect the mechanical properties of an alloy, at both low and high temperatures, occur at grain boundaries. Since the arrangement of atoms is irregular at grain boundaries, there are many vacancies or missing atoms. The space between atoms may be larger than normal, so that individual atoms can move about relatively easily. Because of this, the diffusion of elements (the movement of individual atoms)

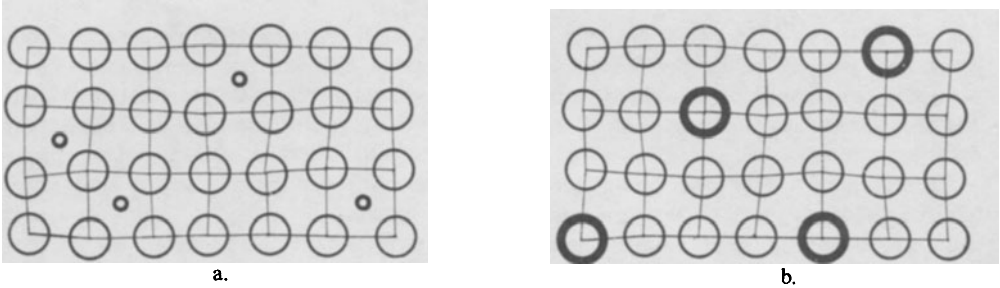

Fig. 4.3 — Illustration comparing the base metal crystal lattice and the crystalline structure of alloys. Left: Substitutional solid solution; base metal lattice is distorted by presence of foreign atoms. Right: Solid solution hardening; foreign atoms locate in interstices of base metal crystalline structure and cause distortion in lattice.

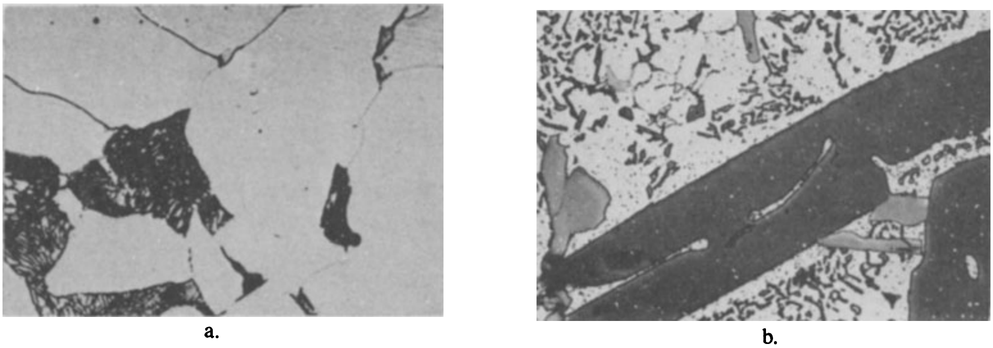

Fig. 4.4 — Left: Typical microstructure of low carbon pearlitic steel containing more than a single phase. Light areas are ferrite, a rather pure iron; dark areas are pearlite, composed of alternating thin layers of ferrite and iron carbide; 100 X (before reduction). Right: An aluminum silicon alloy at 100 X (before reduction), showing a multitude of phases within a single grain.

through the solvent structure generally occurs more rapidly at grain boundaries than it does within the grains. The resulting disarray makes it easier for odd-sized atoms to segregate at the boundaries. This segregation frequently leads to the formation of undesirable phases that adversely affect the properties of the material by reducing its ductility and making it susceptible to cracking during welding or heat treatment.

Grain boundaries increase the strength of materials at room temperature by inhibiting the deformation of individual grains. At elevated temperatures, the ease with which the atoms in the boundaries can slide past one another reduces the strength of the material. As a result, fine-grained materials have better properties for room temperature and low temperature service, while coarse-grained materials are desirable for high temperature service.

The structure of a metal is sometimes classified according to the grain size of the metal. Metals may have a few large grains (coarse-grained) or many small grains (fine-grained) or a mixture of both large and small grains (mixed grain size). The effect of weld metal solidification rate on grain structure is discussed in the following section of this chapter beginning on p. 124.

PHASE TRANSFORMATIONS

Critical Temperatures

At certain temperatures the atoms of many metals change their crystallographic structure. For example, the crystalline structure of pure iron at temperatures up to 910 °C (1670 °F) is body centered cubic. From 910 °C to 1390 °C (2535 °F) the structure is face centered cubic, and from 1390 °C to the melting temperature—1535 °C (2795 °F), it is again body centered cubic. (See Fig. 4.1.) This change in crystal structure is a phase change in the solid state which is known as an allotropic transformation.

Other metals that undergo allotropic transformations at various temperatures are titanium, zirconium, and cobalt. Chemical composition, cooling rate, and the presence of stress influence the temperature at which transformation takes place.

A metal also undergoes a phase change when it melts or solidifies. Pure metals melt and solidify at a single temperature. Alloys, on the other hand, usually melt and solidify over a range of temperatures. The exception to this rule is the eutectic composition, which will be mentioned later.

Phase Diagrams

Events such as phase changes and solidification are best shown by means of a drawing called a phase diagram (sometimes also referred to as an equilibrium diagram or a constitution diagram).

Phase diagrams have been called the metallurgist's road map, for from a diagram of a given alloy system one can find what phases and what percentage of each phase are present for any given alloy composition at any specified temperature. One can also determine what phase changes tend to take place with a change in either composition or temperature or both. However, the phase diagram has at least one significant limitation: It is only an approximation of how alloys actually behave because it describes the behavior of the alloy system only under equilibrium conditions.* Those conditions rarely are encountered in practice. This is especially true in welding, because of the fast heating and cooling rates to which alloys are subjected.

Most readily available phase diagrams describe alloy systems containing two elements, while engineering alloys generally contain many elements, or components. Phase diagrams for systems with more than two components are quite complex and are rather difficult to interpret. Nevertheless, phase diagrams still are the best way to study most alloy systems.

A very simple phase diagram for the copper-nickel alloy system is shown in Fig. 4.5. This is called an isomorphous binary system—that is, a two-element system in which both elements are completely soluble in each other in all proportions at all temperatures, in both the liquid and the solid states. As shown in Fig. 4.5, phase diagrams are drawn with the alloy content plotted on the horizontal axis. The extreme left hand edge of the diagram represents zero percent nickel and 100 percent copper while the extreme right hand edge represents 100 percent nickel and zero percent copper. Temperature is plotted on the vertical axis.

Figure 4.5 shows that at temperatures above the top curve, A, the only phase is liquid metal. This is true for all compositions covered by this diagram. At temperatures below the bottom curve, B, the only phase is solid metal. This, too, is true for all compositions covered by the diagram. All solid alloys formed are single phase only because copper and nickel are completely soluble in each other in the solid state. Thus, an alloy with 30 percent copper and 70 percent nickel is a homogeneous solid solution. It remains solid up to 1330 °C (2425 °F) where it begins to melt. Melting is complete at 1365 °C (2490 °F). This alloy (30 percent copper and 70 percent nickel) is known as monel.

In the region between the curves A (liquid) and B (solids), the solid and the liquid phases coexist. This illustrates the fact that most alloys solidify (go from complete liquid to complete solid) over a range of temperatures. As the diagram shows, complete solidification occurs at a single temperature only for pure copper or pure nickel, in the copper-nickel system.

Figure 4.6 shows the phase diagram for a more complicated system: the silver-copper

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*Equilibrium implies that a metal is stable in a desired state for a given environment. Obtaining this stability requires slow heating and cooling conditions and long hold times.

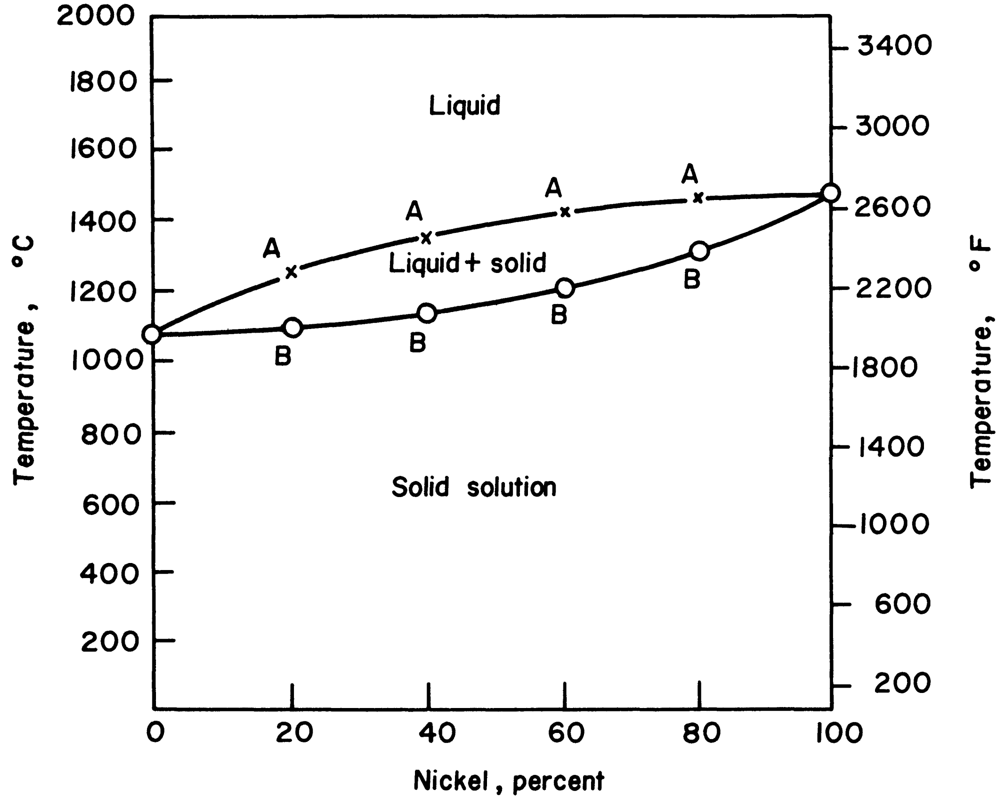

Fig. 4.5 — The nickel-copper phase diagram. Points along the top curve, A, represent the liquidus for each alloy composition. Points along the bottom curve, B, represent the solidus for each alloy composition.

alloys. This diagram is used extensively in designing brazing alloys. All compositions in this system are entirely liquid at temperatures above the lines labeled "liquidus." Similarly, all compositions are solid at temperatures below the line labeled "solidus." However, the solid is present as a single phase in certain parts of the diagram and as two phases in another part. The alpha (α) and beta (β) regions are single phase regions. The alpha region defines the conditions where copper is dissolved in silver in a single phase solid solution. The same is true for the beta region, but in this case silver is dissolved in copper. In the region between the solidus and liquidus lines on the left side of the diagram, the phases present are the liquid solution of copper in silver and solid solution of copper in silver (α + liquid). For the same region on the right side, the phases present are the liquid and solid solutions of silver in copper (β + liquid). Finally, the area labeled $\alpha + \beta$ contains grains of both alpha and beta. Here, also, alpha is a solid solution of copper in silver and beta is a solid solution of silver in copper.

The silver-copper alloy system is one in which each element has only limited solubility in the other. The phase diagram depicts this and shows that as a small amount of copper is added, it dissolves in the silver, but as more copper is added beyond its solubility, beta begins to form. The second solid phase, beta, is copper with some silver dissolved in it.

This phase diagram illustrates another feature—the eutectic point. At this point labeled on the diagram, an alloy of "eutectic" composition solidifies at one temperature, just

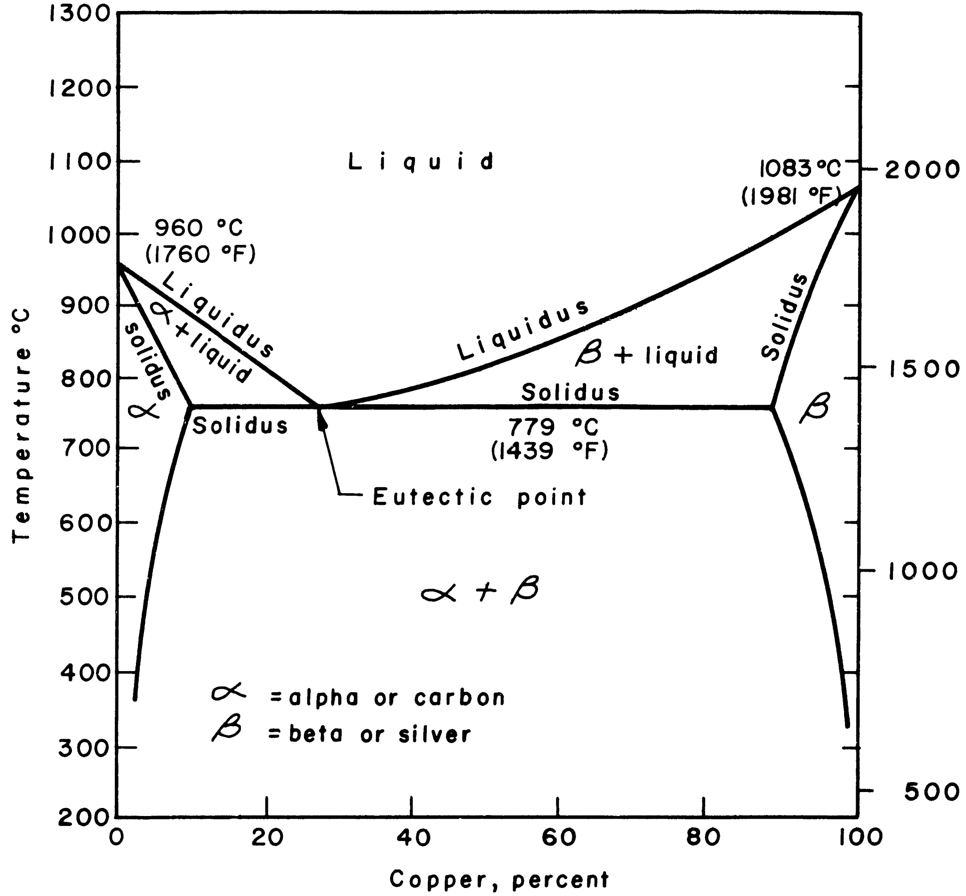

Fig. 4.6 — The silver-copper phase diagram. Note the composition, 28 percent copper -72 percent silver is the eutectic composition.

as a pure metal does. The eutectic composition solidifies somewhat differently, however, for as the liquid cools, both the alpha and beta phases are formed concurrently. Quite frequently these phases occur as alternating platelets, first of one phase, then the other. For this reason, eutectic compositions have a distinctive microstructure.

A final feature of the silver-copper phase diagram is that it shows solid solubility in relation to temperature. The principle is the same as with salt and water, where more salt can be dissolved in hot water than can be dissolved in cold water. In Fig. 4.6, the boundary line between the alpha plus beta region and the alpha solid solution region shifts to lower alloy content as the temperature decreases. This means that when all the copper is dissolved that can be dissolved in silver at a certain temperature, the solubility limit will be exceeded at any lower temperature and some beta phase will form when the alloy is cooled to that lower temperature. This behavior is the principle behind precipitation hardening.

EFFECTS OF DEFORMATION AND HEAT TREATMENT

Deformation and Annealing of Metals

When metals are plastically deformed,* a number of changes occur in their microstructure. Each individual grain must "give" to produce the anticipated overall deformation. During deformation, each grain becomes stronger and, therefore, more difficult to deform further. This process is called work hardening. Because of work hardening, the stress-strain curve in a tension test continues to increase beyond the yield strength of the specimen. (See the section on tensile properties in Chapter 5, p. 155.) Figure 4.7 (a and b) shows some of the property changes and the attendant microstructure changes that typically occur as a metal is worked (deformed) and then heat treated (b and c). When this work is done below the critical temperature for that metal, there is a gradual increase in the hardness or strength of the metal and a decrease in its ductility. These changes result from the phenomenon known as cold work.

If the metal in Fig. 4.7 (stainless steel) is worked (Fig. 4.7a, moderately or 4.7b, severely) and then heated to progressively higher temperatures, several things happen. At low temperatures (95 to 205 °C [200 to 400 °F]—in middle of diagram) there is a steady decline in the residual stress level, but there is virtually no change in microstructure or strength. At about 205 to 230 °C (400 to 450 °F), a relatively low level of stress remains, and the microstructure still looks as it did (Fig. 4.7a and b). The strength of the metal remains relatively unchanged compared to that of the original cold-worked material and the ductility, while improved, is still rather low. This reduction in stress level and the improvement in ductility are attributed to the metallurgical phenomenon called recovery, a term indicating a reduction in crystalline stresses without accompanying structural changes (stress relief).

When the cold-worked metal is heated to a temperature above 230 °C (450 °F), property changes become apparent, as do changes in microstructure. In place of the deformed grains found in Fig. 4.7a or b, a new group of grains form and grow (Fig. 4.7c). These grains consume the old grains, and eventually all signs of the deformed grains disappear. The new microstructure (Fig. 4.7c) resembles the original microstructure (before cold-working) and the metal is softened and made more ductile than it was in the cold-worked condition. This process is called recrystallization, a necessary part of all annealing procedures. (Annealing refers to a heating and cooling process usually applied to induce softening.) When heated to higher temperatures, the grains begin to grow and the mechanical properties may be degraded significantly in some metals.

Annealing, then, goes a step beyond the ordinary stress relief. It accomplishes the maximum stress relief possible. If, for example, stress relief were desirable in a structural member that had been cold-worked to attain design strength, annealing would be too severe a stress relief and softening would reduce the strength of the member below its design strength.

Phase Transformations in Iron and Steel

Iron and steel and their alloys make up the greatest tonnage of any of the metals used in modern engineering structures. An understanding of the metallurgical characteristics of iron and steel, which are largely governed by the phase transformations they undergo, is essential to the successful welding of these metals. Hence this section is devoted to describing the phase transformations in iron and steel and explaining the significance of their phase changes.

Pure iron, as mentioned earlier, solidifies at 1535 °C (2795 °F) and forms a body centered cubic structure called delta iron or delta ferrite. With slow cooling, the delta ferrite persists until at 1390 °C (2535 °F), it transforms into a face centered cubic structure called gamma iron or austenite. The austenite remains down to 910 °C (1670 °F) where it

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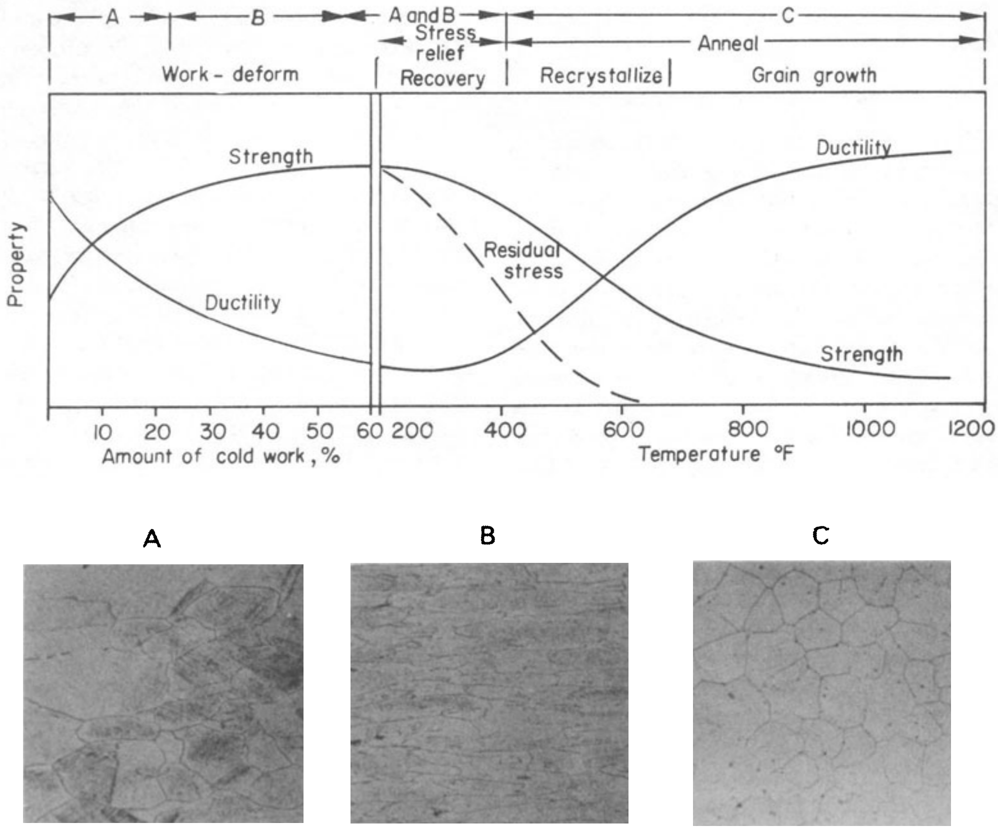
*Deformed to the extent that they do not return to their original shape.



°C	95	205	315	425	540	650
°F	200	400	600	800	1000	1200

Fig. 4.7 — Generalized effects of work hardening and recovery on chromium-nickel stainless steel.

transforms back into the body centered cubic structure known, this time, as alpha iron or alpha ferrite. Delta iron and alpha iron are similar in structure, but they are given different names to distinguish between the temperatures at which they form. This entire transformation process is reversed, of course, when iron is heated. From this, it is evident that iron has two transformation temperatures: 910 °C (1670 °F), where alpha iron transforms to gamma iron on heating (and gamma to alpha on cooling) and 1390 °C (2535 °F), where gamma iron transforms to delta iron on heating (and delta to gamma on cooling).

Steel, fundamentally, is an iron alloy with less than two percent carbon. The presence of carbon alters the temperatures at which freezing and phase transformations occur. The addition of other alloying elements also has some effect on these temperatures. As with other alloy systems, iron-carbon alloys freeze over a range of temperatures, with different liquidus and frequently different solidus temperatures for each composition. As the carbon

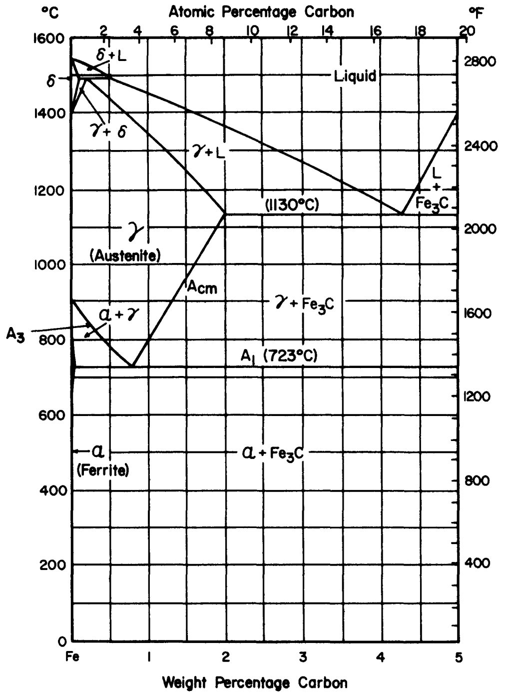


Fig. 4.8 — The iron-carbon phase diagram.

content of iron-carbon alloys increases up to 4.3 percent, the liquidus and sometimes the solidus decrease.

Significant changes in the phase transformation temperatures brought about by variations in carbon content are as follows (see Fig. 4.8):

(1) *Delta ferrite to austenite* (on cooling). This transformation occurs at 1390 °C (2535 °F) in essentially pure iron, but in steel it increases to a maximum of 1492 °C (2718 °F) with increasing carbon content. Delta ferrite cannot exist in steels containing more that 0.50 percent carbon.

(2) *Austenite to ferrite plus iron carbide* (on cooling). This is one of the most important transformations in steel. Control of it is the basis for most of the heat treatments used for hardening steel.

This transformation occurs in essentially pure iron at 910 °C (1670 °F). In steel with increasing carbon content, however, it takes place over a range of temperatures between boundaries A_3 and A_1 (see Fig. 4.8). The upper limit of this temperature range (A_3) varies from 910 °C (1670 °F) down to 723 °C (1333 °F). For example, the A_3 of a 0.10 percent carbon steel is 870 °C (1600 °F), while for a 0.50 percent carbon steel it is 775 °C (1430 °F).

(3) The lower temperature of the range (A_1) remains at 723 °C (1333 °F) for all plain carbon steels regardless of their carbon level.

(4) Austenite can dissolve up to 2.0 percent of carbon in solid solution. However, ferrite can dissolve only 0.025 percent. Below A_1, austenite transforms to ferrite. With carbon content above approximately 0.025 percent, ferrite and the chemical compound iron carbide (Fe_3C), also called cementite, form. Cementite contains 6.67 percent carbon and precipitates in ferrite grains in a lamellar fashion. The resulting grains are known as pearlite.

Most of the alloying elements added to steel (nickel and chromium, for instance) alter the transformation temperatures. Sometimes they do so to a marked extent. Sometimes they even suppress transformation completely. Phase changes which can be attributed to the carbon in steel are shown in the iron-carbon diagram in Fig. 4.8. Room temperature microstructures of iron-carbon alloys at the equilibrium conditions covered by this diagram include one or more of the following constituents:

(1) Ferrite—Solid solution of carbon in alpha iron.

(2) Pearlite—A platelet-like mixture of cementite and ferrite.

(3) Cementite—Iron carbide, Fe_3C, present in pearlite or as massive carbides in high carbon steels.

It must be remembered that these are equilibrium structures and that the hardening of steel by heat treatment is based on producing structures not shown in this diagram, which will be discussed shortly.

It should be noted that the iron-carbon diagram is drawn only to 4.5 percent carbon. Alloys containing more than 5 percent carbon are almost impossible to make, and they have no practical significance.

Man took advantage of the fact that steel can be hardened by heat treatment many centuries before he discovered the mechanism by which hardening occurs. The ability to harden steel by heat treatment is dependent on the transformation of austenite to a constituent other than ferrite or pearlite. On the iron-carbon diagram, the transformation to ferrite and pearlite occurs at or about 723 °C (1333 °F), although this temperature is reduced by fast cooling and by the addition of alloying elements. Transformation to pearlite requires relatively slow cooling and extensive diffusion of the atoms, with their rearrangement into ferrite and iron carbide lamellae (layers). The pearlitic structure, shown in Fig. 4.9, imparts only moderate strength to steel. When the cooling rate of an austenitized steel is increased sufficiently however, marked changes in transformation occur as follows:

(1) The transformation occurs at lower temperatures.

(2) The resulting microstructure is drastically changed and the hardness and tensile strength of the steel increase, with ductility undergoing a corresponding decrease.

A slight increase in cooling rate only depresses the transformation temperature a small amount and produces a slightly finer pearlitic structure. The lamellae are slightly finer, the hardness of the steel is somewhat greater than that of a steel with a coarse pearlitic structure, and ductility is somewhat lower.

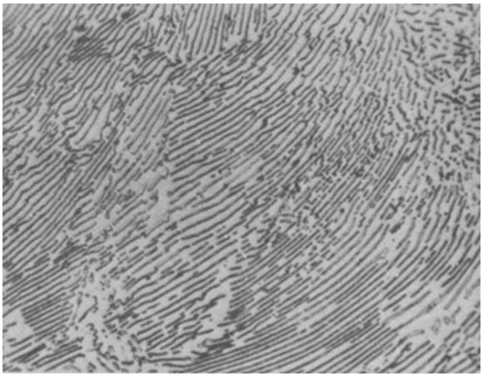


Fig. 4.9 — Typical lamellar appearance of pearlite. 1500 X (before reduction) Etchant: Picral.

At fast cooling rates, still lower transformation temperatures are encountered and bainite forms instead of pearlite.

Bainite has a feathery arrangement of fine carbide needles in a ferrite matrix. It has significantly higher strength and hardness and lower ductility than the fine pearlitic structure.

With still faster cooling rates (severe quenching), martensite forms. Martensite is hard and relatively brittle. Figure 4.10 illustrates its acicular (needlelike) appearance. As-quenched martensite usually is too brittle for practical use, but its ductility can be restored by a process called tempering. This transformation is important in any consideration of welding because the weld metal and part of the heat-affected zone of a welded joint are heated and cooled through this transformation temperature range.

Certain commonly used heat treating terms refer in part to the rate at which austenite is cooled to room temperature. The following treatments are listed in the order of increased cooling rates from above the A_3 temperature:

(1) Furnace annealing: Slow furnace cooling.

(2) Normalizing: Cooling in still air.

(3) Oil quenching: Quenching in an oil bath.

Fig. 4.10 — Quenched martensite (500 X, before reduction, etched) showing acicular structure.

(4) Water quenching: Quenching in a water bath.

(5) Brine quenching: Quenching in a salt brine bath.

The hardness and tensile strength of a specific steel would become increasingly greater if treated in the order of (1) to (5). Treatment in the reverse order would produce increasing ductility.

The nonequilibrium structures just described (except martensite) can be produced not only by cooling at the proper rate, but also by isothermal means. The latter involves holding at a given temperature for a particular length of time.

The Isothermal Transformation or TTT Diagrams

The iron-carbon phase diagram is very useful, but it does not provide information about the transformation of austenite to any structure other than equilibrium structures, nor does it furnish any details about the cooling rates required to produce other structures or the temperatures at which the transformations occur. A more practical diagram is the isothermal transformation diagram or TTT (time-temperature-transformation) diagram. It graphically describes the cooling rate required for the transformation of austenite to pearlite, bainite, or martensite. It also gives the temperature at which such transformations take place. Figure 4.11 shows a TTT diagram for 0.80 percent plain carbon steel.

To produce this diagram, samples of the specific* 0.80 percent carbon steel were heated to their appropriate austenitizing temperature (about 845 °C [1550 °F]) and placed in environments in which they could abruptly fall to a series of temperatures ranging from 705 °C (1300 °F) to room temperature. This was accomplished by plunging the samples into various solutions of brine, oil, or water at the desired temperature, and then holding each specimen at that temperature for a specified length of time. After each specimen had been in its bath for the time specified, it was removed, cooled quickly, and examined under a microscope.

The sample of plain carbon steel in Fig. 4.11 held at 705 °C (1300 °F) did not begin to transform for about 500 seconds (eight minutes) and did not finish transforming until 4000 seconds (about one hour) had elapsed. The structure formed was coarse pearlite, and the sample was fairly soft (15 Rockwell C [Rc 15]).

Transformation was quicker for the specimens held at 565 °C (1050 °F). It started in one second and was completed in five. Transformation took place in the shortest length of time at this temperature. For this reason the "nose" of the curve is located at 565 °C (1050 °F) for this (0.80 percent carbon) plain carbon steel. The microstructure of the steel transformed at this temperature is fine pearlite (with a hardness of Rc 41). As temperature decreased further, the time to start transformation again increased, the microstructure became bainite, and hardness increased still more.

The specimens which were cooled to room temperature rapidly enough to get past the "nose" of the curve had an entirely different microstructure. That structure was martensite. Martensite forms by a transformation which occurs only on cooling. It starts at the M_s (martensite start) temperature, which, for the 0.80 carbon steel in Fig. 4.11 is about 230 °C (450 °F). Martensite transformation is complete when the temperature has dropped below approximately 120 °C (250 °F) for this steel. That temperature is known as the M_f (martensite finish) temperature. As the carbon content of steel decreases, both the M_s and M_f temperatures increase.

The information given by the TTT diagram does not apply to heat treating procedures where continuous rather than isothermal cooling is used. Therefore, continuous cooling transformation (CCT) diagrams have also been developed for steels. These diagrams are closely related to the TTT diagram, and with them the slowest cooling rate which will allow 100 percent martensite to form in a

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*Every composition of steel has its own TTT diagram.

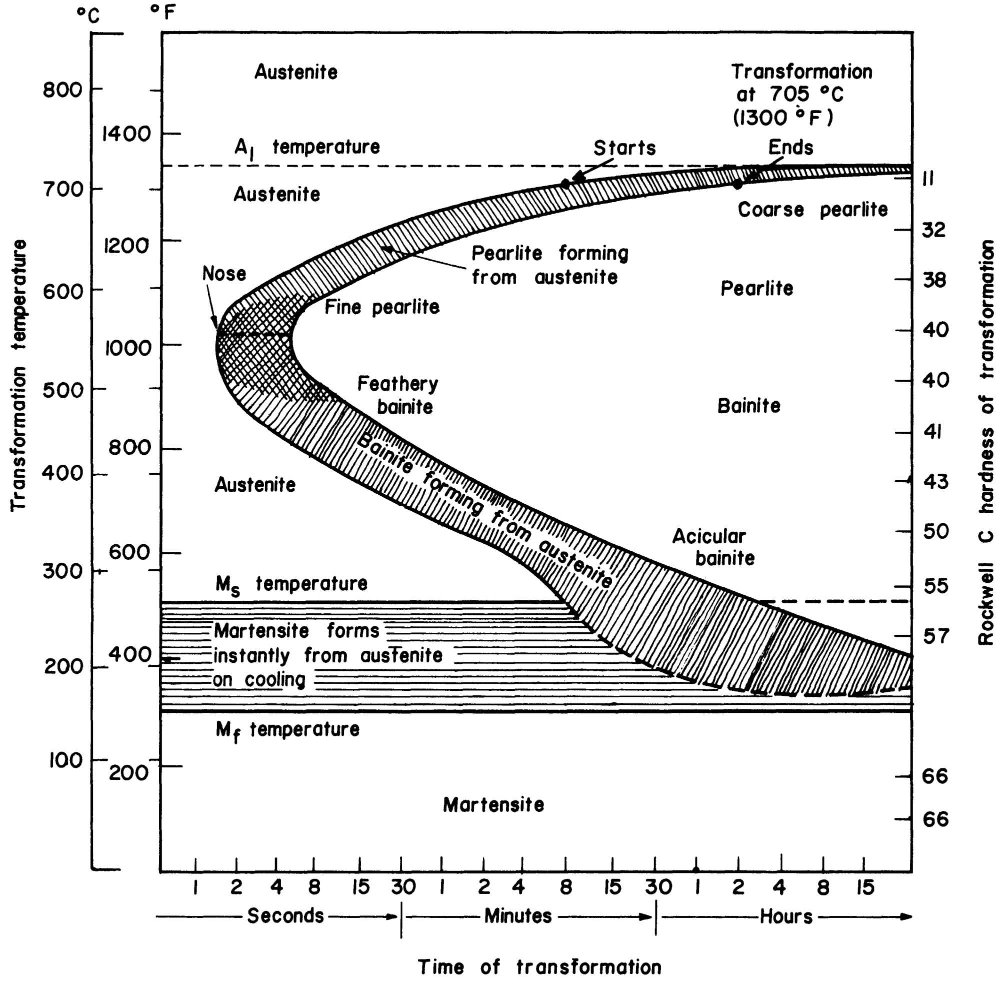


Fig. 4.11 — The TTT diagram for the transformation of austenite in a eutectoid (0.80 percent carbon) plain carbon steel.

given steel can be easily determined. This cooling rate is called the "critical cooling rate." It is the rate at which the cooling curve just misses the "nose" of the CCT curve.

As carbon and alloy content increase, the TTT and CCT curves shift to the right. When the curves move to the right, conditions producing less rapid cooling can be used while still allowing martensite to form. These steels are said to have higher hardenability.

Hardenability

Although TTT and CCT diagrams portray the transformation characteristics of steels, the concept of hardenability presents another method of describing the transformation of austenite in various steels. Hardenability should not be confused with hardness. The maximum hardness of a steel is primarily a function of its carbon content (Fig. 4.12). Hardenability, on the other hand, is a measure of how easily martensite forms on quenching. Certain steels, with very high hardenability, will form martensite even when they are being slowly cooled in air. Other steels—those with very low hardenability—require

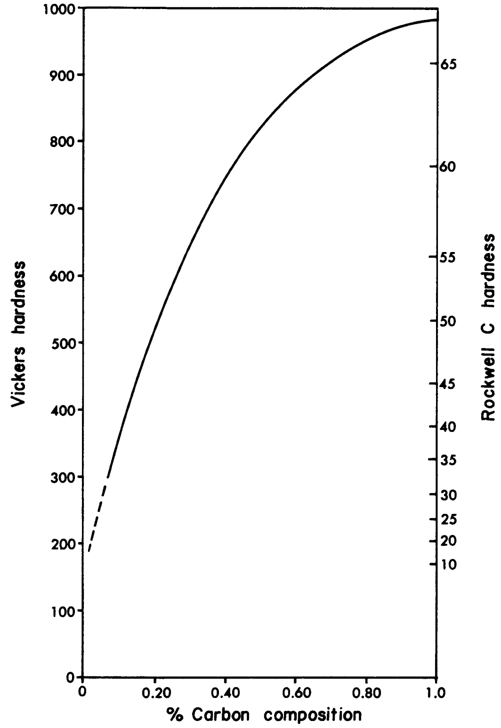


Fig. 4.12 — Maximum hardness of martensite as a function of carbon content.

cooling rates of as much as 555 °C/s (1000 °F/s), if they are to transform completely to martensite. These hardenability characteristics are important since they will determine the extent to which a steel will harden during welding.

Tempering of Martensite

Martensite, just as it is formed, is generally unsuitable for engineering applications because it can be quite brittle. However, a tempering heat treatment can effectively increase its ductility and toughness without significantly reducing its strength. Tempering consists of simply reheating the martensite to some appropriate temperature (always below the A_1) and holding at that temperature for a proper length of time. This permits the as-quenched martensite to change to tempered martensite. Tempering allows the carbon to precipitate in the form of tiny carbide particles. The desired compromise between hardness and toughness can be obtained by choosing the proper tempering time and temperature. Higher tempering temperatures result in softer but tougher steel.

Figure 4.13 illustrates the mechanical properties obtained by tempering a quenched low alloy steel. Quenching and tempering are frequently used to enhance the properties of machinery steels, pressure vessel steels, and structural steels since that treatment develops high yield and tensile strengths, high yield-to-tensile ratios, and improved notch toughness as compared to the same steel in the hot rolled, annealed, or normalized condition. Tempering curves of the types shown in Fig. 4.13 are well-established for most plain carbon and low alloy steels.

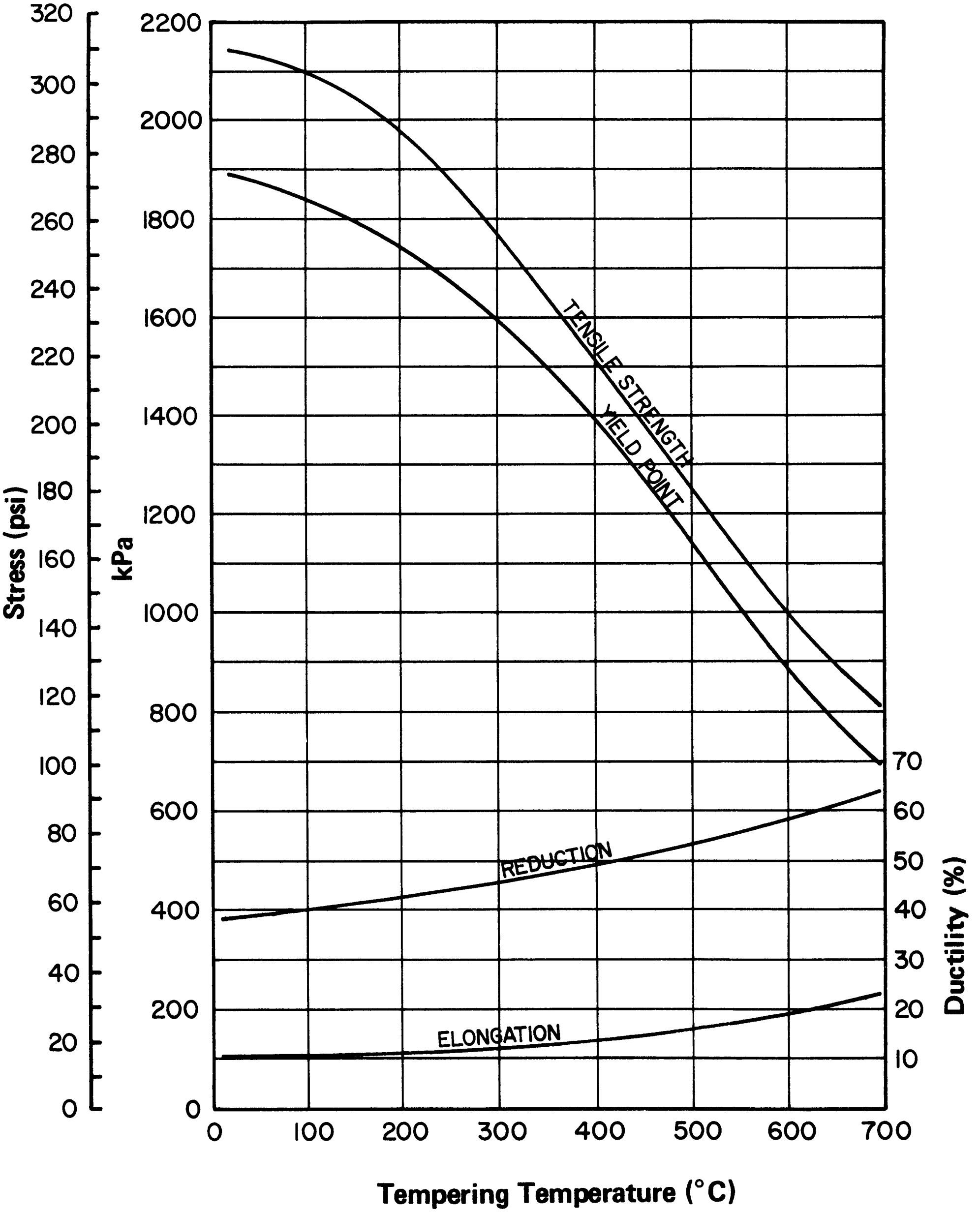
Other Grain Structure Changes

During heat treatment, the grain size of a steel may be refined (reduced) or coarsened (increased). Grain refinement occurs when a steel which will transform is heated to a temperature slightly above its A_3 temperature and then is cooled or allowed to cool to room temperature. A fine grain size is desirable for improved toughness and ductility. Steel forgings and castings frequently are normalized specifically to produce grain refinement.

Steel heated to very high temperatures (sometimes above 900 °C [1650 °F] but certainly above 1095 °C [2000 °F], which is far above the A_3 temperature) undergo grain coarsening. These coarsened grains persist even when the steel is cooled back to room temperature. Thus, when steel is overheated, the grain size will coarsen. Coarse-grained steels usually are inferior to fine-grained steels in weldability, ductility and toughness.

Precipitation Transformations

Precipitation hardening (or age hardening) is another method of strengthening or hardening steel. The method is employed in some of today's important industrial alloy steels. Figure 4.14a shows a portion of the phase diagram for an alloy in which the beta



°C	100	200	300	400	500	600	700
°F	210	390	570	750	930	1110	1290

Fig. 4.13 — Tempering curve for AISI 4140 chromium-molybdenum steel.

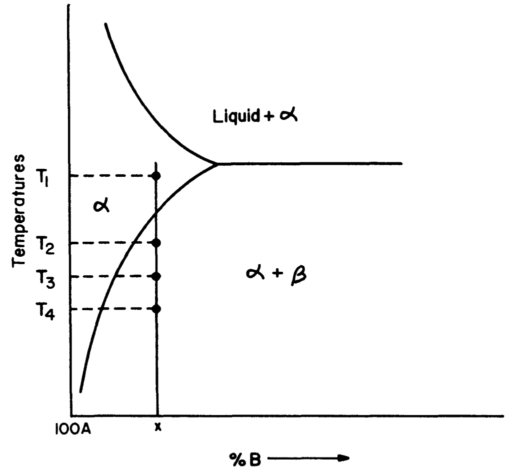


Fig. 4.14a—Phase diagram of a precipitation hardening system.

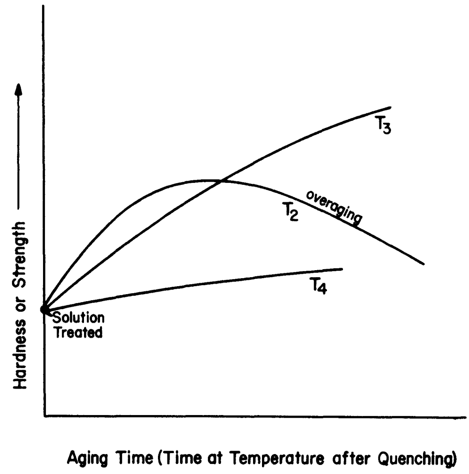


Fig. 4.14b—Microstructural changes in an age-hardening alloy during several stages in the heat treatment.

phase is increasingly soluble in the alpha phase, as the temperature increases. The precipitation-hardenable alloy, X, shows there is a duplex structure of $\alpha + \beta$ at room temperature. By slowly heating this alloy, increased amounts of beta are gradually dissolved in the alpha. When the temperature reaches T_1 (a temperature at which x percent of beta can be dissolved in alpha), the alpha solid solution will have dissolved all of the available beta. This composition will be stable as a single phase solid solution at or above T_1. If alloy X is cooled below T_1, the solid solution will become supersaturated (the alpha can no longer retain the same amount of beta in solution) and the beta which cannot be retained at that temperature must be rejected from the solution. With slow cooling, this beta will precipitate at preferred locations such as the grain boundaries. (Figure 4.15 [a-b-c] shows this sequence). If the same alloy is heated to T_1 and then is cooled rapidly to room temperature, however, there is no time for diffusion and rejection of the beta, and the single phase supersaturated structure is retained (a-b-d).

At room temperature, the structure of the material is identical with the structure at the elevated temperature, but the room temperature structure is not stable. This can be seen from the phase diagram for the system, which indicates that two phases should exist at that temperature. If this alloy is then reheated to a temperature in the range T_2-T_4 shown in Fig. 4.14, the excess beta in solution is precipitated once again. However, it is now precipitated as a finely divided, uniformly distributed beta phase, as shown in Fig. 4.15e. The formation of this precipitate causes distortion in the lattice structure of the alloy. This distortion, and the strain produced, strengthen the alloy and consequently, the material has been *precipitation hardened.* The size and distribution of the precipitated particles significantly alter the strength of the alloy. The time and temperature of the aging affect this distribution and hence, the properties of the alloy. These variations are shown schematically in Fig. 4.14b.

Figure 4.14b identifies the various aging temperatures as T_2, T_3 and T_4 ($T_4 < T_3 < T_2$) and shows the change in hardness that occurs with time at these temperatures. Since the aging of a solution treated alloy is a dynamic process, the hardness of the alloy (which reflects the progress of the aging process) will vary continuously. The rate of change at low aging temperatures is much slower than at high

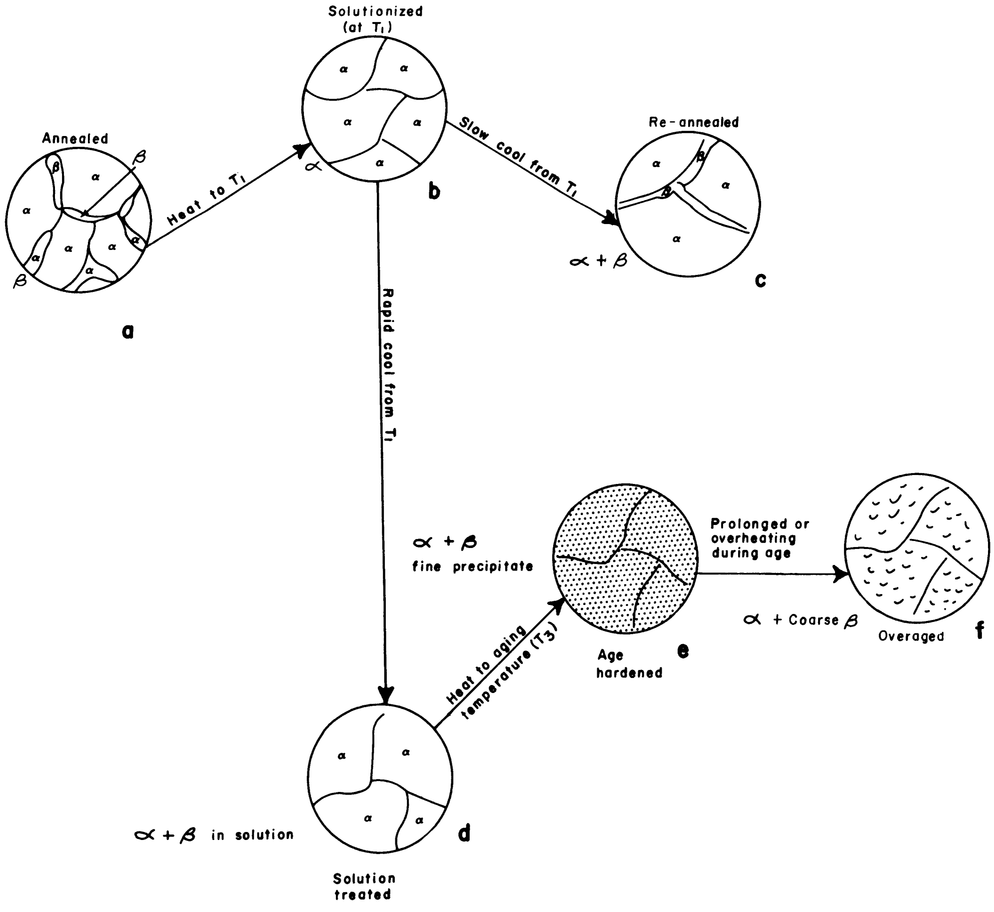


Fig. 4.15 — Microstructural changes in an age-hardenable alloy during several stages in heat treatment.

Table 4.2 — Typical precipitation-hardening alloys

	Typical Alloys of the Base Metal				
Solvent element or base metal:	Iron	Nickel	Aluminum	Magnesium	Titanium
	17-4 PH	Inconel X*	2014	AZ 80 A	6Al-4V
	17-7 PH	René 41	2024	ZK 60 A	4Al-3Mo-1V
	PH 15-7 Mo	Udimet 500**	6061	HM 21 A	16V-2.5Al
	AM 350	Waspaloy	7002	ZE 41 A	6Al-6V-6Sn
	19-9 DL	Inconel 700†	7039	ZH 62 A	13V-11Cr-3Al
	A 286	M 252	7075	EZ 33 A	

*Registered trademark of the International Nickel Co., Inc.
**Registered trademark of Special Metals, Inc.
†Registered trademark of Allegheny-Ludlam Steel Co.

aging temperatures. At sufficiently high aging temperatures the alloy can overage in a short period of time. Overaging is the stage in the process at which the fine particles of precipitate begin to grow and agglomerate. As a result of this, the particles become fewer in number and their strengthening effect diminishes. When the particles are large and well agglomerated, there is no longer sufficient keying or lattice distortion to provide a significant increase in hardness. Overaging can occur in service if temperatures that exceed the aging temperature are encountered for sufficient time.

Table 4.2 lists some precipitation hardening alloys. There are several elements that will produce age hardening in these alloys. Titanium and aluminum are used for this purpose in both the nickel and the iron alloys. Copper is commonly used in aluminum as well as in iron alloys. In aluminum, the hardening agent is the chemical compound $CuAl_2$. Similar compounds can be produced by adding certain amounts of copper to steel, aluminum to magnesium, or chromium to titanium.

The precise mechanism by which the precipitate produces strengthening is not completely understood. It is known that, as the precipitate forms, it strains the crystal structure in which it grows. When the precipitate particles become large (on overaging), this strain is decreased again. It is also known that adding fine particles to the structure, even without straining it, will increase the strength of the structure. The strength will again decrease when the particles grow large. Both effects are found in most precipitation hardening alloys.

The strengthening effect of fine particles alone, called dispersion strengthening, is sometimes used even when no precipitation of the particles occurs. Alloys of this type will have a microstructure consisting of fine particles formed on solidification, as for example, in a eutectic alloy, or by other transformations or techniques.

REVIEW OF COMMERCIAL ALLOYS

A large number of alloys are used commercially in welded products. The most common of these are described in the following pages. For more detailed information, refer to the Supplementary Reading List at the end of the chapter.

Steels

Most commercial steels can be classified according to three groups: plain carbon steel, low alloy steel, and high alloy steel.

*Plain Carbon Steels.** Plain carbon steel, the largest category by tonnage, consists of

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*Chapter 61 in Section 4 of the *Welding Handbook*, Sixth Edition covers these steels in detail. In the Seventh Edition, plain carbon steels tentatively will be covered in Volume 4.

iron, usually with less than 0.5 percent carbon and varying, but minor amounts of manganese, phosphorous, sulfur, and silicon. The properties and weldability of these steels depend mainly on their carbon content, although the other elements do influence these properties to a limited extent. Plain carbon steels frequently are categorized in relation to their carbon content as indicated in Table 4.3.

*Low Alloy Steels.** The carbon content of these steels usually is less than 0.25 percent and frequently is below 0.15 percent. Other alloying elements (nickel, chromium, molybdenum, manganese, silicon) are added to increase the strength of these steels at room temperature and at elevated temperatures, as well as to impart better notch toughness at low temperatures. These elements also alter the response of the steels to heat treatment, and can improve their corrosion resistance. Sometimes these additions reduce the ease with which the steels can be welded.

Modern design requires steels that have higher strength and toughness than the plain carbon and structural steels. A yield strength of 345 MPa (50 000 psi) and a tensile strength of 480 MPa (70 000 psi) are achieved in the as-rolled condition by adding two or more alloying elements; adequate weldability is maintained by restricting the carbon to 0.20 percent maximum. Some of these steels are heat treated up to 690 MPa (100 000 psi) yield strength and they have better notch toughness than the ordinary carbon steel grades. Proper choice of filler metal and welding procedures will develop comparable properties in welded joints in these steels.

A wide variety of steels has been developed for use in machinery parts. These steels, many of which are eminently weldable, have been classified according to chemical composition by the AISI-ASME classification system. Other steels have been developed to meet the needs of the cryogenic industry. Those steels have good notch toughness at temperatures well below zero. Fine-grained aluminum-killed steels with up to ten percent nickel are frequently used for cryogenic service.

Low alloy steels have also been developed for high temperature service in welded structures such as steam boilers, oil refining towers, and chemical processing retorts. Additions of chromium and molybdenum give these steels structural stability and provide high creep and stress rupture values at temperatures up to 595 °C (1100 °F).

*High Alloy Steels.*** This group of steels consists of high quality, expensive steels with outstanding mechanical properties, corrosion resistance, oxidation resistance, and elevated temperature strength and ductility.

Dies, punches, shears, etc. are made from high carbon tool steels that also contain moderate amounts of other alloying elements. These steels have outstanding hardness at room temperature and some of them retain their hardness at elevated temperatures. These steels generally are difficult to work with and require considerable care in welding.

Most of the high alloy steels are stainless steels. Stainless steels resist attack by many corrosive media at atmospheric or elevated temperatures. They contain at least twelve percent chromium and many of the grades have substantial amounts of nickel. Other alloying elements are added for special purposes.

There are three basic types of stainless steel: austenitic, ferritic, and martensitic. Some of these steels are precipitation hardenable. The martensitic stainless steels contain the smallest amount of chromium and they can be quite hardenable. One classic example is the cutlery grades, which are included in this group.

Care must be taken when welding the martensitic steels since martensite tends to be produced in the heat-affected zone, and can be very hard. Preheating and a postheat treatment are necessary to prevent cracking.

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*Chapter 63 in Section 4 of the *Welding Handbook*, Sixth Edition covers these steels in detail. In the Seventh Edi-

**High alloy (stainless) steels are covered in Chapters 64 and 65 of Section 4 of the *Welding Handbook*, Sixth Edition. Stainless steels tentatively will be covered in Volume 4

Table 4.3 — Plain carbon steels

Common name	Carbon content	Typical use	Weldability
Ingot Iron	0.03% max	Enameling, galvanizing, and deep drawing sheet and strip	Excellent
Low Carbon Steel	0.15% max	Welding electrodes, special plate and shapes, sheet, strip	Excellent
Mild Steel	0.15-0.30%	Structural shapes, plate and bar	Good
Medium Carbon Steel	0.30-0.50%	Machinery parts	Fair (preheat and postheat frequently required)
High Carbon Steel	0.50-1.00%	Springs, dies, railroad rails	Poor (difficult to weld without adequate preheat and postheat)

The ferritic steels contain 12 to 27 percent chromium and no austenite-forming elements. The ferrite phase exists up to the melting temperature of these steels and the steels develop little or no austenite upon heating. They are essentially nonhardenable, although some of the alloys (those which can develop small amounts of austenite at the grain boundaries) can produce some martensite on cooling from the austenitizing temperature.

Austenitic stainless steels are produced by adding alloying elements that stabilize the austenite at all temperatures and thus eliminate the austenite-to-ferrite or -martensite transformation. Nickel is the alloying element most frequently used for accomplishing this, although combinations of manganese, carbon, and nitrogen can serve the same purpose.

Chromium, nickel, molybdenum, nitrogen, titanium, and columbium provide special properties of corrosion and oxidation resistance and elevated temperature strength. Carbon also contributes to elevated temperature strength but it reduces corrosion resistance by forming a chemical compound with chromium. These alloys do not undergo the normal austenite-ferrite transformation and for this reason they cannot be hardened by heat treatment. There are, accordingly, no hardened areas in the heat-affected zone of a weld in these steels. The steels usually have excellent weldability. However, there are certain metallurgical considerations which apply to the weld metal in making a sound, serviceable weld.

Aluminum and Magnesium Alloys*

Aluminum alloys rank as some of the most versatile and widely used of the nonferrous metals. Their light weight, good corrosion resistance, and good weldability account for their extensive use. The aluminum alloys can be classified in two broad groups: heat-treatable and nonheat-treatable.

The strength of pure aluminum and the nonheat-treatable alloys are developed by strain hardening and by solid solution. In the most commonly used alloys, manganese and magnesium are the principal alloying elements. In the annealed condition ("soft temper"), the alloying elements provide the strength whereas in the cold worked (or strain hardened) materials, the degree of strain hardening determines the strength.

The alloying elements in heat-treatable aluminum alloys are dissolved in the aluminum at a high temperature and maintained in solid solution by quenching from this temperature. This heat treatment is com-

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*Chapters 69 and 70 cover aluminum and magnesium respectively in Section 4 of the *Welding Handbook*, Sixth Edition. In the Seventh Edition, these metals tentatively will be covered in Volume 4.

monly referred to as a solution heat treatment. The solution of specific elements or compounds in aluminum governs the strength of these alloys in the solution heat-treated condition. The strength of these alloys can be increased by the precipitation, in finely divided form, of a portion of the elements still in solution. This is accomplished by aging the alloy at a moderately elevated temperature (100 to 175 °C [210 to 350 °F]). Alloys responding to either of these precipitation treatments are designated as age hardenable. Strengths may also be increased in the precipitation hardening alloys by strain hardening them after solution heat treatment. Strain hardening may or may not be followed by aging.

Magnesium and its alloys possess distinctive properties that must be taken into consideration when designing structures of these materials. Hence, an understanding of some of the basic metallurgical, chemical, and physical characteristics of magnesium is desirable when working with this metal.

Magnesium has a hexagonal close packed crystal structure and as such has fewer slip planes available for plastic deformation than do aluminum and steel. This factor limits the direction and the amount of plastic deformation possible on magnesium from room temperature up to about 205 °C (400 °F). At temperatures above 205 °C, magnesium can be worked without difficulty, and more easily than many other metals.

In its pure state, magnesium does not have sufficient mechanical strength for structural purposes and the metal must be alloyed with other elements to obtain the desired properties. Aluminum, zinc, manganese, and zirconium are the most common alloying elements in magnesium. The rare earths and thorium are the chief elements used in magnesium for high temperature applications.

Magnesium alloys may be divided into two general groups: those for room temperature service and those for elevated temperature service. The first group consists of the older well-established alloys of the Mg-Al-Zn, Mg-Zn-RE,* or Mg-Zn-Zr series. The elevated temperature group consists of alloys having thorium and rare earths as the chief alloying elements in combination with zinc, zirconium, manganese, and silver.

Copper and Copper Alloys**

Copper serves as a base element for more than one hundred common commercial alloys. The general classification of these alloys is as follows:

Oxygen-bearing copper

Oxygen-free copper

Precipitation-hardening copper

Copper-zinc alloys (brasses)

Copper-tin alloys (true bronzes)

Copper-silicon alloys (silicon bronze)

Copper-nickel alloys

Copper-nickel-zinc alloys (nickel silver)

Copper-aluminum alloys (aluminum bronze)

Copper-beryllium alloys

Fourteen common alloying elements are added to copper, mostly within the limits of solid solubility, therefore producing alloys that are basically single phase. Most of the alloys show no crystallographic changes upon heating and cooling, but some are heat treatable in the same manner as aluminum alloys. Many precipitation-hardening reactions are available in the copper alloys in commercial use, but only a few of the alloys show sufficient response to be properly called precipitation hardened alloys.

Many of the wrought copper alloys are hardened by cold work. Cold worked tensile strengths may be as high as 350 percent of the annealed strength. The application of heat in any quantity will reduce the cold worked strength. If heat is applied for a longer time, recrystallization and annealing may occur, with a substantial reduction in strength.

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*RE is a symbol used for rare earth.

**Chapter 68 in Section 4 of the *Welding Handbook*, Sixth Edition covers copper and copper alloys in detail. In the Seventh Edition, they tentatively will be covered in Volume 4.

The most important age-hardening reactions in copper alloys are obtained with beryllium, chromium, boron, nickel, silicon, and zirconium. These elements produce most of the alloys classified as age hardenable. Care must be taken in welding and heat treating the age-hardenable copper alloys. Whenever possible, complete re-solution and aging should be provided after welding. However, for copper alloys to respond to this treatment, the proper welding process and the proper filler metal must be used.

Nickel-Base Alloys*

Nickel and the high nickel alloys have a face centered cubic structure with physical properties similar to the austenite phase of iron alloys. However, unlike iron, they do not experience any phase transformation. High nickel alloys are noted for their resistance to corrosion and high temperature.

Nickel alloys of commercial importance contain one or more of the following elements: copper, chromium, iron, molybdenum and cobalt. These major alloying elements, with the exception of molybdenum, form binary solid solutions with nickel within the range of concentrations used in commercial alloys, and have relatively little effect on weldability. Molybdenum, when added in amounts greater than 20 percent, forms a second phase with nickel; however, commercial alloys within the two-phase region are weldable. The elements manganese, columbium, carbon, silicon, aluminum, magnesium and titanium are added in smaller amounts.

Many residual elements, particularly sulfur and lead, are practically insoluble in nickel and undergo eutectic reactions that cause hot cracking of the weld. Elements of this nature must be eliminated or controlled by other means to insure weld and heat-affected zone soundness.

Gas reactions may cause porosity in nickel and chromium-free high nickel alloy welds. Filler metals contain a gas-fixing element such as titanium to prevent porosity.

High nickel alloys are classified as either solid solution strengthened or precipitation-hardenable. The latter type requires an age-hardening treatment in order to develop all their properties.

Titanium and Titanium Alloys**

The majority of the titanium alloys are strengthened by one or a combination of three mechanisms:

(1) Lattice distortion through the addition of interstitial alloying elements such as oxygen, nitrogen, hydrogen, and carbon.

(2) Solid solution strengthening by alloying with other metallic elements.

(3) Allotropic transformation.

The allotropic transformation is the familiar solution anneal and age cycle used to strengthen many alloys. It is the basis for heat treatment of titanium. The process uses the allotropic transformation temperature spread in which the beta phase becomes the supersaturated solution and the alpha phase the precipitate. Compound or intermediate phase precipitation is seldom used to strengthen titanium alloys. The effect of alloying elements (including impurities) is to either increase or decrease the ability of the beta phase to become supersaturated. The decomposition of the beta phase during continuous cooling is similar in many respects to that of austenite in steel. Alpha may transform or precipitate from the beta phase by nucleation and growth upon cooling. Indeed, even a martensite-like structure may be formed. The results of decomposition are very different, however. The precipitation of alpha from a metastable beta solution often results in a large strength increase. Titanium martensite, however, is not very hard and thus does not produce the strengthening effects which the same phase produces in steel.

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*Chapter 67 in Section 4 of the *Welding Handbook*, Sixth Edition covers nickel and nickel alloys in detail. In the Seventh Edition, they tentatively will be covered in Volume 4.

**Chapter 73 in Section 4 of the *Welding Handbook*, Sixth Edition covers titanium and titanium alloys in detail. In the Seventh Edition, they tentatively will be covered in Volume 4.

THE METALLURGY OF WELDING

WHAT IS A WELD?

Welding is the most effective method of joining materials. Yet in many ways it is the most complex, especially from a metallurgical point of view. Virtually all types of metallurgical phenomena occur during the course of making a weld. Welding metallurgy is concerned with melting, solidification, gas-metal reactions, slag-metal reactions, surface phenomena, and solid state reactions. As described in the preceding chapter on heat flow, p. 79, these reactions occur very rapidly during welding in contrast to other metallurgy fields such as steelmaking, casting, and heat treatment.

The term *weld* is, unfortunately, ambiguous because it is used in so many ways. Technically, it refers to the area of coalescence produced by the welding process. In describing a weld, it is helpful to be more specific, and thus the term used here, and the one most often meant when a weld is mentioned is a *welded joint,* which includes not only the melted or coalesced zone but also the region around it. Another term often used is *weldment.* This term normally means an assembly, large or small, which contains one or more welded joints.

The welded joint is a composite of all the parts involved in welding and comprises the weld metal, the heat-affected zone, and the unaffected base metal. The metallurgy of each weld area is intimately related to the material as well as the welding process and procedure used. Most typical welded joints, such as those in mild steel, are rapidly solidified, usually fine-grained castings of a chemical composition similar to the base metal. The weld metal, the region which has been melted during welding, is the first of the three parts. It is an admixture of the base metal and, if used, the deposited filler metal. Some welds are autogenous; as this word indicates, such weld metal is composed of only remelted base metal and does not contain any filler metal—as for example, resistance welds and gas tungsten arc welds made without filler metal. In most cases, however, a filler metal is used.

To achieve good properties in the welded joint, the weld metal is usually similar in chemical composition to the base metal, but sometimes the weld metal is significantly different, as in the case of a braze weld in cast iron. The usual intent is to produce a weld metal having properties compatible with rather than an identical composition to the base metal. Therefore, variations on the base metal composition are not uncommon in filler metals.

When a weld is deposited, the first metal to solidify grows epitaxially (with its orientation controlled by the crystal substrate) upon the solid grains of the unmelted base metal. Depending upon composition and solidification rates, the weld solidifies in a cellular or dendritic growth mode. (Dendrite growth is discussed fully in the next section which covers solidification.) Both modes cause segregation of alloying elements, and consequently, the weld metal is less homogeneous on the micro level than the base metal, which has had the benefit of working and heat treatment. For this reason, among others, the strengthening mechanisms which are often used for base materials are not appropriate for the weld metal, and other metallurgical strengthening methods must be used. These methods are also described in more detail in the next section of this chapter.

The second region of the welded joint is the weld heat-affected zone. The heat-affected zone is that part of the base metal which, because of its proximity to the fused metal, has been influenced by the heat generated in the welding process. The thermal cycle of welding will normally bring the metal nugget to its melting temperature, although this condition may be very local, as in a flash weld, or perhaps may even fall short of full melting, as in an ultrasonic or a forge weld. For the vast majority of welded joints, however, a full range of temperatures between ambient and the liquidus, will be represented in the heat-affected zone. The zone may be small in size if the heat is intense and applied to acclimated regions, as in electron beam welding. On the other hand, it may be quite large, as in the case of a high heat input electroslag or submerged arc weld. Figure 3.4, Chapter 3, p. 94 shows several isotherms around the weld puddle for medium and high heat input welded joints in steel. The 540 °C (1000 °F) isotherm in the case of a high heat input welded joint extends out about 25 mm (1 in.) from the weld center line with the weld puddle extending to only about half this distance.

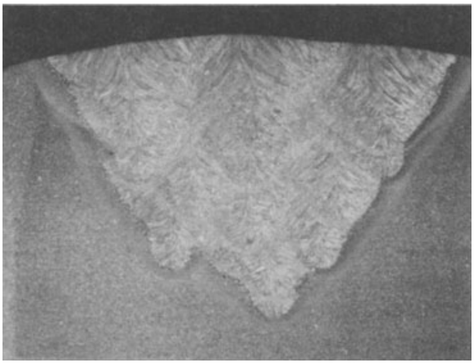


Fig. 4.16 — Low alloy steel weldment. Note heat-affected zone around each weld pass.

Although the heat-affected zone may in theory include all regions heated to any temperature above the ambient, from the practical viewpoint it includes those regions heated by the welding process which are actually influenced by its heat. Thus, for steels, the heat of welding has little influence in a welded plain carbon as-rolled steel for regions heated to less than about 600 °C (1110 °F). For a heat-treated steel quenched to martensite and tempered at 315 °C (600 °F), any heating above this temperature may produce a change in properties of a significant portion of the heat-affected zone. For a heat-treated aluminum alloy age hardened at 120 °C (250 °F), any portion of a welded joint heated above this temperature is a part of the heat-affected zone.

Heat-affected zones are often defined by the response of the welded joint to hardness or etching effect tests. Thus, changes in microstructure produced by the welding heat which are seen in etching or in hardness profiles may be used to define the "heat-affected zone." In many cases these are arbitrary measures of the heat-affected zone, although they may be of practical value in testing and evaluating welded joints. An example of the heat-affected zone in a multipass weld in steel is seen in Fig. 4.16. In this figure, a heat-affected zone can be seen to surround each weld pass; thus it consists of several different regions. The significance of the weld heat-affected zone is discussed later in this chapter.

The third region making up a welded joint is the base metal itself. This is the material to be joined and may be the portion of the weldment over which the welder or welding engineer has the least control. The weld metal and heat-affected zone must be compatible with the base metal to be joined if a successful welded joint is to be produced. When the base metals are simple alloys which achieve their strength by alloy strengthening alone, the welding process can usually produce weld metals and heat-affected zones with compatible properties. When base metals are strengthened by complex heat treatments or mechanical deformation, it may be difficult to produce completely compatible weldments. Again, it may be possible to make the properties of welded joints compatible with those of the base metal, but the particular base metal involved may be prone to one or another kind of weld defect. In this case, serviceable weldments may be difficult to achieve.

The combination of the mechanical, chemical, thermal, and other properties of a base metal go to make up a complex property called "weldability" which is discussed at length later in this chapter.

WELD METAL

As briefly noted already, the majority of welded joints contain a melted zone which, when solidified, comprises the weld metal.

This region consists of metal that may be slightly or even grossly different from the base metal because it is composed of varying mixtures of filler metal and base metal melted in the welding process. The filler metal employed may be tailored to the mechanical properties and chemical composition of the base metal but its structure (as well as even that of an autogenous weld) will be markedly different. This structure, and its attendant properties, are a direct result of the sequence of events that occur just before and during the time when the weld metal solidifies. These events include reactions of the metal with gases in the vicinity of the weld, reactions with nonmetallic liquid phases (slag or flux) during welding, and solid state reactions occurring in the weld after solidification. Each of these phenomena will be considered in detail.

Solidification

As described at the beginning of this chapter, grains or clusters of crystals form when a liquid metal solidifies. This transformation from liquid to solid is governed by the combined processes of nucleation and growth, and the size, orientation, and distribution of the grains produced can influence the mechanical properties and soundness of the solidified structure.

Each grain has some initiating source (nucleus) from which it grows. Nucleation may take place at the wall of the container or from foreign, solid particles suspended in the liquid; these are examples of heterogeneous nucleation. If no heterogeneous nuclei are available, solidification must initiate by homogeneous nucleation from within the liquid, and this requires substantial supercooling (that is, cooling the liquid well below the normal freezing temperature).

The most effective heterogeneous nucleus is a solid particle (seed crystal) of the metal which is solidifying; this kind of nucleation is dominant in solidification of weld metal. In arc welding, melting precedes solidification when the arc approaches a particular area, but a liquid-solid interface is always present (or the puddle falls away), and this constitutes an ideal nucleation site; there is very little supercooling and no homogeneous nucleation. The turbulence of the weld pool frequently causes fragments of solid metal to separate from the liquid-solid interface, and these may act as nuclei. However, most nucleation takes place at the weld fusion boundary, the major liquid-solid interface. Not all of the grains that nucleate undergo extensive growth; some are pinched off during the growth process. This produces fewer but larger grains in the weld metal. The mechanical properties are affected by grain size. An example of weld metal grains nucleated at heat-affected zone grains is shown in Fig. 4.17.

Weld metal often exhibits a structure described as columnar in which the grains are relatively long and parallel to the direction of heat flow. This structure is a natural result of the grains initiating at the weld fusion boundary, and many grains which are favorably oriented grow without interruption until solidification is complete.

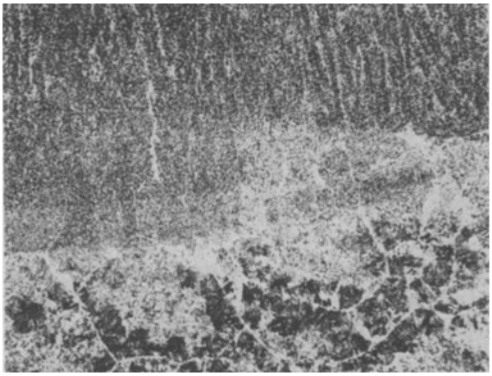


Fig. 4.17 — Weld metal dendrites (top of photograph) growing on coarse grains of base metal heat-affected zone. Note base metal grain boundaries extending into weld metal dendrite boundaries.

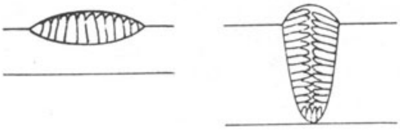
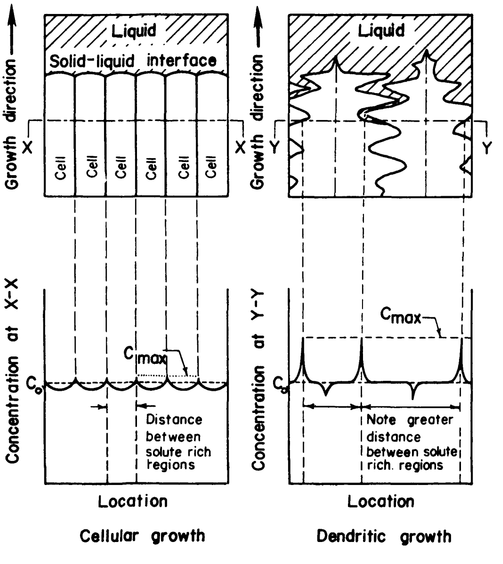


Fig. 4.18—Columnar structure of shallow and deep welds. Left: Shallow weld. Right: Deep pear-shaped weld.

Not all weld metal is coarse grained and columnar. The grain structure varies with different alloys, and can be modified by process variations which alter the pattern of turbulence in the liquid metal. In general, nearly pure metals, and alloys which solidify over a narrow range of temperatures, develop the most columnar and coarse-grained weld metal.

Weld metal can suffer from a subtle solidification defect called "ingotism," a surface of weakness where groups of intersecting columnar grains have been the last metal to solidify. This defect can be serious in electron beam or parallel-gap arc welds where columnar grains growing from opposite sides meet at the midplane of the weld, a location which tends also to act as a repository for impurities and porosity, and is prone to fracture at low strains. The influence of weld shape on this grain structure is shown in Fig. 4.18. The problem of ingotism can best be handled by so manipulating the gap configuration or welding procedure as to change the geometry of the columnar grain structure; these manipulations often include reducing the travel velocity of the heat source.



Cellular growth

Dendritic growth

Fig. 4.19 — Schematic of solute distribution for cellular and dendritic growth patterns.

Rapid solidification of almost any technically important metal alloy involves microsegregation of alloying elements. This unmixing process is associated with, and, in large measure, responsible for the formation of dendrites. A dendrite is a structural feature which reflects the complex shape taken by the liquid-solid interface during solidification (see Fig. 4.17).

The primary dendrites and dendrite arms which form early in solidification are of a higher melting composition than the interdendritic material which freezes later. Those alloy elements which lower the melting temperature are progressively displaced by the growing solid, and must migrate away from the liquid-solid interface by diffusion into and through the liquid. However, diffusion is a slow process, and there is a tendency for low melting liquid to accumulate at the interface. This accumulation impedes growth. The characteristic filamentary, branched configuration of dendrites is a direct consequence of this action: The growing solid dendrite arms literally "reach" through the enveloping layer of low melting liquid.

The spacing between dendrite arms determines the microscale of alloy segregation and is determined by the rate of solidification. The more rapid the solidification, the more closely spaced are the dendrites.

The dendrite arm spacing is a structural feature of quite small magnitude, typically much smaller than the grain size. (It is not unusual for the grain size in some weld metals to exceed 1 mm [0.04 in.]; there may be thousands of dendrite branches within one grain.) There is a unique dependence by the dendrite arm spacing on energy input; in fact, as a diagnostic technique, energy inputs can be estimated with fair accuracy by measuring the dendrite arm spacing when data on welding parameters are not available. Although the tendency is for grain size to increase with energy input, there is no fixed relationship. The grain size can be influenced by nucleating agents (grain refiners), vibration, or other process variables, but the dendrite arm spacing is exclusively a function of solidification rate which is controlled by energy input.*

If weld solidification rates are quite rapid, full dendrites may not develop. Under these conditions, a much shorter projection of the freezing interface into the liquid weld pool occurs which is called a cell structure. Spacings between cells are normally smaller than those between dendrites and segregation of solutes is not so extensive. Examples of dendrites and cells with their corresponding segregation patterns are shown in Fig. 4.19.

Gas-Metal Reactions

In a fusion welding process such as arc welding, the extent to which the metal and the atmosphere interact is strongly dependent on the physical details of the welding process. Thus, in gas metal arc welding (GMAW)-spray transfer, reactions may be quite extensive even though the exposure time is brief. In the first place, the liquid metal transfers across the arc in the form of tiny droplets which offer a very large reacting surface area, and which become superheated to temperatures far above the melting point. Second, the arc atmosphere itself is rendered highly reactive by the dissociation and ionization of gas molecules. An element such as nitrogen, often regarded as relatively inert, becomes highly reactive in an electric arc.

Some processes minimize exposure. Gas tungsten arc welding (GTAW) and GMAW-short circuiting arc are in this category because in these processes liquid metal is transferred in the form of relatively large droplets, thus minimizing the exposed surface area; moreover, these large droplets are never in "free flight" through the high temperature arc plasma, and so never become superheated more than 100 °C (180 °F) above the melting point.

Other processes, such as submerged arc welding (SAW), minimize gas-metal reactions by interposing a protective slag barrier between the metal and the atmosphere. In some cases, such as in electron beam welding (EBW) and GTAW, adverse gas-metal reactions are prevented by insuring that the welding atmosphere is absolutely nonreactive. However, with some of the most productive and economically attractive arc welding processes, notably GMAW and the shielded metal arc welding SMAW processes, the arc atmosphere is inherently reactive, and it becomes necessary to compensate and control the effects of gas-metal reactions.

The earliest attempts at consumable electrode arc welding of steel were made using bare wire electrodes without any control of the arc atmosphere. The early welds produced by this method, while representing the beginnings of a major advance in manufacturing technology, tended to be quite porous and brittle. As the infant welding industry progressed, it was discovered, quite circumstantially, that weld quality sometimes improved when the electrode wire was covered with oxide or drawing lubricant, and so began the arc welding industry.

The improvement of weld quality associated with nonmetallic electrode coverings was partly due to the enhancement of arc stability through promotion of emission and ionization, and partly to the exclusion of air from the arc atmosphere. This exclusion of air was (and still is) accomplished by volatilization or destructive distillation of compounds in the electrode covering.

It is now recognized that the exclusion of air from the arc atmosphere is absolutely vital to the production of high quality arc welds in steel. This fact can be somewhat perplexing since in other metal processing operations, steel is melted and poured in air without any concern at all. However, as previously noted, the gases nitrogen, oxygen, and water vapor are rendered highly reactive in an electric arc and thus can be harmful.

Control of oxygen is basic in fusion welding of steel. To some degree, oxygen is always present in or available to the liquid weld metal, but the concentration varies widely with the oxidizing potential of the arc atmosphere and with the composition and surface condi-

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*See the discussion of solidification rates in Chapter 3, p. 88.

tion of the metal. A major concern is to prevent oxidation of carbon, the reaction most frequently responsible for porosity in steel weld metal:

$$\mathrm{C} + \mathrm{O} \rightarrow \mathrm{CO} \text{ (gas bubbles)}$$

This unfavorable reaction is usually prevented by deoxidation; elements having a high affinity for oxygen, such as aluminum or silicon, are introduced into the weld metal in order to react preferentially with oxygen:

$$\begin{aligned} \mathrm{Si} + 2\,\mathrm{O} &\rightarrow \mathrm{SiO_2} \\ 2\mathrm{Al} + 3\,\mathrm{O} &\rightarrow \mathrm{Al_2O_3} \quad \text{(nonmetallic inclusions)} \\ \mathrm{Mn} + \mathrm{O} &\rightarrow \mathrm{MnO} \quad \text{(deoxidation products)} \end{aligned}$$

In fact, the chemical control in welding may be regarded as a battle in which carbon competes with the deoxidizing elements for the available oxygen. To avoid porosity, it is important to insure that the deoxidizing elements win this competition.

The deoxidation reactions in steel have the mildly undesirable side effect of producing nonmetallic inclusions. These may rise to the surface of the weld pool or may remain in the deposit in the form of complex oxides. Such inclusions are generally very fine and widely dispersed and unless extensive have little significant effect on mechanical properties. The nonmetallic deoxidation products are far preferable to porosity.

However, excessive concentrations of aluminum and silicon should be avoided; otherwise, there may be serious loss of ductility and toughness, especially at low temperatures. It is therefore important to balance the quantity of deoxidizers provided with the oxidizing potential of the weld system. The ideal chemistry incorporates deoxidizers slightly in excess of that theoretical minimum amount needed to react with the available oxygen. Achieving this balance requires a compatible selection of the process and materials comprising the welding system.

The principal sources of oxygen are the arc atmosphere, the oxide or scale on the surfaces of the workpieces, and the oxygen which initially may be present in the metal. Deoxidizers (aluminum and silicon) are usually available from alloy elements in the electrode, constituents in the covering of a consumable SMAW electrode, or in the core of a GMAW flux cored electrode. For example, if the arc atmosphere is 100 percent carbon dioxide, and therefore strongly oxidizing, it is essential to supply a relatively large quantity of deoxidizer; on the other hand, if the atmosphere is argon containing two percent oxygen, far less deoxidation is necessary.

These requirements present a compatibility problem: a filler metal which is of the ideal composition for the welding of steel with the GMAW process using argon-two percent oxygen, may produce a porous weld in an atmosphere of 100 percent carbon dioxide. Conversely, a filler metal (whether flux cored or not) which produces a satisfactory weld in 100 percent carbon dioxide, may not be suitable for use in the argon-two percent oxygen atmosphere because of over-deoxidation. The effect of under-deoxidation is porosity which is readily detected and frequently rejectable. The effect of over-deoxidation (loss of ductility and impact resistance) is more subtle and not detectable by nondestructive means.

The problem of compatibility between the welding environment and materials has been somewhat intensified by the development of the GMAW process, because with GMAW the user has independent control over the filler metal composition and the arc atmosphere. On the other hand, in SMAW the electrode manufacturer is entirely responsible for compatibility because he provides the arc atmosphere and deoxidizing capacity as an integral unit.

Water vapor can be harmful, particularly as a source of hydrogen which can cause porosity and embrittlement. Porosity can be controlled by excluding the gas, or by insuring that the molten metal has sufficient fluidity to allow the gas to escape. A far more serious effect of hydrogen is the formation of cracks in high carbon and alloy steel welded joints. This effect is also dependent on solid state reactions in steels and will be discussed later. Water vapor can also be harmful in welds because it produces a loss in arc stability.

In nonferrous alloys, the primary gas-metal reactions of concern are the solution, reaction, and evolution of hydrogen or water vapor. These gases therefore should be excluded from the molten pool. In aluminum and magnesium, the hydrogen is often introduced from hydrated oxides on the surfaces of the wire or workpieces, and evolves during solidification to produce porosity. For this reason, wires for welding are stored in sealed, desiccated containers, and mechanical cleaning or vacuum heating at 150 °C (300 °F) is recommended for workpieces or wires which have been exposed to moist air. For aluminum alloys, a small concentration of chlorine gas in the arc atmosphere reduces porosity.* For magnesium, the hydrogen solubility difference between the liquid and solid states is less than that for aluminum, so the tendency for hydrogen-produced porosity is reduced.

In the case of copper and copper alloys, hydrogen reacts with oxygen in the liquid metal during solidification to produce water vapor and thus porosity. The filler metals for copper alloys contain deoxidizers to prevent this reaction. Alloys of zinc, aluminum, or beryllium are not porosity prone because these elements themselves have a deoxidizing effect. Nickel-copper and nickel alloys are more prone to porosity, and filler metals for these alloys contain strong deoxidizers.

Titanium alloys are embrittled by contact with a number of gases such as nitrogen, hydrogen, or oxygen, and these elements must be shielded from the arc atmosphere. Welding is done in vacuum or under carefully shielded conditions.

Liquid-Metal Reactions

During the welding process, nonmetallic liquid phases are frequently produced that interact with the liquid weld metal. These may be deliberately produced, as is the case with slag layers formed by the melting of flux in the SMAW, SAW, and electroslag (ESW) or electrogas (GMAW-EG, FCAW-EG) processes. They may also be produced as a result of reactions occurring in the molten weld pool and may remain in or on top of the weld metal after welding, as, for example, is the case with fine inclusions in carbon dioxide-shielded gas metal arc welds. When slag layers are formed, a variety of chemical reactions occur between the liquid metal and slag, reactions that are quite similar to those which occur during the refining of the metal when it is produced from ore. The slag which is formed from the welding flux is therefore an important part of the welding process.

In general, flux layers are used almost exclusively in ferrous welding. The surface films produced in the welding of aluminum, titanium, copper, and other metals are composed of oxide layers resulting from an imperfect gaseous shielding on the weld metal. Similar layers occur in gas metal arc welds in steel.

The flux layers used in the SMAW, SAW, and ESW or GMAW/FCAW-EG processes are designed to absorb deoxidation products produced in the arc and molten metal. The quantity and type of nonmetallic deoxidation products generated in arc welding steel are directly related to the specific shielding and deoxidants used. These nonmetallics, primarily silicates of aluminum, manganese, and iron, may float to the surface of the weld pool and become incorporated in the slag, but some will remain in the metal as inclusions. The cleanliness of the weld metal is influenced by the quantity of nonmetallics produced, and by the extent to which they can be removed with the slag. Clearly, the more strongly oxidizing is the arc environment the more deoxidation is required, and the greater the quantity of nonmetallics produced.

An important feature of deoxidation is the composition of the resulting nonmetallics. Aluminum is a powerful deoxidizer but is best used in conjunction with silicon, which is somewhat less powerful, and manganese, which is relatively weak. In concert, these elements form liquid products of deoxidation which readily agglomerate, float, and are fluxed from the liquid metal into the slag. Deoxidation with aluminum alone tends to result in dirty weld metal because the fine dis-

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*Since chlorine attacks tungsten, it cannot be used in gas tungsten arc welds.

persion of solid nonmetallic particles produced is likely to remain in the weld metal. In practice, silicon and manganese react with the bulk of the dissolved oxygen, and sufficient aluminum is provided to insure a very low final oxygen concentration, thus preventing any oxidation of carbon which might cause porosity. Ideally, the quantity of aluminum introduced, together with silicon and manganese, should be just enough to leave about 0.01 percent metallic aluminum (but not more than 0.05 percent) in the weld metal.

In addition to the deoxidation function, welding slags may also aid in removing sulphur and phosphorus from the deposit. In this regard they are much like metallurgical slags; that is, an oxidizing basic (lime rich) slag is necessary to perform this function. The extent to which welding fluxes can act in this capacity is not clear, however, only the lime-rich fluxes (for example, the coverings for EXX18 electrodes) can perform this function.

Another important effect that results from the interaction of the liquid and solid state is the weld defect referred to as hot cracking. This phenomenon arises whenever, during the solidification of the weld metal, the interdendritic liquid (the last region to freeze) has a substantially lower freezing temperature than the bulk dendrite. Under these conditions, shrinkage stresses produced during solidification become applied to this small liquid region and produce interdendritic cracks. These cracks are called hot cracks because they occur at temperatures close to the bulk solidification temperature. They are promoted by any compositional variations in the weld metal that produce a low melting interdendritic liquid.

In ferrous alloys, including the stainless steels and nickel alloys, the most common cause for this cracking is the presence of low melting iron and alloy sulfides that wet the dendrite surfaces. However, in some ferrous alloys, such as stainless steels, silicates have also been found to produce cracking. The control of cracking in these alloys is usually accomplished by controlling the amount and type of sulfides that form and the minor alloy constituents that may promote cracking. Thus, in ferrous welds, manganese-to-sulfur composition ratios of 30 or more are used to prevent hot cracking in weld metal, although when harmful alloy elements such as carbon, phosphorus, and perhaps nickel are present, the manganese-to-sulfur level may have to be increased. In stainless steels of the austenitic type, a duplex microstructure in the weld metal, such as austenite and delta ferrite, will effectively prevent cracking. For this reason, weld metals for these alloys are compounded to contain two to eight percent ferrite. Ferrite in greater amounts may adversely affect weld metal properties.

In nonferrous alloys, hot cracking, when encountered, may be caused by the fact that the alloy composition exhibits a liquid-solid region extending over a wide range of temperatures on its phase diagram. In such a position on the diagram, the large freezing point range for the dendritic and interdendritic material promotes shrinkage stresses imposed on the interdendritic region, which cracks. In these alloys, the cracking may be reduced or eliminated by increasing the alloy content of the weld metal to reach a composition whose liquidus-to-solidus temperature gap is decreased.

Solid State Reactions

In terms of the behavior of weld metals, there are a number of solid state reactions that are important as strengthening mechanisms in the weld metal itself. These will be discussed in detail later in this chapter. In terms of interactions occurring during the welding process, however, there are some important phenomena involving solid state transformations and subsequent reactions with dissolved gases in the metal. The most significant of these phenomena is the formation of cold cracks in weld metal (or heat-affected zones), often referred to as delayed cracking.

This type of cracking is confined to steels, and in particular to steels which can transform to hard transformation products upon cooling from the weld thermal cycle. These steels, called hardenable steels, have compositions that permit the normal transformation products in steel to be bypassed in favor of a hard and highly (internally) strained phase called martensite (refer to the earlier discussion of martensite on p. 110.)

The cracking defect itself occurs after the weld has cooled well below the melting temperature, sometimes hours or even weeks after welding. It is always associated with the presence of hydrogen in the weld metal which remains there during solidification and subsequent transformation. Since this type of cracking is always associated with hydrogen and martensite, the following two precautions are universally used to minimize the risk of delayed cracking: (1) preheat and other process variables which are adjusted to keep the cooling rate low enough that hard structures are not produced in the weld and, (2) steps to exclude hydrogen from the welding environment or quickly diffuse it away from the martensite after welding.

There is no question that hydrogen promotes cracking in hardenable steels. The fundamental details are not clear, but they apparently relate to phase transformations and attendant changes in hydrogen solubility during cooling.

At high temperature (above 800 °C [1470 °F]) the steel is face centered cubic austenite, a form in which hydrogen is quite soluble. Upon cooling, the austenite transforms either to an aggregate of ferrite and carbide or to martensite, and there is a drastic reduction in hydrogen solubility. In a plain carbon steel, this transformation takes place at a relatively high temperature (near 700 °C [1290 °F]), even if cooling is rapid. Consequently, there is sufficient mobility so that much of the rejected hydrogen can diffuse out of the metal. Moreover, the high temperature transformation product (ferrite plus carbide) which forms in the heat-affected zone is relatively ductile and crack resistant.

A rapidly cooled hardenable steel transforms at a much lower temperature (generally below 400 °C [750 °F] and often near room temperature), so the hydrogen is locked into the structure which may also be hard and brittle. It is this combination which induces cracking. The association of hydrogen with cracking led to the development of low hydrogen electrodes.

Low hydrogen electrode coverings must be kept as nearly moisture free as possible because water is a potent source of hydrogen. For this reason, the electrodes frequently are supplied in hermetically sealed containers. Contact with humid air will cause harmful hydration. Ideally, the electrodes should be used immediately upon removal from their sealed container. When this is not possible, the exposed electrodes should be stored in a desiccated environment or at a temperature of about 130 °C (265 °F). It is important to recognize that electrodes which have become hydrated by exposure to the atmosphere may not be readily dried since some of the moisture combines chemically with constituents of the electrode covering. Information on rebaking (drying) procedures for these electrodes may be found in the latest edition of the Structural Welding Code, AWS D1.1 (paragraph 4.9) and from the electrode manufacturer.

The problem of delayed cracking is not as severe with weld metal as it is in the weld heat-affected zone and will be discussed again under that topic.

Strengthening Mechanisms in Weld Metals

The final mechanical properties of weld metals are, to a large extent, established at the time that solidification is complete. Relatively few commercial applications of welds require or even permit the weld to receive a full reheat treatment and thus the strength and toughness of the weld may be entirely dependent on the composition of the weld nugget and the technique by which it was deposited. In some instances, the welded joint receives a postweld heat treatment at high enough temperatures to soften a hardened heat-affected zone and to relieve residual stresses, but this treatment will usually not increase the strength of the weld metal, and may not improve its toughness. In carbon steels it frequently does improve toughness, however.

The properties of the weld metal, especially its strength, are therefore usually governed by solid solution strengthening and fine particle strengthening effects. For this reason, the manganese content of ferrous alloy welds is usually higher than that of the base metal, although the carbon content is lower. The reduced carbon content is often required to control hot and cold cracking and to maintain the toughness of the weld metal. The natural solidification structure of most weld metal is fine. Even though the solidification dendrites appear large, the fine dendrite branching between the major dendrite columns produces a fine microstructure resulting from the beneficial strengthening mechanisms.

Precipitation hardening or martensitic strengthening is not commonly employed in weld metals because a heat treatment is required subsequent to welding. In a limited number of cases, however, the actual weld deposition procedure may act as a sufficient quench to the weld metal to produce a heat treatment effect. Thus, an alloy steel weld metal deposited at a sufficiently low heat input may transform to martensite with its attendant hardening effect. The composition of some aluminum alloy weld metals is such that the welding procedure leaves the weld in the solution treated condition, and it will subsequently age at room temperature to a higher strength level.

Postweld heat treatments usually soften weldments, but the preceding discussion shows that this is not always true of a precipitation hardening weld metal. The postweld heat treatment of a material such as an aluminum alloy may produce hardening, and in ferrous alloys containing vanadium, it may also precipitate alloy carbides which have a hardening effect.

THE HEAT-AFFECTED ZONE

The response of the area next to the fusion line in a welded joint is quite dependent on the nature of both the material welded and the welding process or procedure. Since the weld thermal cycle is generally a rapid one, the materials most influenced by welding will be those strengthened by heating and quenching heat treatments. Nevertheless, it must also be remembered that the temperatures in the weld heat-affected zone vary between the ambient and the liquidus temperature. At temperatures close to the liquidus, many metallurgical processes that proceed slowly at lower temperatures (because they depend on solid state diffusion) such as recrystallization annealing, solution treatment, tempering, and aging, can proceed to completion quite rapidly.

The influence of welding on some materials can act simultaneously as both a rapid heating and cooling and an annealing cycle depending on the part of the heat-affected zone referred to. Thus in order to understand the various effects of weld heat on the heat-affected zone, it is simplest to discuss these effects in terms of four different types of metal alloys which may be welded. These are: (1) metal alloys that are alloy (solid solution) strengthened, (2) alloys that are strengthened by cold work, (3) alloys that are precipitation hardened, and (4) alloys that are transformation (martensite) hardened. Even though some materials are strengthened by more then one of these processes, for simplicity the processes will be considered separately.

Alloy Strengthened Materials

Metals and alloys that are strengthened by alloying alone, that is, by solid solution strengthening, are normally the easiest to weld from the standpoint of the heat-affected zone. If they undergo no solid state transformations, the effect of the thermal cycle is quite minimal, and the properties of the heat-affected zone will be little changed by welding. Since the region next to the fusion line will be heated very close to melting, some grain growth may occur in this region. This will normally have only a modest influence on mechanical properties, but in the case of some body centered cubic metals, particularly the refractory metals, coarse grain size in the weld heat-affected zone may increase their transition temperature and reduce ambient toughness.

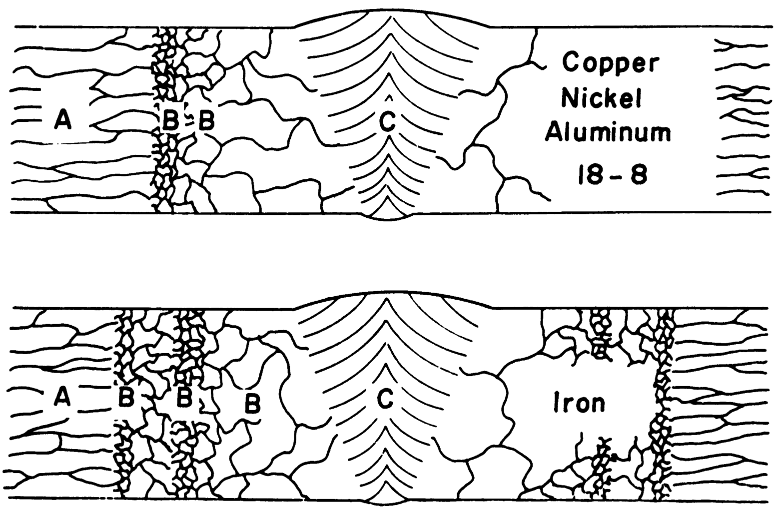


Fig. 4.20— Recrystallization of cold worked base metal in the vicinity of a weld. A: Cold worked metal (elongated grains). B: Recrystallized metal (equiaxed grains). C: Weld metal (columnar grains). Above: Weld in alloys without phase change. Below: Weld in iron or steel.

Of much greater concern are the materials that are not used in the heat treated condition but are from an alloy system which will respond to heat treatment. For example, hot rolled steels do not achieve their mechanical properties through special heat treatments but rather through alloying of iron with carbon, manganese, and perhaps several other alloy elements. When welded, these materials can sometimes transform to martensite from the weld thermal cycle. This transformation will lead to a major change in the properties of the heat-affected zone, and these materials must be considered as transformation hardening alloys. This type of material will be discussed later.

Materials in the alloy-strengthened group are annealed aluminum alloys, annealed copper alloys, and very low carbon, hot rolled, or annealed steels. Annealed ferritic and austenitic stainless steels come under essentially the same category; however, the austenitic stainless alloys have a special heat-affected zone problem called "sensitization." These steels rely on high levels of chromium (about 18 percent) for good corrosion resistance. When the austenitic alloys are welded, the region in the heat-affected zone between about 550 °C and 650 °C (1020 and 1200 °F) will be in the right temperature range for the chromium present to combine with carbon and chromium carbides which will precipitate in the grain boundaries in this heat-affected zone region. This precipitation reduces the effective chromium content to a level susceptible to rapid corrosion, and the region is said to be "sensitized." There are three solutions to this problem: Reduce the carbon content of the steel (that is, to use extra low carbon grades) add to the steel alloy elements which combine with carbon (titanium or columbium), or reheat the weldment to 980 °C (1800 °F) and rapidly cool it to room temperature so that the grain boundary carbides are dissolved and do not have a chance to reform.

Strain Hardened Materials

Since all strain hardened materials will recrystallize when heated close to their melting points, it is to be expected that a heat-affected zone containing these materials will soften considerably from its cold worked hardness. The heat-affected zone structure will be that shown in Fig. 4.20. In the figure, the cold worked base metal shows the typical elongated and crushed grains resulting from mechanical deformation. At some point in the heat-affected zone, the base metal reached a temperature just high enough to cause recrystallization and this is detected by the presence of fine, equiaxed grains in the microstructure. At the fusion line, the cold worked structure has been completely recrystallized and the new grains have grown to a large size. The weld metal grain (dendrite) size is usually as large or larger than this coarse-grained heat-affected zone. As might be expected, the coarse-grained heat-affected zone no longer has the strengthening effect of cold work and thus is much softer than the cold worked strength level of the base metal. Under such circumstances, the weldment will not generally be able to meet the strength specifications for the base metal and a lower strength will have to be accepted. As a result, the strength of the weldment probably will be close to that of the annealed plate.

In the case of cold worked materials which transform when heated, the effects of welding are even more complex. As shown in Fig. 4.20, these materials, principally iron and steel alloys, will have two recrystallized zones. The first zone results from recrystallization of the low temperature alpha phase (refer to the iron carbon phase diagram, Fig. 4.8) which has been cold worked. The second recrystallized region results from the fact that the ferrite phase transforms between 723 and 910 °C (1333 and 1670 °F) to the gamma phase, which also brings about a recrystallization. Thus the microstructure of these alloys will show two recrystallized regions in the heat-affected zone.

Precipitation Hardened Materials

The alloys that are strengthened by precipitation hardening respond to the heat of welding much as the work hardened alloys do; that is, the heat-affected zone undergoes an annealing cycle. In this case, however, the response of this zone is more complex since the welding thermal cycle produces different effects in different regions of the heat-affected zone depending on the peak temperature achieved. Since this type of alloy normally receives a three step heat treatment involving a solution treatment, a quench from the solution treatment temperature, and an aging heat treatment (see page 113—117), it is to be expected that any alloy in the aged condition will be substantially reheat treated by welding. At the regions closest to the weld, the metal is heated close to melting and this thermal cycle acts as a re-solution treatment of the alloy. Since welding thermal cycles are usually rapid, the cooling rate from this treatment is usually fast enough to serve as a quench and the resulting structure is a single phase solid solution region. This region is usually relatively soft, and often coarse grained as well, but can be hardened by an aging treatment following welding.

The region next to this has been heated close to but below the solution treatment temperature. This region will therefore become "overaged" during the weld thermal cycle. Subsequent heat treatment cannot reharden this region unless a full retreatment of the joint using a solution treatment and a quench and aging cycle is employed. Regions farther away from the weld will be given a slight aging treatment but usually this is of little consequence unless the temperature of the region rises close to that used for solution treatment. Figure 4.21 illustrates the regions developed in the heat-affected zone of a precipitation hardened alloy.

While it is almost impossible to weld high strength precipitation hardenable alloys without some loss of strength, a variety of techniques may be used to minimize this loss. The most effective of these techniques is to re-solution treat and quench and age the weldment. This technique is the most difficult to do, and in the case of large weldments, may not be practicable. A second approach would be to re-age the weldment only. This raises the strength of the solution treated region of the heat-affected zone, but does not improve the strength of the overaged zone. The third approach is to simply accept the strength loss in the weldment and design on that basis—a pro-

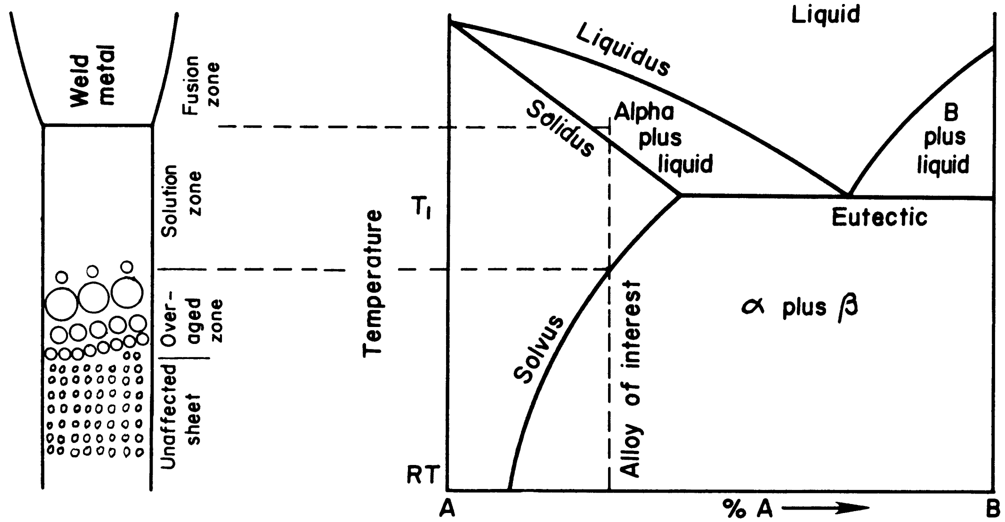


Fig. 4.21 — The influence of the weld thermal cycle on a precipitation hardening alloy. Left: The weld heat-affected zone regions. Right: The corresponding positions on the phase diagram for the alloy.

cedure that is not very cost effective since alloy strengthened materials having the same strength level are usually less expensive than the higher strength precipitation hardening alloys. Another alternative is to weld the alloy in the solution treated condition and use aging only after welding. The overaged zone is still weakest, but the overall effect may be an improvement over the aged and welded condition.

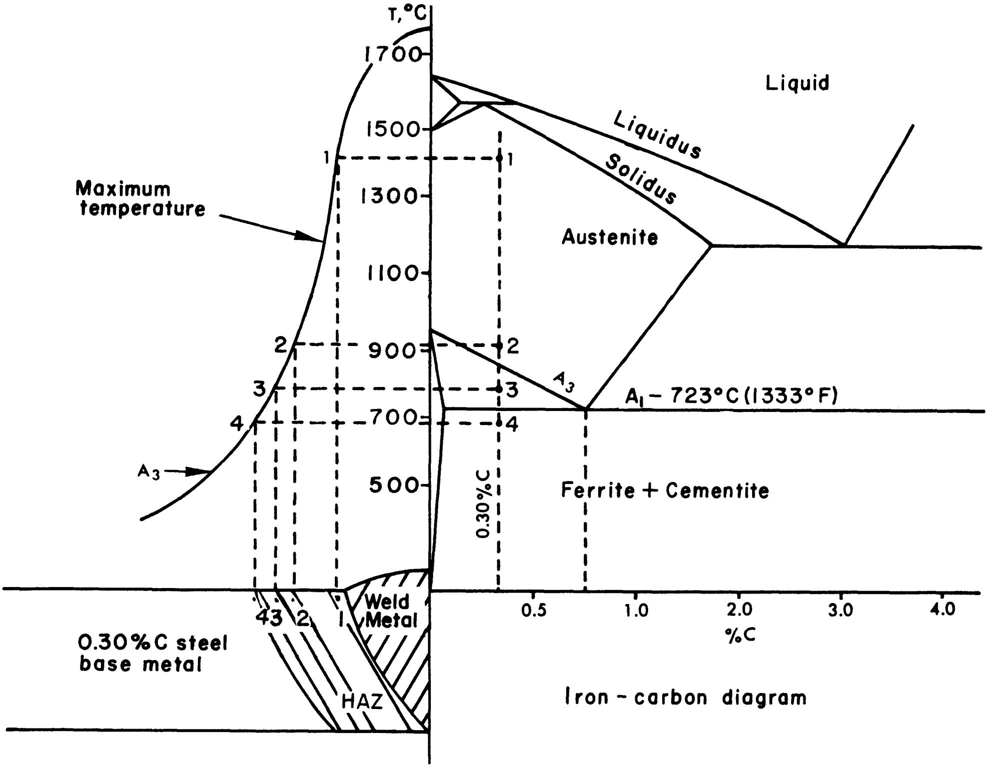
Since it is the weld thermal cycle that is damaging to the strength of the heat-treated material, it is always advisable to avoid high heat input processes when welding these alloys. Thus, electron beam welds in precipitation hardening alloys produce the best joint efficiencies while submerged arc or electroslag welds produce the poorest.

Another problem that often occurs in precipitation hardening alloys, but is by no means exclusive to them, is heat-affected zone hot cracking. These cracks occur because regions next to the weld fusion line are heated to such a temperature that some of the phases present may melt. If these phases lie near or along grain boundaries, they wet the boundaries and cause intergranular separation. They are, in most respects, like weld metal hot cracks but are usually small (sometimes called microcracking) and lie next to, but on the heat-affected zone side of, the fusion line. This type of hot cracking is usually eliminated by control of the base metal composition.

Transformation Hardening Materials

The transformation hardening alloys of interest are the steels with enough carbon and alloy content present to transform to martensite upon cooling from welding. These may be steels which are already heat treated to tempered martensite prior to welding, or simply steels that have the right composition to transform to martensite even though they have never been deliberately heat treated. In either case, the sequence of regions in the weld heat-affected zone is approximately the same. These regions, along with the pertinent phase diagram, are shown in Fig. 4.22.

Next to the fusion line will be a region (region 1) heated close to the melting point, and this will consist of material heated high into the austenite temperature range. This material will be extremely coarse grained, and if the cooling rate is high enough, can readily transform to martensite. It will normally be a



°C	1700	1500	1300	1100	900	700	500
°F	3090	2730	2370	2010	1650	1290	930

Fig. 4.22 — Relation between the peak temperatures experienced by various regions in a weld, and how these correlate with the iron-carbon phase diagram.

high hardness zone. Next to this will be a region (region 2) heated just into the all-austenite range. This will normally be fine grained and will not readily transform to martensite. It will be of moderate hardness only. The next region away from the weld (region 3) will be the "intercritical zone." This area has been heated partially into the austenite range and thus is a mixed structure. A small amount of martensite may form in this zone. This area is usually not very hard, but if martensite is present, it may be somewhat brittle.

The final region (region 4) of the weld heat-affected zone in this case is the tempered zone. In this region the metal is not heated high enough to form austenite (that is, it is less than 723 °C [1333 °F]), but rather the welding heat serves to temper the metal to a soft condition.

The zones just described are not independent of the welding process or procedure. Intense energy welds produce narrow heat-affected zones but also induce high cooling rates, thus promoting martensite. High heat input welds create larger zones, but may produce slower cooling rates, thus making softer heat-affected zone regions.

It might seem that producing martensite in the weld heat-affected zone would not be such an undesirable feature of welding this

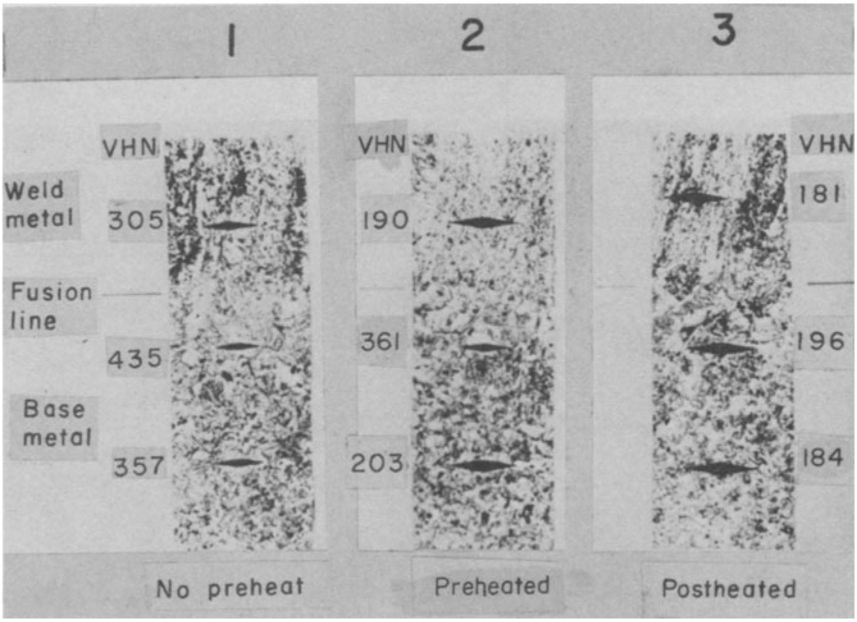


Fig. 4.23 — Weld zone hardness. Weld bead on 25 mm (1 in.) 0.25 percent carbon steel. Knoop Indenter, 500 gram load. Nital etch. 100 X.

kind of alloy since martensite is hard and strong, but there are several problems that martensite may present. The first of these concerns the properties of this zone; it is hard but often brittle, and thus not acceptable. This brittleness normally increases as the carbon content of the steel increases.

Secondly, the presence of martensite promotes cold or delayed cracking in the heat-affected zone just as it does in weld metal. Once again, martensite alone will not cause cracking; there must be two elements present in addition to martensite: hydrogen and restraint-induced stresses. While all three of these elements can be controlled in welding, this type of cracking occurs much more commonly in heat-affected zones than in weld metals, and thus is often known as "underbead cracking," that is, in the heat-affected zone under the weld bead.

The procedures used to eliminate this cracking are, first, to remove hydrogen from the area (as described in the weld metal case). This includes the use of low temperature postheating to hasten the escape of hydrogen from the weld area. One of the more common sources of hydrogen is the welding electrode, since hydrogen normally enters the heat-affected zone by diffusion from the molten weld metal. Thus low hydrogen electrodes may be used to suppress cracking in the heat-affected zone. Secondly, restraint may be decreased by control of joint design. Third, steps may be taken to prevent the formation of martensite by selecting a base metal that has a low cracking tendency (discussed later under base metal properties) or by preheating the joint. This latter step not only thoroughly dries the joint and thus eliminates hydrogen (water) but also allows the cooling rate from welding to be adjusted so that no martensite will form. The hardness of a weld heat-affected zone is usually a good indication of the presence of martensite and thus potential cracking. Cracking rarely occurs at weld hardnesses of VHN 250 or less, but is common as the VHN approaches 450.

Figure 4.23 shows three welds in a steel that were given different thermal treatments. The first weld was made without preheat, thus hard martensite formed. The second was made on a preheated plate. The third plate was heated to a high temperature, usually between 550 and 650 °C (1020 and 1200 °F) after welding. This treatment is a form of "postheating" or postweld heat treatment and may be done both to improve the toughness of the hard martensitic zone and soften the hard martensite to prevent cracking. It will also reduce the residual stresses of welding and may be done for this reason alone. If only the prevention of underbead cracking is desired, a much lower temperature postweld heat treatment may be used. Holding a complete welded joint in the 200 °C (390 °F) range for a number of hours will allow any hydrogen present to diffuse out of the steel before it can induce cracking. For this reason, when welding underbead crack sensitive steels, it is common practice to preheat before welding and maintain the preheat temperature for some hours after welding is complete (up to ten hours for thick welded joints.)

When welding hardenable steels that have already been heat treated to martensite and then tempered, some other special precautions may be necessary. It is not desirable to soften (over temper) the region heated to less than 723 °C (1333 °F) next to the weld, so welding heat inputs should not be too large. Indeed, in some of these steels the heat input used is deliberately designed to produce martensite in the weld heat-affected zone. These steels fall in the low alloy-high strength steel category, and reference should be made to manufacturer-recommended welding procedures when welding these steels.

Steels in this category may also demonstrate heat-affected zone hot cracking (microcracking). This hot cracking is produced by the same mechanisms mentioned for weld metals and precipitation hardening alloys. In steels, high levels of carbon and sulfur promote hot cracking while manganese reduces it. If the manganese-to-sulfur ratio in the steel is 60 or greater, hot cracking is not likely to occur.

BASE METAL

The third component in a welded joint is the base metal to be joined. Most of the common engineering materials available today are readily weldable. However, there are materials that are more difficult to weld successfully if their full service characteristics are to be retained. In selecting a material for a particular use, therefore, one should carefully consider its welding behavior with the available joining methods as well as its performance characteristics. All too often appropriate matching of the joining process and procedure with the material and application are considered so late that the modifications then necessary result in poor economy or performance. The key property of a weldment system from a joining viewpoint is the complex characteristic called weldability.

Weldability

Weldability is the capacity of a metal or combination of metals to be welded under fabrication conditions into a specific, suitably designed structure, and to perform satisfactorily in the intended service. The better the weldability, the easier it is to meet these requirements. Weldability is a complicated property, however, and not easily defined. It encompasses the metallurgical compatibility of a metal (or alloy) with any specific welding process, the ability of the metal to be welded with mechanical soundness, and the serviceability of the resulting welded joints. Metallurgical compatibility implies that the base metals and weld metal can be combined within the degree of dilution encountered in a specific process without the production of deleterious constituents or phases. The mechanical soundness must meet soundness requirements and normal engineering standards. The serviceability factors concern the ability of the finished weldment to meet special requirements such as low temperature impact, high temperature stability, or other designated qualities.

The weldability and metal combinations vary considerably with the welding process used. The heat effects and dilution percentages* vary from essentially zero for ultrasonic and explosion welding to extremely high heat effects and dilution percentages in certain types of submerged arc welding. In resistance welding, the base metal may account for 100 percent of the weld metal. Many dissimilar metal combinations previously considered unweldable may be joined by welding processes with essentially no dilution. Pressure welding, friction welding, ultrasonic welding and low dilution metal arc welding such as GMAW-short circuiting arc (GMAW-S) have increased the combinations of materials that may be successfully joined.

The surface condition, chemistry, and mechanical properties of the base metals have a decided effect on the production of a sound weld. It is obvious that control of the major alloying elements is necessary to meet service requirements. The proper range or level of the major alloying elements is normally guaranteed by the specification to which the base metals are ordered. However, the proportions of these alloying elements may have a profound effect on the weldability. For example, the carbon-silicon and chromium-nickel ratios in austenitic stainless steels strongly affect the hot cracking susceptibility of these alloys.

The major alloying elements are at least defined by ranges, and in some cases by ratios. The residual elements, which may cause extreme difficulty in welding, are not always specified to insure satisfactory weldability. The specific elements and tolerable levels of residuals should be defined for each type of alloy.

Reviewing what has just been said about the weld area, in terms of weldability, the as-received strength of the materials must be known and welding techniques modified to achieve the required and finished temper. The heat of welding performed on cold worked materials will reduce the mechanical properties by relieving stresses or by causing complete recrystallization. Welding techniques on cold worked materials must be designed to minimize heat input. Likewise, quenched and tempered structures must have minimal heat input to retain their properties. Age-hardenable materials with very stable precipitates may be welded in the aged condition if heat input is minimized; but in any aged material, a small solution-annealed area will be present in the heat-affected zone. Materials that age at low temperatures, that are in the age-hardened condition, and that have less stable precipitates will be severely overaged in the heat-affected zone when high heat input is used.

The surface condition of the base metals may adversely affect the production of a sound weld. Moisture on the surface of ferrous materials may add hydrogen to the weld metal and result in both porosity and hydrogen underbead cracking. Moisture in other materials will almost always produce porosity. Other surface contaminants, such as sulfur or lead-bearing materials, may result in hot shortness on a macro or micro scale, by the formation of low melting constituents. The effect of a contaminated base metal surface varies in extent with various alloys. Oxides such as rust and mill scale on ferrous materials may not only prevent adequate fusion, but may also prevent adequate wetting and slagging action. Refractory oxides such as those of titanium or aluminum may melt at considerably higher temperatures than the base metal and, therefore, prevent proper fusion.

Metallurgical Considerations

As previously suggested, many welded joints employ filler metals that do not match the base metal. In all such applications, the metallurgical consequences of mixing these materials must be considered. Certain general rules, based on solubility relationships of the metals under consideration, are applicable.

In general, elements can be mixed in the

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*In a weld bead containing both filler metal *A* and base metal *B*, the percent of base metal *B* in the total weld ($A + B$) is spoken of as the percentage by which the filler metal has been diluted:

$$\% \text{ dilution} = \frac{B}{A + B} \times 100.$$

liquid state and not cause difficulty in the solid state if the mixture will form a solid solution. When the solubility range is large, as in the case of the copper-nickel system (100 percent solubility), the elements can be diluted in large percentages without the formation of unwanted secondary phases. When the solubility limit is grossly exceeded, embrittlement may occur. Supersaturation may also occur because of the sluggishness of solid state reactions, but then precipitation will result when the metal is reheated to an elevated temperature (age hardening). When understood and planned for, this behavior may be used to advantage; but when not expected, the embrittlement of the welded joint will probably be harmful.

In addition to solid solubility, weldability also is affected by the formation of low melting eutectic phases between metals, and by low melting metals and nonmetals. Since these materials freeze at temperatures below that of the matrix, they lead to hot shortness or hot cracking. An extreme example is the effect of sulfur on nickel, producing the nickel/nickel-sulfide eutectic that does not freeze until approximately 540 °C (1000 °F), whereas nickel freezes at approximately 1450 °C (2640 °F).

Certain metal systems demonstrate allotropy; that is, they have the ability to change their crystallographic structure during changes in temperature. Several problems may result from these crystallographic changes, because of abrupt volume changes, drastic solubility changes (especially the solubility of gases), the formation of brittle phases and major changes in mechanical properties. For example, the austenite-to-martensite transformation is responsible for underbead cracking in carbon and low alloy steels.

Certain combinations of elements produce gassing. When, for example, oxygen-bearing copper is subjected to a hydrogen-containing atmosphere, water vapor is formed which ruptures the metal. Gassing may also occur in carbon, carbon-molybdenum, and chromium-molybdenum steels when these metals are subjected to a hot hydrogen containing atmosphere. Carbon in the presence of oxygen may produce carbon monoxide and carbon dioxide, which will cause porosity in metals. Hydrogen and sulfur may produce hydrogen sulfide.

The solubility of gases in molten metal is high, compared with the solubility in the solid state. Oxygen solubility in carbon steel for example, changes from 0.16 percent to much less than 0.01 percent at room temperature. Due to the extreme decrease in solubility, oxygen is expelled from the freezing metal; in many cases, however, it never gets to the surface. Even if oxygen is not present in high amounts in the base metals, it may enter the molten pool during welding. If unable to escape at sufficiently high temperature, the gas will form porosity in the weld metal. Oxygen porosity can be easily controlled by the addition of proper deoxidizing agents. These elements possess high affinity for oxygen, combine with the oxygen and become slagged out of the molten pool. Typical deoxidizers in steel are titanium, aluminum, zirconium, vanadium, and silicon.

Dissimilar Metal Weldability Problems

The combination of metals with different mechanical and physical properties can easily result in weldability problems. Problems may occur when similar base metals are welded with a dissimilar filler metal, or when dissimilar base metals are joined. When the weld metal is much stronger at high temperature than the base metal, high stresses may be set up in the heat-affected zone of the base metal. If plastic flow cannot take place to relieve these stresses, cracking in the heat-affected zone may result. When the mechanical properties of the base metal involve high yield strength paired with low ductility, the base metal may also crack in welding.

Matching the physical properties of the components of a welded joint is also important. When an extreme difference in coefficient of expansion exists between the weld metal and the base metal or metals, thermal gradients in postweld heat treatment or service will cause stressing at the interfaces, which may result in failures. Filler metals should be selected to provide a gradual change from one base metal to the other whenever possible.

The thermal conductivity differences between metals must be recognized when welding dissimilar metal joints. The material with higher thermal conductivity should be preheated, or the welding techniques should be modified to provide more heat input to that metal.

When the melting points between base metals or between base metals and filler metals differ, techniques minimizing shrinkage stresses must be used to prevent hot tensile failures in the base metal with the lower melting point. If the joint is highly restrained, hot tensile failure results from the freezing of the weld metal when the heat-affected zone of the lower melting base metal is in the mushy stage since the mushy heat-affected zone cannot withstand tensile stresses.

Effect of Alloying Elements on Weldability

The elements added intentionally or as residuals determine the metallurgical characteristics of the weld metal and base metal. Alloying elements are added for one or more of the following purposes:

(1) To form interstitial alloys and increase mechanical properties by lattice distortion.

(2) To form substitutional alloys and strengthen the metal by solid solution hardening.

(3) To provide deoxidation of molten metal without loss of primary alloying elements.

(4) To increase or decrease hardenability of the heat-affected zone (metals exhibiting martensitic transformations).

(5) To form age-hardening precipitates.

(6) To form carbides.

(7) To provide nuclei for grain size control.

(8) To minimize segregation.

(9) To raise or lower ductile-to-brittle transformation temperature.

(10) To control amount, distribution, and shape of inclusions.

The only elements capable of forming interstitial alloys are carbon, hydrogen, oxygen, nitrogen, and boron. When these are present as alloying elements, very small amounts result in very great changes in mechanical properties. The effects of carbon and boron on hardenability in steel are a good example of this fact. Complete control of interstitial alloying is necessary for the attainment of sound welded joints. The pickup of carbon from carbonaceous materials, or of boron in gas welding from borate fluxes, may promote cracking in welds.

Substitutional solid solutions are formed when the atomic diameters of the elements in the crystal lattice and the alloying element are within approximately ± 15 percent. As an element is added by substitution, the original crystal lattice is distorted in linear relation to the amount of alloying element added. The hardness and strength are increased in linear fashion. When alloying takes place in the weld metal or base metal and remains within the limits of the substitutional solid solution, few welding problems result. When solid solubility is exceeded, secondary phases, intermetallics, or complete rejection of one of the elements occurs. Many special metallurgical characteristics depend on exceeding solubility limits, but whatever reaction occurs, it usually increases difficulties in achieving weldability. The corrosion resistance of almost all materials decreases when secondary phases or intermetallics are formed. Cracking may occur when large amounts of elements are rejected, such as copper or lead in steel.

Gassing on a major or minor scale due to the decrease in oxygen solubility, and the combination of oxygen with other elements such as carbon, must be considered in the manufacture of base metals. The solubility of metals for oxygen and other gases decreases rapidly with temperature, and porosity results when the molecular gas is trapped in the metal. Alloying agents such as titanium, aluminum, zirconium, vanadium, and silicon all have greater affinity for oxygen than iron and, therefore, may act as deoxidizers in carbon and low alloy steels. Other alloy systems utilize other deoxidizing agents; for example, aluminum, zinc, silicon, zirconium, and phosphorus are used in copper alloys. All fusion welds require deoxidizing agents, unless the welds are made in a vacuum or under a special atmosphere. Even gas metal arc and gas tungsten arc welds using inert gases require deoxidizers to prevent gassing from the atmosphere. The greater the amount of metal melted, the greater the need for deoxidizers. When welding thin sections of metal by the GTAW process, the addition of filler metal is often required only to provide adequate deoxidation of the metal.

Alloying elements in steel may be added to increase the hardenability. This is accomplished by reducing the critical cooling rate and the temperature of the austenite-to-martensite transformation. The elements having the greatest effect on the hardenability of steel are carbon, manganese, molybdenum, chromium, vanadium, nickel, and silicon. The effect of these elements on controlling the tendency to form heat-affected zone martensite, and thus cold cracking, is expressed in many formulas, called carbon equivalent (CE) formulas. A common one is:

$$CE = \%\,C + \frac{\%\,Mn}{4} + \frac{\%\,Ni}{20} + \frac{\%\,Cr}{10} + \frac{\%\,Cu}{40} - \frac{\%\,Mo}{50} - \frac{\%\,V}{10}$$

The hardenability of weld metal and base metal in carbon and low alloy steels affects the weldability in two ways. The chances for hydrogen underbead cracking increase with increased hardenability, and the depth at which hard brittle martensite is formed increases. When CE by the above formula exceeds 40, underbead cracking can occur. Cracking is also influenced by welding preheat and other factors, however.

Two other methods of increasing hardness are the formation of age-hardening precipitates and the formation of carbides. It is rare when spontaneous aging, caused by multipass welding, can result in appreciable hardening and attendant decrease in weldability. In most materials that will age with short times at temperature, the major problem is softening due to overaging.

Most age hardening reactions have little effect on weldability, since the normal percentages encountered in standard nonage hardening materials will not cause significant precipitation. When unusual combinations are joined, the age hardening reactions must be considered.

Nonmetallics are normally to be avoided, but not in the case of carbides. Chromium, molybdenum, tungsten, titanium, and columbium* carbides may be required to produce needed high temperature properties. In any case, when a carbide is formed, the matrix is depleted of both carbon and the carbide-forming element. This depletion is innocuous for almost all carbides except chromium carbide. When this is formed in stainless steels, the matrix in the grain broundary area is depleted of as much as 70 percent chromium which may lead to intergranular corrosion in the weld heat-affected zone.

Grain refiners are added to metals to provide nuclei for the formation of many small grains, and thereby to minimize poor properties due to coarse-grained structures. Basically speaking, all grain refiners provide high melting intermetallics or nonmetallics (oxides, carbides, etc.) that form in the molten metal, and nucleate grain growth. Aluminum, vanadium, titanium, zirconium, and nitrogen act as grain refiners in carbon and low alloy steels; zirconium and titanium are used in aluminum alloys; iron, aluminum, and titanium are used in copper alloys. Most good deoxidizers also act as grain refiners when fine oxides are not floated out of the metal. Grain refiners are important to weldability since decreased columnar grain size always improves the ductility and minimizes hot short cracking by better distribution of low melting constituents.

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*Element 41, which was named columbium by its discoverer in 1801, has been renamed niobium. In order to prevent misunderstanding among those who have become familiar with the name columbium, the American Welding Society, together with other American societies concerned with the manufacture, use, or fabrication of metals, will continue to refer to this element as columbium.

Effect of Process and Process Variables

Temperature distribution and cooling rates are discussed in Chapter 3, p. 79. The effects of heat input, including preheat, and the type of welding process utilized, normally control the cooling rate of the molten pool and heat-affected zone. In metals exhibiting high hardenability, slow cooling rates are encouraged to minimize heat-affected zone cracking. In other alloys exhibiting solid state phase transformation, slow cooling may also be beneficial. In most face centered cubic materials, however, slow cooling is detrimental. All grain boundary problems are aggravated by the formation of coarse grains since the available grain boundary surface decreases in relation to volume. In metals that age harden, slow cooling may age greater areas in the heat-affected zone. High heat input and slower cooling always increase the amount of dilution, which may, as previously indicated, be detrimental.

Preheat, which is a method of producing slow cooling, is desirable in carbon and low alloy steels because it minimizes the hardness of the heat-affected zone, lowers shrinkage stresses, allows more hydrogen to diffuse out of the weld and minimizes very thin martensitic zones.

The heat pattern or distribution may be a function of many variables, such as polarity, shielding gas, arc length, electrode manipulation (whether automatic or manual) and thermal conductivity of the base metal. The pattern of heat input and its intensity determine the shape of the molten pool and weld metal. Weldability may be drastically changed when the weld metal and the dilution pattern are altered.

The selection of the best welding techniques and sequences requires application of all the factors that have just been discussed affecting weldability. Special techniques for welding are only required when special problems are present. These may occur when the base metal is not chemically satisfactory, when the physical or metallurgical properties of the base metals, the filler metals or both are decidedly different, or when residual stresses are extremely high. Distortion, weld metal, and base metal cracking, and porosity may be eliminated or reduced by appropriate modification of the welding technique and sequence.

SUMMARY

The production of a sound welded joint requires a thorough understanding of all of the metallurgical factors that are involved. From the control of the chemical composition and heat treatment of the base metal, through the selection of the proper process and procedure, to the utilization of the proper filler metal, the welder and welding engineer must combine the elements of the welded joint requirement with the available materials to produce a satisfactory joint. The number of principles to be considered is extensive and may seem formidable to some, but properly understood, they also permit a great deal of flexibility in the selection of alternate approaches to the same weldability problem. Thus, when a welded joint cannot be successfully produced by one means, a second, perhaps more fruitful method may be tried. The large number of approaches is well illustrated by the problems and solutions suggested in Table 4.4. In this table, a variety of typical welding problems involving a broad range of materials is listed. In each case, a suggested solution, based on both metallurgical principles and experience, is presented. This table is not to suggest, however, that all weldability problems can be solved with current technology, but it does point out that many weldability problems can be and have been solved by careful consideration of the metallurgical factors related to joining.

WELDABILITY TESTING

The term weldability, defined on p. 137, is so all-inclusive that it is sensitive to all the significant parameters encountered in fabrication and service. No single test or combination of tests can accurately predict the performance of most structures because the variables of restraint, fit-up, surface condition, service stresses, etc. are generally impossible to forecast and therefore to duplicate.

Even with these limitations, weldability testing can provide useful clues as to the precautions such as appropriate process selection, preheat, energy input, joint design, and so forth which may be required for a reasonable degree of confidence in the resulting welded joint.

Numerous weldability tests have been devised, all of which can be classified as either (1) theoretical, (2) simulated, or (3) actual welding. These categories are described in the following paragraphs.

THEORETICAL TESTS

An example of the theoretical weldability test is the Jominy Hardness-Bend Ductility System devised in 1943. This system predicts the heat-affected zone cooling rate of a given weld from experimentally based tables that relate cooling rate to heat input, plate thickness, and preheat.

A series of notched bend specimens are austenitized at 1150 °C (2100 °F) and cooled at the calculated rates to duplicate the expected hardness of the heat-affected zone. If the specimens can be bent through 10-20 degrees, they are considered sufficiently ductile for most applications.

Another theoretical approach for steel consists of predicting heat-affected zone hardness from the composition of a steel. In this case, a modified carbon equivalent formula is combined with a heat flow equation applicable to the given weld. The following "rule of thumb" exemplifies this type of approach: If the calculated heat-affected zone hardness is below VHN 300, hydrogen cracking is very unlikely, while predicted hardnesses above VHN 400 indicate high susceptibility to cracking.

Obviously, the theoretical approaches do not take the effects of weld metal into account and since cellulosic weld electrodes have a much greater tendency to cause heat-affected zone cracking than low hydrogen electrodes, the ten degree bend criterion may not be applicable in many cases. The VHN 300 limit is generally conservative. Also, the effect of preheat may not be correctly rated by these methods. It has been shown that preheating to 100-150 °C (210-300 °F) does little to affect the cooling rate in the transformation range (that is, the heat-affected zone hardness is not affected); however, the hydrogen-induced cracking tendency decreases greatly. Thus calculated weldability formulas may not take into account all of the welding variables involved.

SIMULATED TESTS

To simulate the heat effect of welding, and thus create a synthetic weldability test, two general types of apparatus are available: (1) a unit which heats and cools a metal specimen over a thermal cycle exactly like that found in a particular weld, and (2) a unit which not only heats and cools the specimen over the weld thermal cycle, but which also can apply a controlled tension load to the specimen at any time during the cycle.

Table 4.4 — Typical welding problems

Cause	Remedies
Cracking — Weld Metal	
High rigidity of joint	Reduce cooling rate (preheat); mechanically relieve residual stresses (peening); minimize shrinkage stresses (backstepping block sequence). Increase strength of weld metal or build up greater cross section of weld beads.
Excessive alloy pickup from base metal	Change current level and rate of travel; weld with straight polarity if possible (emissive coating on wires and electrodes); overlay base metal at low amperages prior to welding joint.
Defective electrodes (moisture, eccentricity, poor striking ends, poor core wire)	Change electrode; grind striking ends to proper dimensions; bake electrodes (low hydrogen).
Poor fit-up	Reduce root gap; clad edges; weld with poor fit-up technique.
Small bead	Increase cross-sectional area of weld, use larger electrode.
High sulfur in base metal (carbon and low alloy steels)	Use process with high level of sulfur-fixing elements (basic slag from EXX15, 16, 18).
Angular distortion (weld root in tension)	Change to balanced welding on both sides; consider peening; preheat.
Unsound welds	See Porosity and Inclusions, below.
Crater cracks	Fill in crater prior to withdrawing electrodes; use tapering device for gas tungsten arc.
Cracking — Base Metal	
Hydrogen in welding atmosphere (underbead cracking — ferrous metals, H_2O embrittlement — oxygen-bearing coppers)	Use hydrogen-free process (GMAW, GTAW, etc.; low-hydrogen electrodes; SAW); high preheats, postweld aging or anneal.
Hot short cracking of base metal (copper alloys)	Low heat input, high speed welding, thin beads, change material.
High strength with low ductility	Use annealed or stress-relieved material.
Hot tensile cracking of base metal in heat-affected zone (copper alloys)	Weld with electrode matching melting point of base metal
Excessive stresses	Redesign; change welding sequence (cladding or buttering technique); use intermediate stress relief.
High hardenability (steel)	Preheat; increase welding conditions to slow-cool weld beads; postheat prior to cooling from interpass temperature; weld with austenitic electrode.
Brittle phases	Solution heat treat prior to welding.
High lead content	Change material; weld with minimum heat input.
Porosity	
Excessive hydrogen, oxygen, nitrogen in welding atmosphere	Use low hydrogen process (GMAW, GTAW, SAW); use filler with high deoxidizers.
High rate of weld freezing	Preheat; increase heat input; use lower melting filler.
Oil, paint or rust on base metal	Clean joint surfaces.
Dirty surface on GMAW electrode	Use specially cleaned wire.
Improper arc length, current, or manipulation	Obtain better control of welding parameters.
Zinc volatilization in copper	Use ECuSi electrodes; reduce heat input.

Table 4.4, continued — Typical welding problems

Cause	Remedies
	Porosity
Galvanized coatings on steel	Use E6010 electrode with manipulation to volatilize zinc ahead of molten pool.
Excessive moisture in electrode or joint	Use dry materials.
High sulfur base metal	Use electrode with basic slagging reactions.
	Inclusions
Failure to remove slag from previous deposit	Clean surfaces and previous beads.
Entrapment of refractory oxides	Power wire brush previous bead.
Tungsten in weld metal	Use high frequency to initiate arc; improve manipulation.
Improper joint design	Increase included angle of joint.
Oxide inclusions (GMAW, GTAW)	Provide proper shielding and coverage.

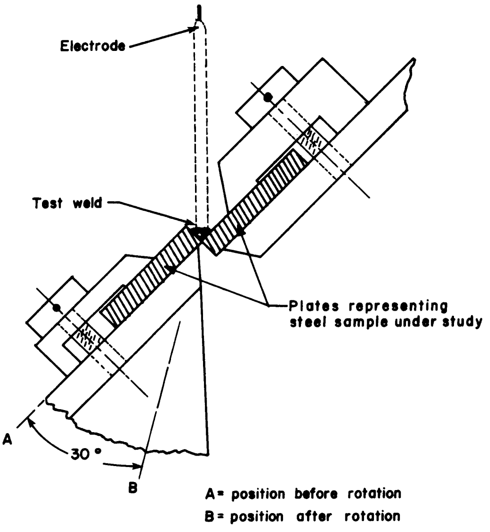

Fig. 4.24 — The Murex test showing basic outline.

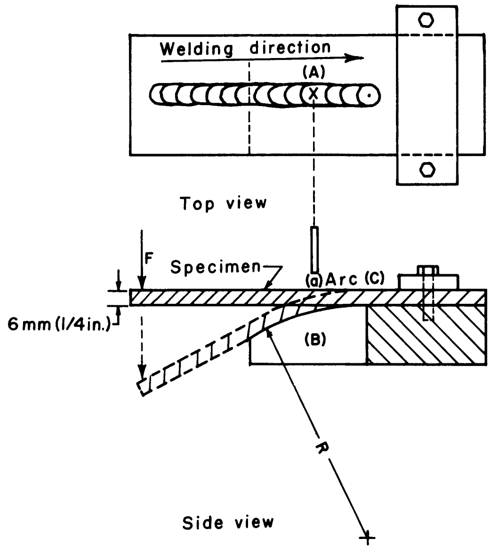

Fig. 4.25 — The Varestraint test showing basic outline.

While these tests provide very useful information regarding the mechanical properties of various areas within the heat-affected zone, during as well as after the weld cycle, they cannot account for residual and reaction stresses, hydrogen pickup, and other conditions which may be imposed on production welds.

ACTUAL WELDING TESTS

An extensive variety of actual welding tests have been devised to measure the weldability characteristics of steel. In general, these tests serve one or both of two purposes. First they are used to calibrate the weldability

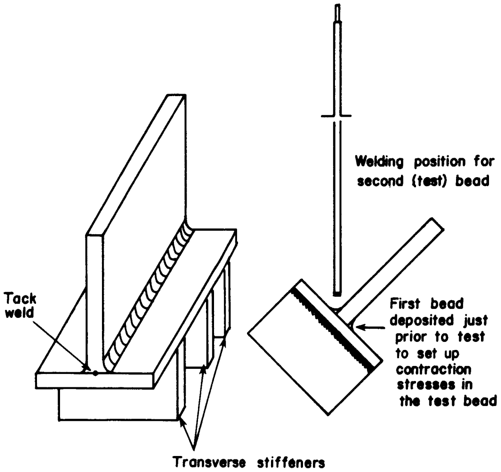

Fig. 4.26 — The T-joint test showing basic outline.

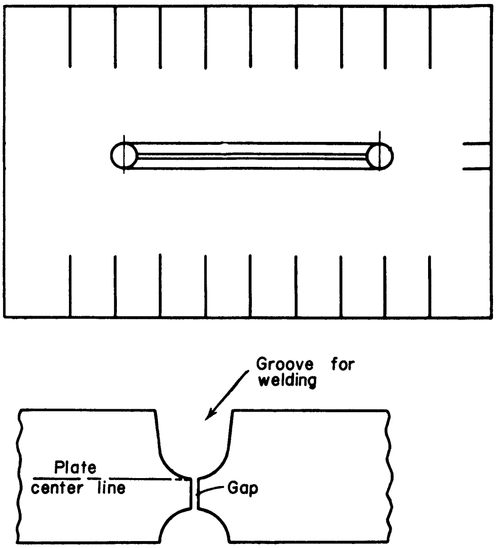

Fig. 4.27 — The Lehigh test showing basic outline.

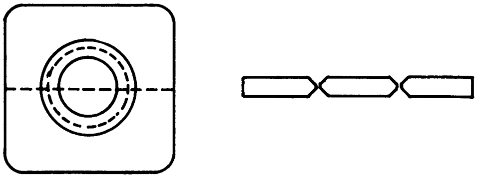

Fig. 4.28 — The circular-patch test showing basic outline.

of particular grades or individual heats of steel. For this purpose the specimen dimensions and welding conditions are prescribed and fixed to make the steel sample the only variable. Second they are used to establish a compatible combination of steel, filler metal, and welding conditions that will produce welded joints satisfactory for the application. In effect these tests fall into two groups: those used to assess fabrication weldability and those used to measure service weldability. The fabrication tests evaluate whether a particular material and process can be used to produce a joint acceptably free of defects. The service tests measure whether the properties of the welded joint are satisfactory for service.

Fabrication Weldability Tests

The tests in this category determine the susceptibility of the welded joint to cracking and can be grouped according to the type of cracking that they produce.

(1) *Hot-Cracking Tests*

(a) *The Murex test* (Fig. 4.24) is conducted on two plates which are welded while mounted in a fixture that provides a means of rotating the plates with respect to each other at various speeds. Susceptibility to hot cracking is indicated by the extent to which the weld metal cracks at various rates of strain during solidification.

(b) *The Varestraint test* (Fig. 4.25) also utilizes external loading to impose plastic deformation in a plate while a weld bead is being deposited on the long axis of the plate. By the choice of the radius to which the plate is bent, the severity of deformation causing cracking can be determined.

(c) *The T-joint test* (Fig. 4.26) uses a restrained T-configuration to measure the hot cracking tendency in a fillet weld. The second bead is deposited immediately following the first bead on the other side so that the rotation strains generated by the contraction of the first bead are imposed on the second bead during deposition.

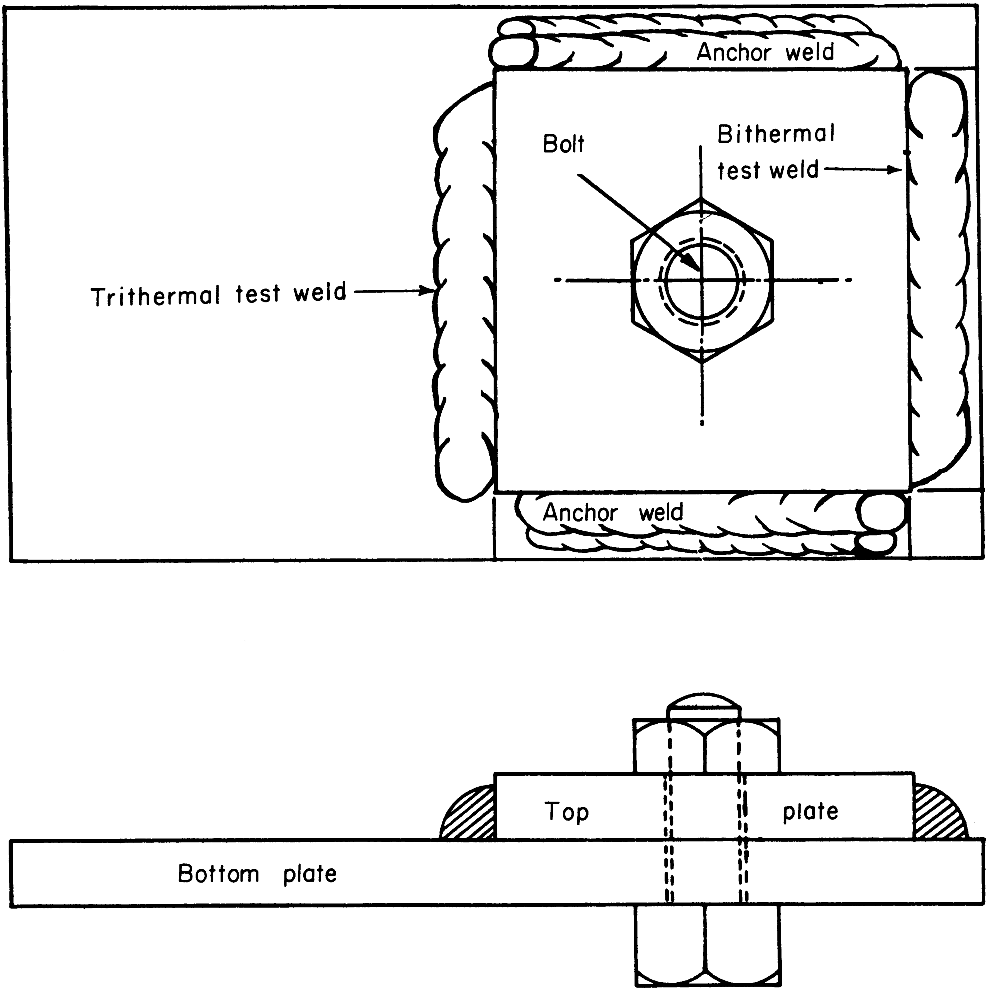

Fig. 4.29 — The controlled-thermal-severity test showing basic outline.

(2) *Root-Cracking Tests*

(a) *The Lehigh restraint test* (Fig. 4.27) provides a means of imposing a controllable severity of restraint on the root bead deposited in a butt weld groove with dimensions to suit the application. By testing a series of plates in which the weakening side-slits are varied in depth, a critical restraint for cracking can be determined for the chosen welding conditions. This specimen is equally useful for hydrogen-induced cracking studies.

(b) *The circular-patch test* (Fig. 4.28) comprises a plate with a circular hole cut into it and a patch fitted to create a circular weld groove. When a weld bead is deposited, the circular configuration magnifies the stresses placed on the weld metal because of thermal contraction. Restraint can be varied in a given plate thickness by adjusting the plate size and patch diameter.

(3) *Hydrogen-Induced Cracking Tests*

(a) *The Lehigh restraint test* (Fig. 4.27)

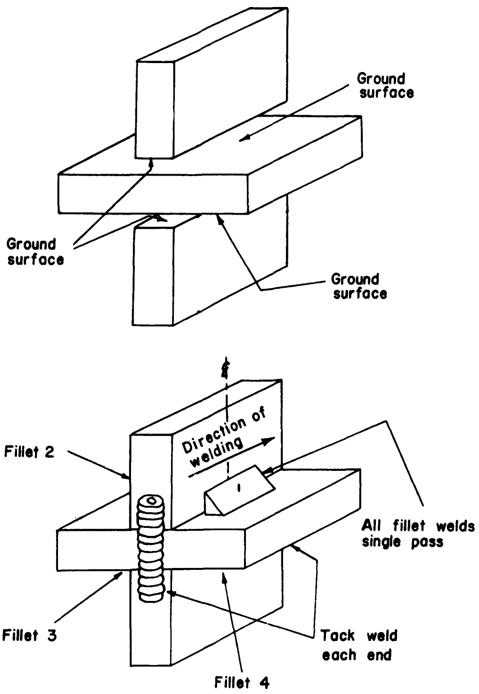

Fig. 4.30—The cruciform cracking test showing basic outline.

described previously is capable of indicating quantitatively the susceptibility of weld metal or base metal to hydrogen-induced cracking, including delayed cracking.

(b) *The controlled-thermal-severity test* (Fig. 4.29) consists of a plate bolted and anchor-welded to a second plate in a position to provide two fillet (lap) welds. The fillet located at the plate edges has two paths of heat flow. The lap weld located near the middle of the bottom plate has three paths of heat flow, thus inducing faster cooling. Further control of the cooling rate is possible by varying the plate thicknesses.

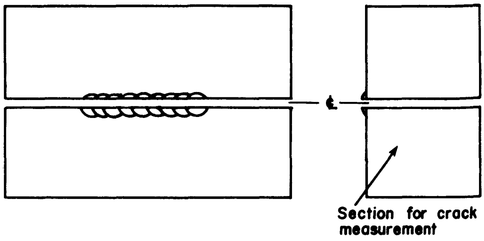

Fig. 4.31 — The longitudinal-bead-weld cracking test showing basic outline.

(c) *The cruciform cracking test* (Fig. 4.30) comprises three plates with ground surfaces tack welded at the ends to form a double T-joint. Four test fillet welds are deposited in succession in the order shown, with complete cooling between deposits. Cracking, detected by cross-sectioning, is most likely to occur in the third bead. Careful fit-up of the plates is necessary to obtain reproducibility.

(d) *The longitudinal-bead-weld cracking test* (Fig. 4.31) uses a bead-on-plate weld deposited on a small plate partly immersed in water. The electrode specified is E6010 to provide a high potential of hydrogen in the arc atmosphere. Cracking is measured on a ground center line section of the weld obtained after the specimen has been aged 24 hours and thermally stress-relieved to avoid possible grinding cracks.

Service Weldability Tests

This class of tests is designed to measure mechanical properties that are considered vital to the satisfactory performance of the welded joint in service. These tests are discussed in Chapter 5.

BRAZING AND SOLDERING METALLURGY

Unlike welding, brazing and soldering are performed at temperatures below the solidus of the base materials.* Metallurgical considerations that affect these processes range from liquid metal properties and solidification to base metal surface interactions and the physical and environmental conditions under which the joints are made.

Brazing and soldering have several advantages over welding. For one thing, they minimize the degradation of the base materials since melting is not involved and peak temperatures are controllable. In addition, they reduce oxidation, minimize residual stresses and distortion, and make possible a more cosmetic joint appearance. Finally, brazing and soldering lend themselves to high speed automation.

However, several disadvantages can be anticipated from brazing and soldering. Brazed and soldered joints cannot easily be tested nondestructively. There is also the problem of brittle intermetallic compounds forming in specific materials systems (such as during the soft soldering of steel). Depending upon the complexity of the components, jigs and fixtures may have to be designed and utilized, and costly precision fitting joints are generally required.

Brazing filler metals have a liquidus above and soldering filler metals a liquidus below 450 °C (840 °F). In both processes, the filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction. In braze welding, a fillet is used to join the components being brazed and the filler metal is *not* distributed in the joint by capillary attraction.

The capillary flow of the liquid metal into the joint generally depends upon its surface tension, wetting characteristics, and physical and metallurgical reactions with the base material and oxides involved. The flow is also related to the generation of hydrostatic pressure within the joint. Figure 4.32 is an idealized presentation of the wetting concept. A contact angle of less than 90 degrees measured between the solid and liquid usually identifies a positive wetting characteristic. Contact angles greater than 90 degrees are usually an indication of no wetting.

In some brazing and soldering processes, wetting and spreading are assisted by the addition of flux. In vacuum brazing, however, flow and wetting are dependent upon the surface interactions between the liquid metal and base metals themselves. Fuel gases, hydrogen, and vacuum systems provide the most common types of controlled atmospheres.

Fluxes perform functions similar to controlled atmospheres in providing surfaces receptive to wetting and spreading. Most oxides are readily displaced or removed by flux. Oxides of chromium, aluminum, titanium, and manganese are more difficult and may require special treatments.

A brazing or soldering cycle generally consists of heating to, residing at, and cooling from a peak temperature. During the time at peak temperature when liquid filler metal is present in the joint, metallurgical reaction can occur with the base metal. This reaction is generally referred to as erosion or dissolution. The rate of dissolution of the base metal by the filler metal depends on the solubility limits of the filler and base material, the quantity of brazing filler metal available to the joint, the brazing cycle, and the potential formation of lower temperature eutectics.

In some important metallurgical systems,

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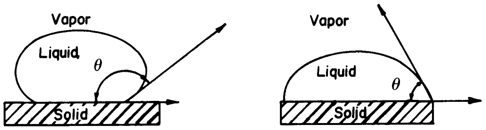
*Brazing and soldering are discussed in Chapter 1, pp. 23 and 25 respectively.



a. Contact angle greater than 90° - no wetting

b. Contact angle less than 90° - wetting

Fig. 4.32 — Wetting angles of filler metals used in brazing and soldering.

an interlayer of intermetallic compound forms between the filler metal and the base metal during the joining operation. The degree of intermetallic growth and the type of phases present can substantially alter the joint properties. Phase diagrams may be used to predict intermetallic compound formation.

Once the filler metal has solidified to form the joint, subsequent effects are controlled by diffusion phenomena within the joint. For example, it is possible through high temperature aging of a soldered joint to convert the filler metal to an intermetallic compound. When titanium, for example, is joined with a pure tin filler metal, it is possible by subsequent aging or heat treatment to completely diffuse the tin into the base metal so that a joint effectively no longer exists. This method of metallurgical joining has been defined as liquid-activated diffusion bonding, but actually, it is an extension of the joining mechanism in brazing and soldering.

Impurities and contaminants are important factors to be considered with these processes. The limitations on residual elements should be stated explicitly in the filler metal specifications to insure consistent melting and joint flow characteristics. Contaminants caused by mishandling materials or as a result of preparation for joining can affect the formation of the joint and the joint properties. For example, residual sulfur compounds can cause poor flow or result in hot cracking in certain brazed or soldered joints.

The properties of the resulting joints are dependent upon successful metallurgical bonding at the interfaces and on the final composition of the filler metal within the joint area. Most joints of this type are overdesigned to insure failure in the base material. However, the metallurgical properties of the joint can be important when high temperature service or exposure to corrosive media is to be expected.

Strength measurements are made in shear, in tension using a peel method, or by hardness traverses across the joint area. Dynamic properties of joints are measured in creep, fatigue, and under stress corrosion conditions. Consideration must be given to all these factors when selecting a more suitable brazing or soldering filler metal. Extreme care is necessary in the interpretation of mechanical properties of joints made with filler metals that melt below the base material. Results may or may not reflect the actual joint depending on the joint design selected and the method of testing.

Liquid filler metal penetration between the grain boundaries of the base metal has previously been recognized within joints. If excessive, this penetration can lead to embrittlement problems. Base materials in a stressed state are particularly susceptible to liquid metal penetration. For example, where copper-based filler metals are used on high iron-nickel alloys under stress, rapid failure can result. Since the diffusion rate of alloying elements, especially those forming interstitial solid solutions, is greater between the grains rather than inside the grains where slight solubility exists, grain boundary penetration (and cracking) will be greater. If a eutectic is formed to fill the crack or boundary as it separates, then little damage is done and this is known as an intrusion. Where high solubility exists, intergranular attack generally is not so intense. When rapid failure of a joint or adjacent material occurs during the manufacturing operation, the boundary penetration phenomena should be suspected.

The dynamic characteristics of the brazing and soldering processes are receiving increasing recognition, and careful consideration is being given to the subsequent diffusion and metallurgical changes that can occur in service. At elevated temperatures, intermetallic compounds still grow in the solid state as a direct result of diffusion. This means that the metallurgical and mechanical properties of these joints can change during service. The soldered joints in electrical generating machinery exposed to elevated temperatures for as long as 30 years are one example of such a change. Preferential attack of particular phases by corrosive media must also be taken into account. Precise knowledge of the behavior of joints at high temperatures as influenced by service conditions is mandatory if the application is to be successful. Galvanic effects are more likely where a widely differentiated dissimilar metal is used or where the brazing or soldering filler metal solidifies with large discrete heterogeneous phases which behave in an anodic manner. The complexity of the metallurgy involved should not be a deterrent to the use of these processes, however. Their excellent utility in service has been proven.

SUPPLEMENTARY READING LIST

Baker, R.G. 1969. Metallurgical research and welding practice. *Welding Journal* 48 (7): 323s-331s.

Benton, W.P., Jr. 1974. Weldability of low alloy steels for line pipe fittings. *Welding Journal* 53 (8): 361s-367s.

Berardi, M.P., Zotos, J., and Weiss, S. 1970. Metallurgical characteristics of pulsed, high pressure weldments. *Welding Journal* 49 (6): 258s-292s.

Brazing Manual. 2d ed. Miami: American Welding Society, 1963.

Bruckner, W.H. *Metallurgy of Welding.* New York: Pitman Publishing Company, 1954.

Doty, W.D. 1971. Weldability of constructional steels, USA viewpoint. *Welding Journal* 50 (2): 49s-57s.

Flinn, R.A. and Trojan, P.K. *Engineering Materials and their Applications.* Atlanta: Houghton-Mifflin, 1975.

Grosvener, A.W., ed. *Basic Metallurgy.* Metals Park, Ohio: American Society for Metals, 1954.

Guy, A.G. *Elements of Physical Metallurgy.* 2d ed. Reading, Massachusetts: Addison-Weseley, 1960.

Introductory Welding Metallurgy. Miami: American Welding Society, 1968.

Kammer, P.A., Monroe, R.E., and Martin, D.C. 1972. Weldability of tantalum alloys. *Welding Journal* 51 (6): 304s-320s.

Linnert, G.E. *Welding Metallurgy,* 2 vols. 3d ed. Miami: American Welding Society, 1965-1967.

Metals Handbook, vols. 1, 7, 8, and 9. 8th ed. Metals Park, Ohio: American Society for Metals, 1961-1974.

Nippes, E.F. 1959. The weld heat-affected zone. *Welding Journal* 38 (1): 1s-18s.

Oates, R.P. and Stout, R.D. 1973. A quantitative weldability test for susceptibility to lamellar tearing. *Welding Journal* 52 (11): 481s-491s.

Savage, W.F. and Adams, Comfort A. April, 1967. Solidification, segregation, and weld defects. Lecture at American Welding Society Annual Meeting, Detroit, Michigan.

Stout, R.D. and Doty, W.D. *Weldability of Steels,* ed. Epstein, S. and Somers, R.E. 2d ed. New York: Welding Research Council, 1971.

Structural Welding Code, AWS D1.1 (latest edition, as revised). Miami: American Welding Society.

Soldering Manual. Miami: American Welding Society, 1959.

Udin, H., Funk, E.R., and Wulff, J. *Welding for Engineers.* New York: John Wiley and Sons, 1954.

Welding Handbook, Sect. 4. 6th ed. Miami: American Welding Society, 1972.

Van Vlack, L.H. *Elements of Material Science and Engineering.* Reading, Massachusetts: Addison-Wesley, 1975.

5

Testing for Evaluation of Welded Joints

Prepared by a committee consisting of:

R. J. CHRISTOFFEL, *Chairman*
General Electric Company
J. W. FISHER
Lehigh University
M. HENTHORNE
Carpenter Technology Corporation
R. P. HURLEBAUS
The Budd Company
F. J. LOSS
Naval Research Laboratory
C. F. MEITZNER
Bethlehem Steel Corp.
B. R. SOMERS
General Electric Company

5

Testing for Evaluation of Welded Joints

INTRODUCTION

All types of welded structures, from bridges and jet engines to metal trash cans, are expected to serve some function. Likewise the welded joints comprising these structures or components are expected to possess certain service-related capabilities or properties. To assure that their intended function is fulfilled, a test of some type is usually performed. The ideal test, of course, is the observance of the structure in actual service. Generally, however, such observance is not possible because of the obvious cost and time factors. It is therefore necessary to utilize a test structure or specimen and a test method which may not resemble the actual welding situation, but which must be related to it and the expected performance of the structure involved.

This chapter is devoted to the testing methods which can be used to examine and evaluate the expected performance of welded joints.* For each method, the chapter describes the phenomenon being tested, the test methods which may be used, and finally how the results may be applied with special consideration of their relationship to welded joints.

The problem of predicting the performance of structures from a "laboratory" type test is a complex one, since the size, configuration, environment, and type loading are rarely identical. In welded joints, the complexity is further increased by the nature of the joint which is far from homogeneous, metallurgically or chemically. In addition to the base metal, the welded joint consists of weld metal and a heat-affected zone. The latter regions, besides differing from the base metal, are themselves composed of a multitude of metallurgical structures as well as chemical heterogeneities. A variety of properties are thus to be expected throughout the welded joint. Any test, then, will measure either the properties of some discrete portion of the joint or some composite average of all or a portion of the joint. When testing a welded joint, the investigator not only has the problem of relating the test to the service of the actual structure, but also of determining whether the true properties are measured by the limited region tested. The reader therefore should use care in the interpretation and application of any test results.

When selecting a test method, the function to be performed by that test must be considered and balanced against its time and cost.

Note: The SI (metric) and U.S. customary values given in this chapter are not, in most cases, exact equivalents. The SI values are the primary measurements used in this and all Volume 1 chapters. The secondary U.S. measurements (given parenthetically in text) are rounded off conversions from the SI values. For a further explanation of the system of measurements used in Volume 1, refer to the Foreword on p. xi.

*The reader should note that weld cracking tests are not covered in this chapter. They are covered in Chapter 4, however, under the general heading of "Weldability Testing" (see pp. 143-148).

Both the tension and hardness tests, for example, provide a measure of strength, yet the hardness test is the simpler and less costly of the two. The hardness test would be totally inadequate if the purpose is to establish the strength of a welded joint. On the other hand, it should be perfectly satisfactory as an in-process control test to assure, for example, that the proper heat treatment is performed. Thus the reader should recognize that each test has its range of applicability which is neither all-encompassing nor completely insignificant.

TENSILE PROPERTIES—STRENGTH AND DUCTILITY

Tension and bend tests are frequently used to evaluate the breaking strength and ductility of a material and to determine that the material meets applicable specification requirements. Welding results in metallurgical (and often compositional) differences in the welded joint, and it is important to know the effects of these changes on, mechanical properties. Therefore, tension and bend tests are frequently made which may indicate the suitability of the welded joint for service and are often used to qualify welding procedures or welders according to specific code requirements. The following sections will discuss the use of tension and bend tests, particularly as applied to welded joints.

TENSION TESTS

Base Metal Tension Test

Longitudinal or Transverse Test. The basic data on the strength and ductility of materials are generally obtained from an engineering tension test in which a machined specimen is subjected to an increasing uniaxial load while simultaneous observations of linear extension are made. Specimens oriented parallel to the direction of rolling are designated longitudinal; those oriented at 90 degrees to the rolling, transverse. The test results are plotted in the form of a stress-strain curve (see Fig. 5.1) in which the nominal stress is calculated by dividing the load by the original specimen area, and the nominal strain is calculated by dividing the elongation of the specimen gage length by its original gage length. This approach contrasts with that of using the instantaneous (rather than initial) values of cross-sectional area and gage length to determine stress and strain. If instantaneous values are used, the result is called a true stress-true strain curve. However, the true stress-true strain curve is more difficult to obtain than the engineering stress-strain curve and therefore is used only when an accurate representation of the basic plastic flow characteristics of the material are required. In testing welded joints, the engineering approach is used almost exclusively.

The yield strength from the engineering stress-strain curve is generally measured at some arbitrary amount of extension under load or permanent plastic strain (offset) or, for certain steels that exhibit such a phenomenon, at the point (called the yield point) at which plastic extension occurs with no increase in load. The ultimate tensile strength is calculated by dividing the maximum load in the engineering curve by the original specimen area. Typical stress-strain curves for various constructional steels are shown in Fig. 5.2.

Two standard measurements of ductility are derived from the engineering tension test—the percent elongation and the percent reduction of area. The percent elongation is the ratio of the increase in gage length to its original gage length. Because a measurement of percent elongation includes both the uniform strain and the local or necking strain, this ductility value is affected by the choice of original gage length. Therefore, valid comparisons of percent elongations can be made only for identical gage lengths. The percent reduction of area is the ratio of the decrease in cross-sectional area after fracture to the original cross-sectional area.

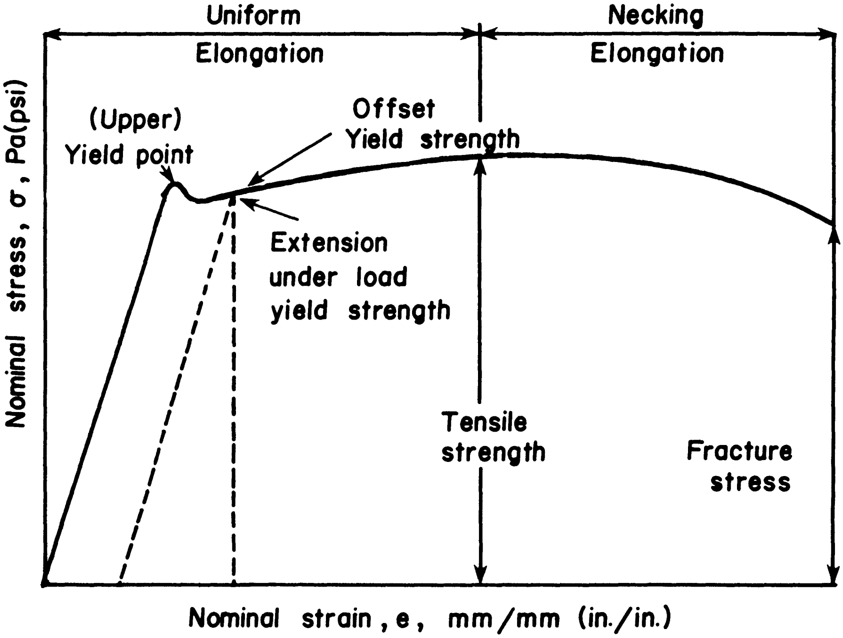


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Fig. 5.1—Engineering stress-strain curve.

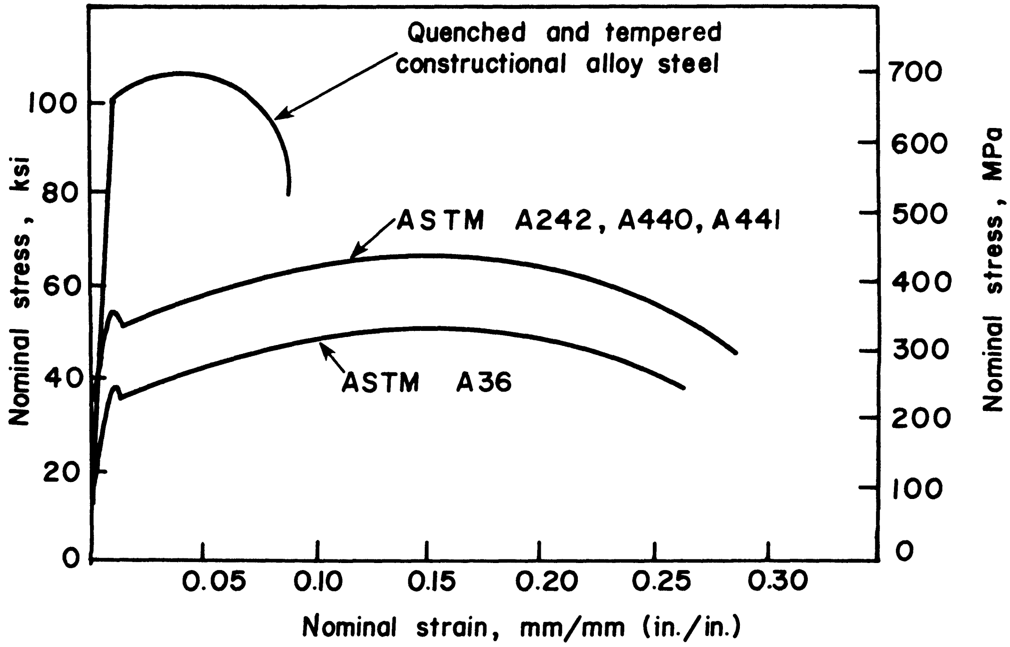

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Fig. 5.2—Nominal stress-nominal strain curves for various constructional steels.

The details of specimen preparation and test procedures for smooth tension tests are described in Standard Methods for Mechanical Testing of Welds, AWS B4.0 and Standard Methods of Tension Testing of Metallic Materials, ASTM E8 (latest editions). Further details on specific specimens or test requirements for welded joints should be obtained from the applicable codes or specifications such as the Structural Welding Code, AWS D1.1, or the ASME Boiler and Pressure Vessel Code, Section IX.

Through-Thickness (Short Transverse) Test. It is well-known that rolled plate and sheet products, both ferrous and nonferrous, are frequently anisotropic in nature; that is, their properties may vary in different orientations with regard to the rolling direction. Test specimens are normally machined in the plane of rolling, either longitudinal or transverse to the final direction of rolling, since properties in these orientations are usually relevant to service applications. There is frequently little difference in tensile properties between longitudinal and transverse tests, although the transverse test may show slightly lower ductility. Test results from specimens taken in the "through-thickness" direction (perpendicular to the plane of rolling) exhibit considerably more scatter than the conventional longitudinal or transverse tests, and the properties in the through-thickness (short transverse) direction are highly dependent on material and rolling history. In many engineering materials, through-thickness tensile strengths may be slightly lower than those of conventional tests while tensile strength and ductility, as indicated by elongation or reduction in area, may be much lower.

Because of these different properties in the thickness direction, tension tests have been employed to determine the suitability of material for use when welded joint details cause high tensile stresses to be applied normal to the surfaces of these products. These tests generally take one of two forms. If the rolled product is thick enough, small tensile bars may be made with their axes in the thickness direction. This method provides test data on the strength and ductility of the material in this orientation, at least for that portion of the thickness within the gage section of the specimen. For thinner materials or when it is desirable to test a greater percentage of the material thickness, tabs or round bars may be welded onto either side of the specimen surfaces to provide additional material for machining larger tensile test bars. In most cases, elongation or reduction in area rather than tensile strength is the appropriate criterion for indicating weakness through the thickness.

Finally, when a particular joint detail is in question, tests representing the actual weld cross section, such as a cruciform joint, can be tested. Such tests provide some indication of joint strength properties, but give less information about ductility.

Among other applications, through-thickness testing has been used in recent studies of lamellar tearing of welded joints in structural steels as well as in the evaluation of the thickness direction properties of unrecrystallized refractory alloy sheets for aerospace applications.[1] In the latter case, pull tabs were brazed onto the sheet surfaces.

Weld Tension Test

The tension testing of welds is somewhat more involved than for base metal because the weld test section is heterogeneous in nature, composed of the deposited weld metal, the heat-affected zone, and the unaffected base metal. To obtain an accurate assessment of the strength and ductility of welds, several different specimens may be used (see Fig. 5.3). In some cases the weld reinforcement is left intact on the test specimen. The various weld tension test specimens are discussed in the following sections.

All-Weld-Metal Test. In a commonly used weld tension test, the axis of the test bar is parallel to the axis of the weld, and the specimen is machined so the entire bar consists of deposited weld metal. In general, the only complication associated with this method is the possible dilution (or alloying) of the weld

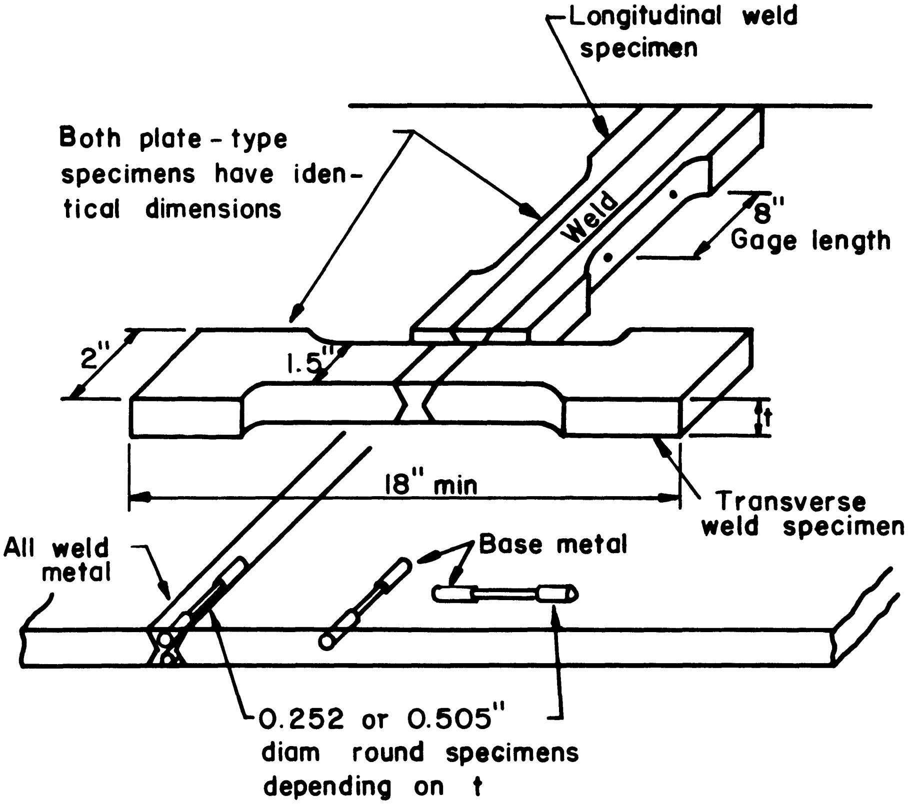

Fig. 5.3—Typical tension test specimens for evaluation of welded joints. (For SI equivalents of U.S. customary values, see the table on p. 216.)

deposit by base metal melting. If the test is to be representative of the weld metal per se, base metal melting should be minimized in depositing the weld. In this case, surfacing of the groove edges with the appropriate electrode is sometimes used, and the weld may be made under specified conditions to provide results comparable to all-weld-metal tests on other electrodes (see, for example, Specification for Bare Mild Steel Electrodes and Fluxes for Submerged Arc Welding, AWS A5.17). However, if the weld metal properties desired are those of a particular weldment, obviously the welding process and procedure to be used in actual fabrication should be employed regardless of the amount of dilution from the base metal.

Transverse Butt Weld Test. Interpretation of test results for the welded joint as a whole is complicated by the different strengths and ductilities generally found in the various regions of the joint. This lack of uniform properties is particularly important with the transverse test specimen (see Fig. 5.3) in which straining and failure will tend to occur primarily in the weaker areas of the gage section. For example, if the weld metal strength exceeds that of the base metal, most of the plastic strain occurs in the base metal, with resultant necking* and failure outside of the weld area. In such a case, the test indicates that the weld strength is above the ultimate tensile strength achieved in the specimen but does not give any

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*Local reduction in the area of the cross section caused by stretching.

indication of the weld ductility. Quantitative comparisons of various weld metals are not possible when failures of this type occur.

When the weld strength is considerably lower than that of the base metal, most of the plastic strain occurs in the weld. The localization of strain in this case will result in low values of tensile elongation, as indicated by measurements over the normal gage lengths. It is obvious, then, that transverse weld specimens may provide a measure of joint efficiency in terms of strength, but do not provide a good measure of weld ductility. As with the elongation, it is also not possible to obtain a reliable measure of yield strength across a welded joint, since the conventional use of yield strength depends on uniform straining within the specified gage length.

Because of the factors just cited, the primary information gained from the transverse weld test is the ultimate tensile strength; yield strength and elongation requirements are generally not specified. In spite of these deficiencies, the transverse weld test is the standard accepted ASME test for procedure qualification and is also quite widely used for the same purpose in various codes, since it does indicate whether or not the weld strength equals the base metal tensile strength or some other specified minimum value.

Longitudinal Butt Weld Test. In the longitudinal weld tension specimen, the direction of loading is parallel to the weld axis, but the test differs from the all-weld-metal specimen in that the gage cross section contains weld, heat-affected zone, and base metal (see Fig. 5.3). All of these zones must strain equally and simultaneously. Weld metal, regardless of strength, elongates with the base metal until failure occurs. Poor weld or heat-affected zone ductility may force fracture initiation to occur at strength levels considerably below that of the surrounding unwelded base metal. On the other hand, there are instances where the use of a lower strength but more ductile (and possibly less crack sensitive) weld metal is preferred. For example, a girth weld in pipe is stressed less across the weld than along the weld (nominally, transverse stress is one-half longitudinal stress due to internal pressure). In this case, lower strength weld metal may be completely adequate.

Because of the factors just described, longitudinal weld tests can provide more information about the composite joint than the transverse test, particularly when weld and base metal strengths differ significantly. Of course, a considerably greater length of welded joint is required for longitudinal than for transverse testing.

Tension-Shear Test

Fillet Weld Shear Test. Tension-shear tests may be used to evaluate the shear* properties of fillet welds. Such tests are usually intended to represent completed joints in weldments and so are prepared using similar procedures. Two basic specimen types, transverse and longitudinal, are employed (see Fig. 5.4).

Of the transverse-shear specimens, double lap specimens are preferred because they are more symmetrical and therefore the stress state under load better approaches pure shear. In the single lap joint, pure shear loading requires special test fixtures to align the specimen or prevent bending, particularly for thick plates where eccentric loading becomes significant. Consequently, single lap specimens are generally not used for plates over 6 mm (1/4 in.) thick. The data obtained from transverse fillet weld tests are the weld shearing strengths, reported as either load per lineal millimetre (inch) of weld or megapascals (pounds per square inch) based on the weld throat.

The longitudinal fillet weld shear test measures the strength of the fillet weld when the specimen is loaded parallel to the axis of the weld. The weld shearing strength is reported as load per lineal millimetre (inch) of weld for welds which fail.

All of the fillet weld shear specimens are sensitive to specimen preparation procedures. Gaps between the overlapped plates of single lap specimens affect the stress concentration at the root of the welds and can cause inconsis-

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*Shear strain is caused by a force tending to produce sliding on a plane within a material.

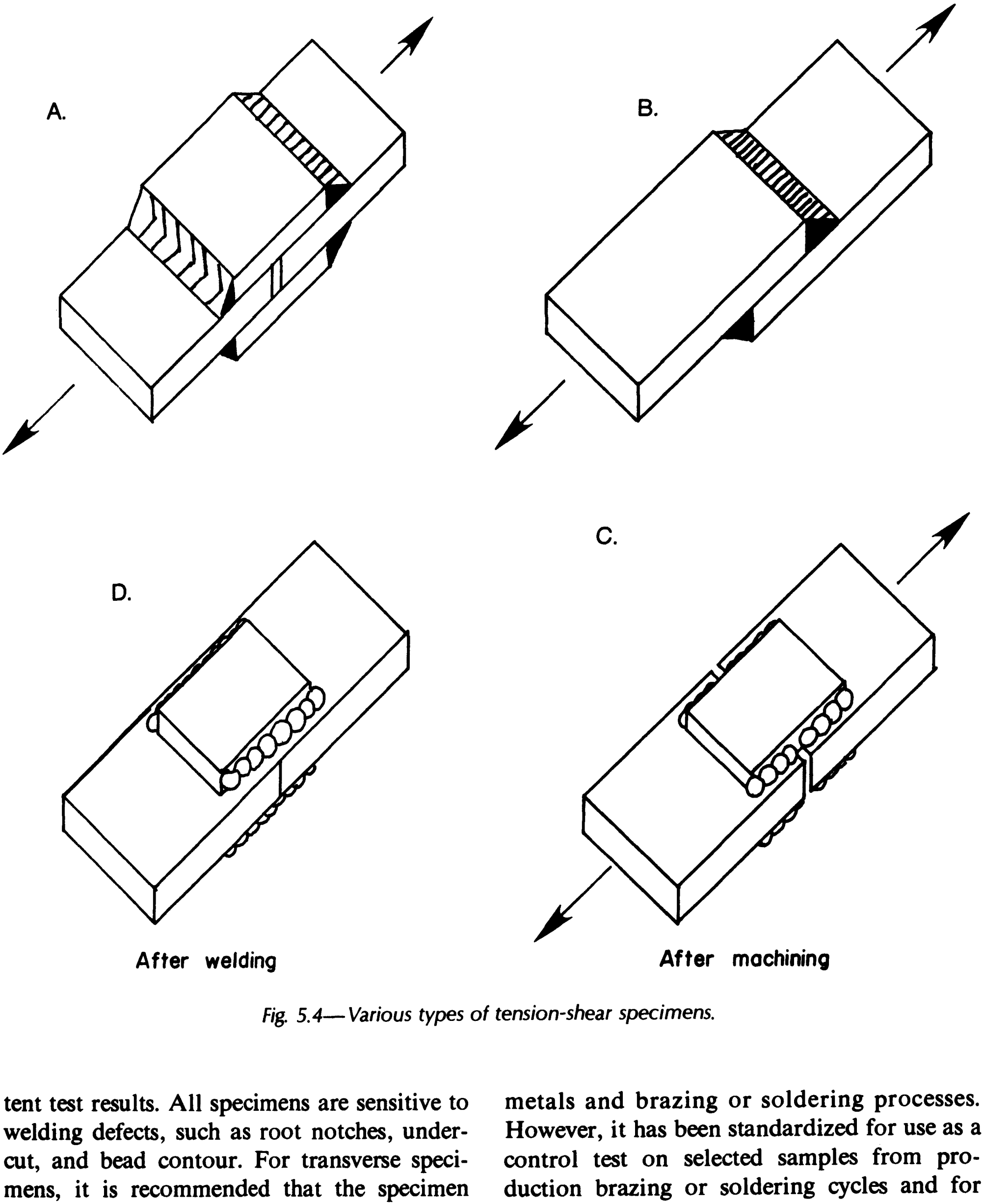


Fig. 5.4—Various types of tension-shear specimens.

tent test results. All specimens are sensitive to welding defects, such as root notches, undercut, and bead contour. For transverse specimens, it is recommended that the specimen edges be machined to eliminate crater effects and to provide a notch-free edge.

Tension-Shear Test for Brazed and Soldered Joints. The tension-shear test is used to determine the strength of the filler metal. There are a variety of specimen types used for this test as indicated in Fig. 5.5. The test is used primarily as a research tool for the development of filler metals and brazing or soldering processes. However, it has been standardized for use as a control test on selected samples from production brazing or soldering cycles and for comparison of filler metals produced by various manufacturers.

Two single thicknesses (3 mm [1/8 in.]) of ferrous or nonferrous alloys are joined with soldering or brazing processes and filler metals. The shear strength of the filler metal is calculated from the quotient of the tensile load at failure and the bonded area.

This test specimen requires suitable fixturing during bonding to maintain accurate alignment of the specimen.

Tension Tests for Resistance Welds

Tension-Shear Test. The tension-shear test is the most widely used method for determining the strength of resistance spot welds. It is also used for evaluation of weld schedules for ferrous and nonferrous alloys. The test specimen in Fig. 5.6 is made by overlapping suitable size coupons and making a spot weld in the center of the overlapped area. A tensile test machine is used to make the test.

The test is used mainly to establish ultimate shear strength when the specimen is tested in tension. When this test is used in combination with the cross-tension test (Fig. 5.7), the cross-tension strength/tension-shear strength ratio is referred to as a measure of ductility.

When gages less than about 1 mm (0.04 in.) are tested, a plug will usually be pulled from one sheet. This condition is typical of the fracture due to the eccentric loading caused by the overlapped sheets. As the thickness of the sheets or strength increases, the weld will fracture by a shearing across the nugget (weld metal) at the interface.

When the thickness becomes large such as 4.8 mm (0.19 in.) and greater, the wedge grips

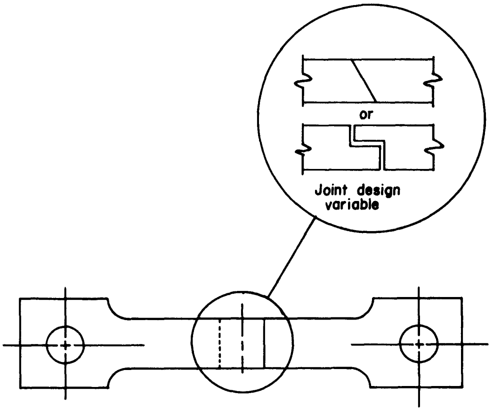


Fig. 5.5—AWS standard shear test specimen for brazed joints. (Refer to Standard Method for Evaluating the Strength of Brazed Joints, AWS C3.2.)

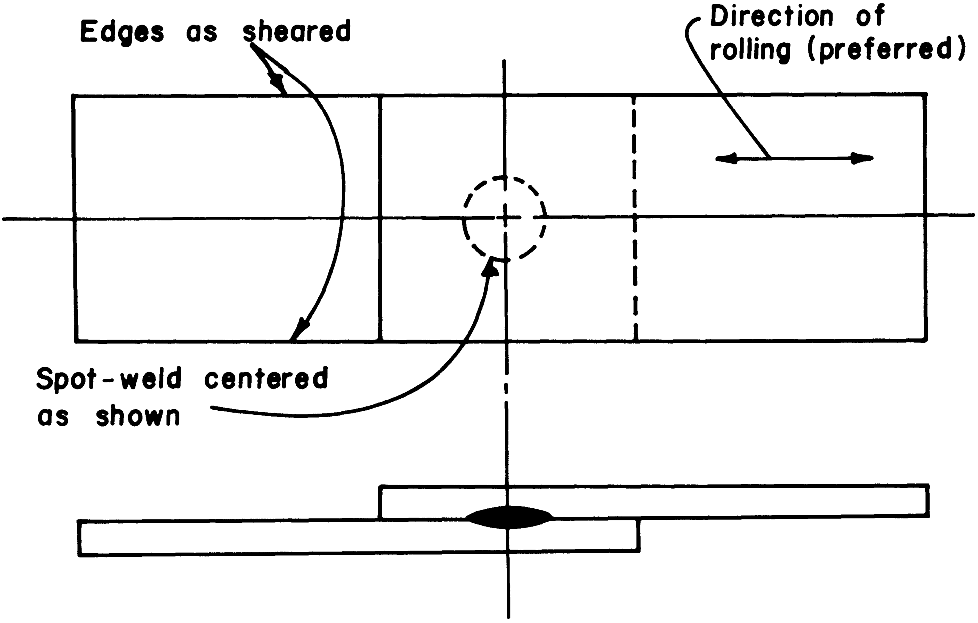


Fig. 5.6—Tension-shear test specimen.

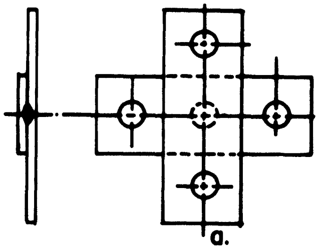
of the test machine should be offset to reduce the eccentric loading which is accentuated by the thickness of the specimen. A more precise shear load will be imposed on the spot weld, thus minimizing a tension or peeling component.

The tension-shear test is commonly used in production assurance testing because it is an easy and inexpensive test to perform. Coupons welded at regular intervals are tested to evaluate the adherence of the weld schedule to a prior established standard of test results. The reader is directed to Recommended Practices for Resistance Welding, AWS C1.1, for more details with respect to test specimen dimensions and test fixtures as well as statistical methods for evaluating resistance weld test results. This publication is also applicable for the direct-tension test described in the next section.

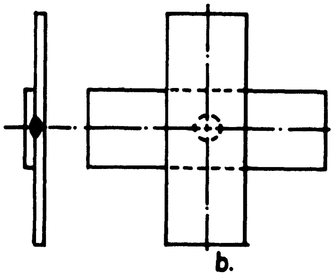
Direct-Tension Test. The direct-tension spot weld test is used to measure the strength of welds for loads applied in a direction normal to the spot weld interface. This test is used mostly for weld schedule development and as a research tool for the weldability of new materials. The direct-tension test can be applied to ferrous and nonferrous alloys of all thicknesses. The direct-tension test specimen is used to determine the relative notch sensitivity of spot welds.

There are two types of specimens used for the direct-tension test. The cross-tension specimens of Fig. 5.7 can be used for all alloys and all thicknesses. When the metal gage is less than 1 mm (0.04 in.), it is necessary to reinforce the specimen to prevent excessive bending. There are two types of test jigs for cross-tension specimens as shown in Fig. 5.8 for thicknesses to 4.9 mm (0.19 in.) and Fig. 5.9 for greater thicknesses.

The U-specimen is used in the second type



Thickness up to 4.8mm (0.19in.)



Thickness over 4.8mm (0.19in.)

Fig. 5.7—Cross-tension test specimens.

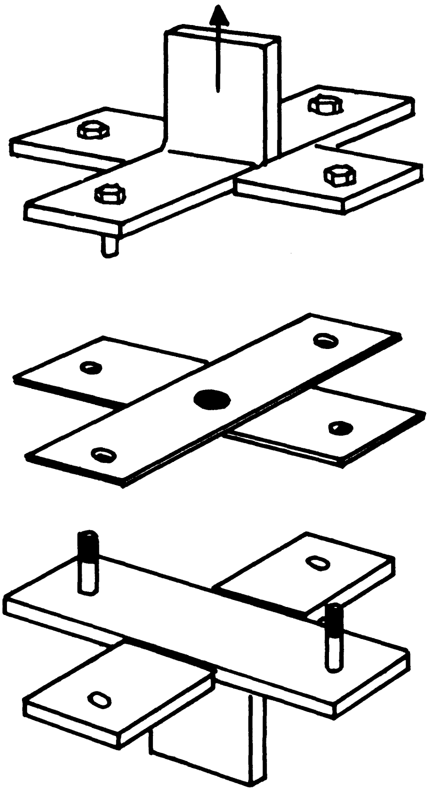


Fig. 5.8—Jig for cross-tension test (for thicknesses up to 4.8 mm [0.19 in.]).

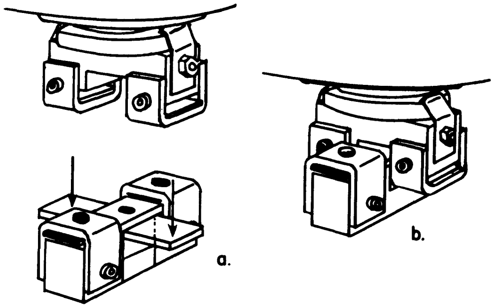


Fig. 5.9—Jig for cross-tension test (for thicknesses 4.8 mm [0.19 in.] and over).

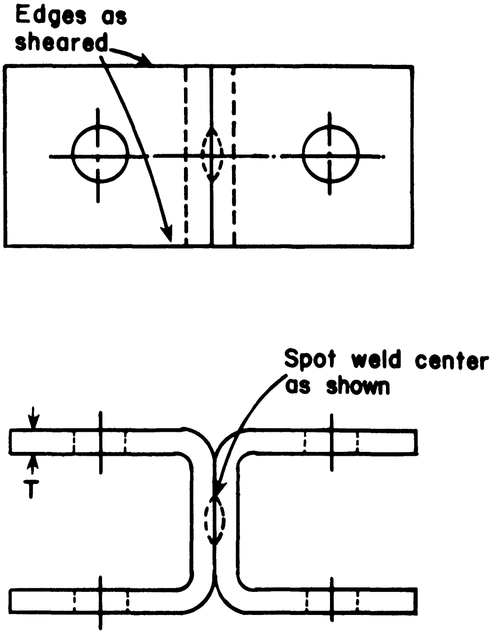


Fig. 5.10—U-test specimen.

of direct-tension test (see Fig. 5.10). The U-channels are spot welded back-to-back to form the test specimens. The specimens are assembled on filler blocks with pull tabs for applying a tensile load to the spot weld through the pin connections. The maximum load, which causes the weld to fail either by pulling a plug or by tensile failure across the weld metal interface, is measured. The direct-tension load is normally less than the tension-shear load for the same size weld and alloy.

The ratio of the direct-tension load to the tension-shear load is a measure of the notch sensitivity of the weld. The ratio should be greater than 0.5 for the spot weld to be considered ductile or having low notch sensitivity. Table 5.1 shows typical ratio ranges for several commonly spot welded alloys. The values of 0.30 and lower are indicative of brittle or notch sensitive welds. Values of 0.50 and greater are typical of welds in low carbon steel, austenitic stainless steel, and nickel-base alloys, which are less notch sensitive.

The direct-tension test is not normally used in production control because it requires an elaborate specimen.

Peel Test. A variation of the direct-tension test is the peel test which is commonly used as a production control test. The test is shown in Fig. 5.11. The size of the plug or button is measured or correlated with weld sizes having known strengths that are produced by satisfactory production weld schedules. This weld test is fast and inexpensive to perform. However, high strength or thicker specimens may fracture at the interface without producing a plug.

HARDNESS TESTS

Hardness testing may be used in weld evaluations, either alone or to complement information gained through the tension or bend tests previously described. Routine testing methods for the hardness testing of metals are well established. These include the Brinell, Vickers, and Knoop hardness tests, which use the area of indentation under load as the measure of hardness, and the Rockwell test, which relates hardness to the depth of indentation under load.

Hardness measurements can provide information about the metallurgical changes caused by welding. In constructional steels, for example, rapid cooling from high heat-affected zone temperatures may cause the formation of martensite* of much higher hard-

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*Refer to discussion of martensite on p. 113 of Chapter 4.

Table 5.1—Ratio of direct-tension to tension-shear test specimen loads

Material	Typical ratio range
Low carbon steel	0.60 to 0.99
Medium carbon steel (0.2C)	0.18 to 0.21
Low alloy high strength steel	0.21 to 0.28
Austenitic stainless steel	0.55 to 0.82
Ferritic stainless steel	0.25 to 0.33
Aluminum-base	0.37 to 0.43
Nickel-base	0.71 to 0.81
Titanium-base	0.27 to 0.52

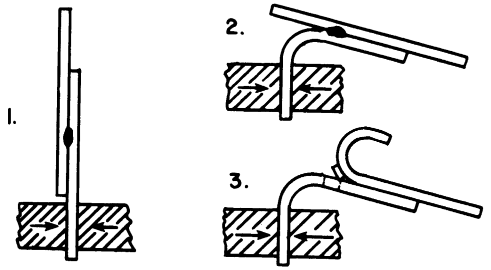


Fig. 5.11—Peel test. Step 1: Grip in vise or other suitable device. Step 2: Bend specimen. Step 3: Peel pieces apart with pincers or other suitable tool.

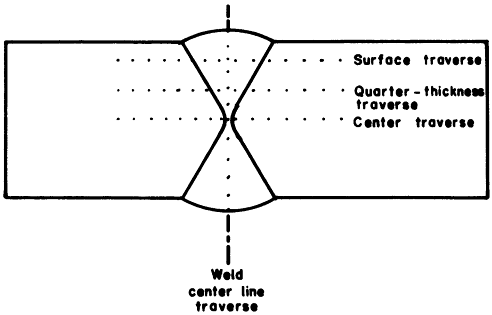


Fig. 5.12—Typical hardness traverses for a double-V groove welded joint.

ness than the base metal. In heat-affected zone areas where the maximum temperature is lower, however, the hardness may be lower than the base metal due to tempering effects. Welding of cold worked or age-hardened materials may result in significantly lower heat-affected zone hardnesses due to recovery and recrystallization or overaging. Hardness values in a welded joint are usually sensitive to such conditions of welding, as the process used, heat input, preheat or interpass temperature, electrode composition, and plate thickness.

Hardness testing of welds is performed on ground, polished, or polished and etched cross sections of the joint area. Indentations are made in the specific areas of interest, including the weld center line, face or root regions of the deposit, the heat-affected zone, and the base metal. Frequently traverses covering all of these areas are made, with indentations spaced at regular intervals along the line of the traverse (see Fig. 5.12). Traverses along the weld center line from root to reinforcement or weld surface may be used to determine multiple pass effects, such as the presence of alloy buildup in successive passes of submerged arc welds.

Which hardness test is used depends primarily on the hardness or strength of the material, the size of the welded joint, and the type of information desired. The Brinell test produces a large indentation, typically 2 to 5.6 mm (0.08 to 0.22 in.) in diameter, and is thus suited only for large welds, as in heavy plates. The Rockwell test produces a much smaller indentation more suited for hardness traverses, but even this test is macroscopic in scale in the sense that the indentations may be larger than the precise areas of interest (for instance, the fusion line or the coarse grain region of the heat-affected zone). The Vickers and Knoop tests make relatively small indentations and thus are well-suited for hardness measurements of the various regions of the heat-affected zone and for fine-scale traverses.

Table 5.2—Conversions for Brinell and Rockwell hardness and approximate tensile strength for carbon steels

Brinell Indent. diam. mm	Brinell Indent. diam. in.	Brinell No.*	Rockwell B	Rockwell C	Tensile strength, approx. values of MPa	Tensile strength, approx. values of ksi
2.25	0.089	745		65.3		
2.30	0.090	712		—		
2.35	0.092	682		61.7		
2.40	0.094	653		60.0		
2.45	0.096	627		58.7		
2.50	0.098	601		57.3		
2.55	0.100	578		56.0		
2.60	0.102	555		54.7	2055	298
2.65	0.104	534		53.5	1986	288
2.70	0.106	514		52.1	1889	274
2.75	0.108	495		51.6	1855	269
2.80	0.110	477		50.3	1779	258
2.85	0.112	461		48.8	1682	244
2.90	0.114	444		47.2	1593	231
2.95	0.116	429		45.7	1510	219
3.00	0.118	415		44.5	1462	212
3.05	0.120	401		43.1	1393	202
3.10	0.122	388		41.8	1331	193
3.15	0.124	375		40.4	1269	184
3.20	0.126	363		39.1	1220	177
3.25	0.127	352	(110.0)	37.9	1179	171
3.30	0.130	341	(109.0)	36.6	1131	164
3.35	0.132	331	(108.5)	35.5	1096	159
3.40	0.134	321	(108.0)	34.3	1062	154
3.45	0.136	311	(107.5)	33.1	1027	149
3.50	0.138	302	(107.0)	32.1	1007	146
3.55	0.140	293	(106.0)	30.9	972	141
3.60	0.142	285	(105.5)	29.9	951	138
3.65	0.144	277	(104.5)	28.8	924	134
3.70	0.146	269	(104.0)	27.6	896	130
3.75	0.148	262	(103.0)	26.6	876	127
3.80	0.150	255	(102.0)	25.4	848	123
3.85	0.152	248	(101.0)	24.2	827	120
3.90	0.154	241	100.0	22.8	800	116
3.95	0.156	235	99.0	21.7	786	114
4.00	0.157	229	98.2	20.5	765	111
4.05	0.159	223	97.3	(18.8)	-	-
4.10	0.161	217	96.4	(17.5)	724	105
4.15	0.163	212	95.5	(16.0)	703	102
4.20	0.165	207	94.6	(15.2)	689	100
4.25	0.167	201	93.8	(13.8)	676	98
4.30	0.169	197	92.8	(12.7)	655	95
4.35	0.171	192	91.9	(11.5)	641	93
4.40	0.173	187	90.7	(10.0)	621	90
4.45	0.175	183	90.0	(9.0)	614	89
4.50	0.177	179	89.0	(8.0)	600	87
4.55	0.179	174	87.8	(6.4)	586	85
4.60	0.181	170	86.8	(5.4)	572	83
4.65	0.183	167	86.0	(4.4)	558	81
4.70	0.185	163	85.0	(3.3)	545	79
4.80	0.189	156	82.9	(0.9)	524	76
4.90	0.193	149	80.8		503	73
5.00	0.197	143	78.7		490	71
5.10	0.201	137	76.4		462	67
5.20	0.205	131	74.0		448	65
5.30	0.209	126	72.0		434	63
5.40	0.213	121	69.8		414	60
5.50	0.217	116	67.6		400	58
5.60	0.220	111	65.7		386	56

* Values above 500 are for tungsten carbide ball; below 500 for standard ball.

Relationship of Hardness to Strength and Other Properties

Attempts have been made to correlate hardness with strength for certain materials. An example is given in Table 5.2 which shows a correlation of hardness with tensile strength for carbon steels. Such correlations should be used with caution when applied to welded joints due to the heterogeneous makeup of the joint. It has been observed that tensile fracture can occur at loads significantly higher than the hardness of the weakest heat-affected zone region would have predicted, simply because the weaker zones were mechanically constrained by adjacent stronger material during testing.

Hardness has been related to service properties of weldments, and in some cases maximum weld or heat-affected zone hardnesses have been specified.[2] This is particularly important for weldments exposed to hydrogen-bearing environments such as sour-crude in the case of pipelines. High hardness coupled with hydrogen can and has caused cracking. However, there is a problem of nonstandardized methods of hardness measurements for welds, since the value obtained can be quite dependent on the test method used, including

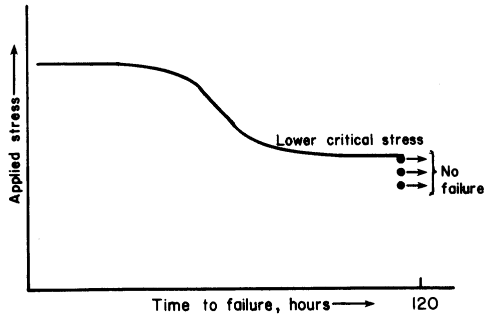


Fig. 5.13—Schematic of data obtained from constant load rupture (CLR) test.

the size of indentation as well as the location of the indentations in the joint.

CONSTANT LOAD RUPTURE TESTS

Tensile-type specimens have been used by some investigators as a means of assessing the susceptibility of particular materials or microstructures to hydrogen embrittlement and hydrogen-associated weld cracking. This type of testing is referred to as the constant load (notched) rupture test. In this test, notched tensile bars of the materials in question are synthetically charged with hydrogen, either cathodically or through exposure to hydrogen-bearing atmospheres at elevated temperatures. In the latter case, cooling rate from the exposure temperature can be a variable. The hydrogen-charged specimens are subsequently subjected to a constant load test, and time to fracture is evaluated as a function of the applied load.

The data from constant load rupture testing are usually presented in the form shown schematically in Fig. 5.13, which illustrates a curve of the shape frequently observed. At the higher stress levels, failures occur at relatively short times. At somewhat lower stress levels, data may be scattered but generally there is a longer time span to failure. Below a certain stress failures do not occur, resulting in a lower plateau sometimes referred to as the lower critical stress (LCS). Comparison of materials is made on the basis of the times to fracture at various stresses as well as the magnitude of the LCS. The knee of the curve often occurs at intervals of less than one hour, while maximum times (no failure) range up to 120 hours. The LCS value may be 30-80 percent of the notched tensile strength measured with no hydrogen charging, depending on the material.

BEND TESTS

Various types of bend tests are used to evaluate the ductility and soundness of welded joints. Bend specimens may be longitudinal or transverse to the weld axis and may be bent in simple three- or four-point bending (free bend) or around a mandrel of specified diameter (guided bend). Typical free and guided bend testing fixtures and loading are illustrated in Fig. 5.14.

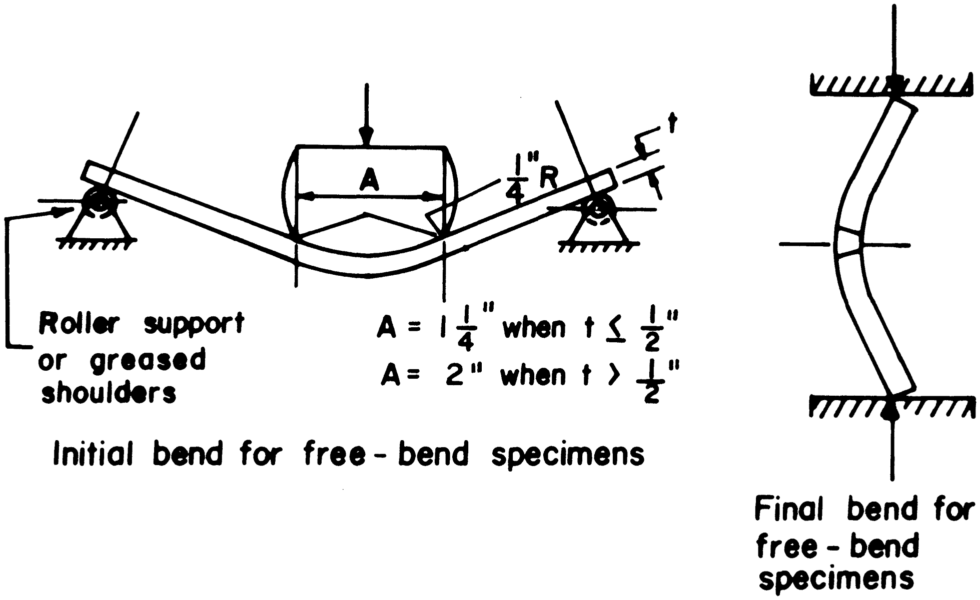
The top and bottom surfaces of a welded plate are frequently designated as the face and root surfaces, respectively. Face bends have the weld face on the convex (tension) side of the bent specimen; with root bends, the weld root is on the convex side. In bend testing thick plates, transverse slices are usually cut from the welded joint and bent so that one of the cut side surfaces becomes the convex side of the bent specimen; these are referred to as side bends. The relative orientations of these specimens are illustrated in Fig. 5.15.

Bend test results are expressed in various terms—percent elongation in outer fibers, minimum bend radius prior to failure, go or no-go for specific test conditions, and angle of bend prior to failure. Elongation is considered to provide the most reliable and reproducible data. Elongation occurring in the outer fibers, at the outer radius, is determined from gage marks that are scribed, inked, or shot etched on the specimen prior to bending or approximated from the following formula:

$$e = \frac{t}{2R+t} \times 100$$

where

e = percent elongation
t = initial plate thickness, mm (in.)
R = radius of curvature at the inside surface of the bend



Initial bend for free-bend specimens

Final bend for free-bend specimens

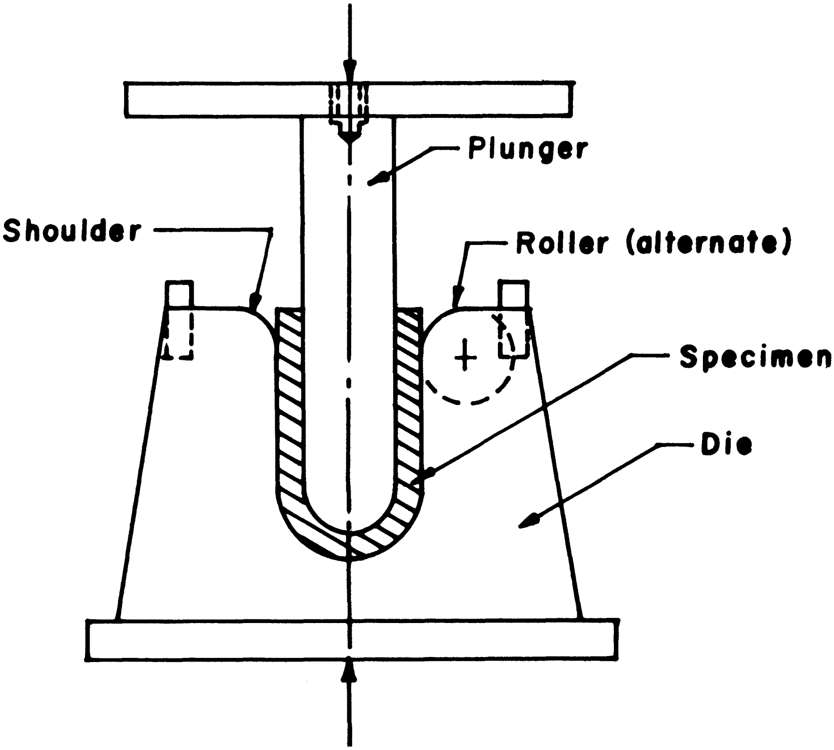


Fig. 5.14—Typical fixtures for free bend testing (top) and guided bend testing (bottom). (For SI equivalents of U.S. customary values, see the table on p. 216.)

For testing relatively thin materials, (less than 4.8 mm [3/16 in.]), bending the specimen over a succession of decreasing radii dies provides a good measure of ductility. The radius of the last die used before failure is recorded as the bend radius. In each case, the specimen is forced to the bottom of a standard V block by progressively smaller radii dies.

Transverse bend tests are useful in qualifying welders and welding operators because they quite often reveal the presence of defects that are not detected in tension tests. However, the transverse specimen suffers from the same weakness as the transverse weld tension test in that nonuniform properties along the length of the specimen can cause nonuniform bending. For example, very narrow welds such as those made by electron beam welding may contribute very little information on weld ductility. Thus, the transverse bend test is sensitive to the relative strengths of the weld metal, the heat-affected zone, and the base metal.

Several different types of problems can develop in transverse bend specimens. An overmatching weld strength may prevent the weld zone from conforming exactly to the bend die radius and may force the deformation out into the base metal, causing less than the desired elongation of the weld. With an undermatching weld strength, the specimen may tend to kink in the weld, resulting in a sharper bend radius in this area and thus more severe elongation in the weld. When transverse free bend tests are used for welded quenched and tempered steels, excessive stretching of the overtempered region of the heat-affected zone may lead to early failure in this area before full extension of the weld metal is achieved.

The above problems of weld mismatch can be avoided by using longitudinal bend specimens in which the weld runs the full length of the bend specimen; the bend axis is then perpendicular to the weld axis. In this test, all zones of the welded joint (weld, heat-affected zone, and base metal) are strained

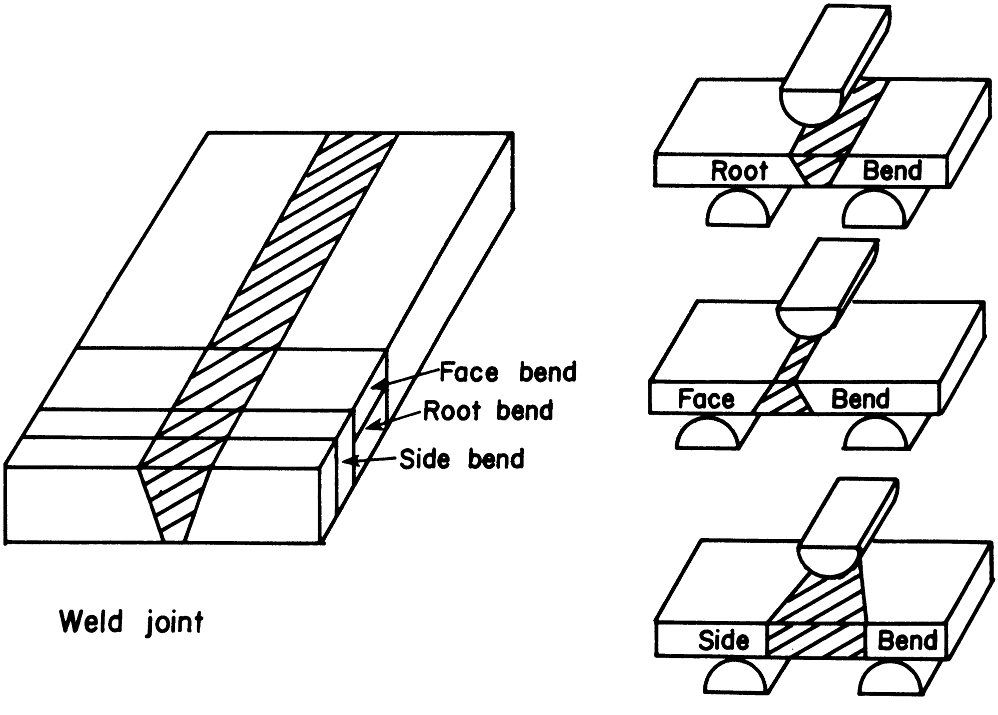


Fig. 5.15—Relative orientations of face-, root-, and side-bend tests from a welded plate.

equally and simultaneously. This test is generally used for evaluations of joints in dissimilar metals.

It should be noted, however, that tests aimed at detecting gross weld flaws that are inherently oriented parallel to the weld axis—such as incomplete fusion, inadequate joint penetration, or undercut—necessitate transverse-loading tests. Side-bend specimens strain the entire weld cross section and are thus especially useful for exposing defects near midthickness that might not contribute to failure in face- or root-bend tests. They are also used for relatively thick sections (over 19 mm [3/4 in.]), since in these tests all of the weld thickness may be included in the test.

Codes generally specify a maximum allowable size of fissure for bend tests made for procedure or welder qualification. More detailed descriptions of bend test procedures and requirements should be obtained from applicable codes, such as AWS or ASME codes. Applicable standards are the latest editions of ASTM E 16 for free bend tests and E 190 for guided bend tests, as well as AWS B4.0, Standard Methods for Mechanical Testing of Welds.

Notched Bend Test

The previously described bend tests are conducted on smooth ground specimens with the weld reinforcement removed. Though a variety of notched bend tests have been devised and used in research, notched slow bend tests are not in common industrial use. Among those which have been used for research purposes are the Naval Research Laboratory bead-weld nick-bend test and the Kinzel test. These tests evaluate material transition temperatures from the ductile to brittle fracture mode and indicate the effects of welding on the materials in question. However, these methods have largely been replaced by dynamic tests of welded joints (such as Charpy and drop weight) or by slow bend K_{Ic} or crack opening displacement (COD) tests. These latter methods are discussed in the following section on fracture toughness.

FRACTURE TOUGHNESS

Fracture toughness is a property of the metal which defines its resistance to brittle fracture. This section explains the concept of fracture toughness and its dependence upon such variables as temperature, strain rate, section thickness, and strength level. The common engineering test procedures for measuring toughness are described, as well as the more research oriented linear elastic fracture mechanics (LEFM) approach applicable under conditions of substantially inelastic behavior.

In designing with ductile materials, the failure-safe load carrying capability of an engineering structure is normally based on a stress analysis to assure that the nominal stresses are below yield.* Failures that occur under elastic (below yield) loading are broadly classified as brittle fractures. These failures can result from the effects of small discontinuities or crack-like defects that do not greatly alter the nominal stress distribution and are customarily neglected in the stress analysis.

Under conditions of high mechanical restraint, a discontinuity can greatly decrease the high ductility that may have been predicted on the basis of smooth tensile specimens and could cause brittle fracture in the structure. It is therefore evident that a complete fracture-safe analysis requires proper attention to the role of the discontinuity. For many classes of structures, such as ships, bridges, and pressure vessels, experience with specific designs, materials, and fabrication has established a satisfactory correlation between notch test standards for the metal and acceptable service. The problem is how to insure the soundness and integrity of a new design.

One of the motivations for the application of fracture mechanics concepts and tests to welded joints is the possibility of designing safely against the effects of commonly occurring weld discontinuities. It is widely recognized that welded joints almost always contain some discontinuities and this places the designer using welded joints in a dilemma. The designer wants to use joints that are entirely free of flaws, but this is not realistic. The practical approach is to recognize that they are present, and to place a reasonable limit on their size. But how shall the decision be made as to what size discontinuities are acceptable? While conventional toughness testing procedures are not able to deal directly with this problem, fracture mechanics tests, where applicable, specifically define a relationship between flaw size and fracture stress for a given material or weldment and thus permit a direct estimate of allowable flaw sizes for different geometrical configurations and operating conditions. The specification of flaw sizes and inspection for flaws can be referred to a rational and logical procedure rather than one based solely on experience or opinion. However, as weldments of greater strength and more complicated design are introduced, there will be less engineering experience, and design strength can no longer be proven. Consequently, there will be a greater need for the designer to take an analytical approach to the problem of discontinuities.

There exists no single method for fracture-safe assurance for all toughness levels and structural designs. The wide current emphasis on LEFM procedures tends to give a misleading impression that LEFM can provide

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*Failure could result even when the stresses are below yield due to other phenomena such as fatigue crack propagation or a hostile environment leading to stress corrosion cracking, hydrogen embrittlement, etc. These topics are discussed later in this chapter in the sections on fatigue (starting p. 186) and corrosion factors (starting p. 201), as well as in Chapter 4 (pp. 126-128 and 129-130) and Chapter 6 (p. 236).

assurance of fracture safety in all instances. For this reason, it is necessary to define the limitations of LEFM and to understand other procedures for evaluating toughness and how they relate to structural behavior.

CONCEPTS RELATING TO FRACTURE TOUGHNESS

Mechanical Constraint

A grasp of the concept of mechanical constraint is central to a firm understanding of fracture toughness. This concept can be illustrated by the behavior of a notch in a uniformly loaded plate in tension (see Fig. 5.16). The tensile stress, σ_{y_1}, causes a small element bordering the notch tip to contract in the x-direction and to assume a new shape (shaded). A similar element further removed from the discontinuity will contract to a lesser extent because the stress elevation in σ_y, due to the notch, diminishes with the distance from the notch. A triaxial stress distribution is therefore created which serves to inhibit the plastic flow of the metal and results in the phenomenon of mechanical constraint. All real metals exhibit some degree of plasticity at the tip of a discontinuity in a stressed body, however, and the level of fracture resistance or "fracture toughness" is directly proportional to the extent of this plastic zone. Consequently, the reduction in plasticity attributable to triaxial stresses (mechanical constraint) is equivalent to a reduction in fracture toughness.

With nominal section stresses still below yield, the stress concentration at a notch and the triaxial stress distribution near the notch tip causes the local stress to be not only equal to but also greater than the value of yield stress as measured in a smooth tensile specimen. For sufficiently thick sections, the magnitude of triaxial stress increases with notch depth to a maximum or plane strain value described below. To prevent brittle fracture due to the localized reduction of ductility at the notch tip, the metal must exhibit a corresponding resistance to fracture or fracture toughness.

The degree of triaxiality or mechanical constraint developed for the notched body of Fig. 5.16 depends on both the notch depth and the section thickness. With a shallow notch, the illustrated elements at the crack tip will sense the presence of the free surface and the σ_x and σ_z stresses cannot greatly exceed the yield stress level. Similarly, if the body is thin, the σ_z stress cannot achieve a level above the uniaxial yield stress.

A condition of plane strain constraint is said to exist when further increases in notch depth or section thickness do not result in further increases in the stress triaxiality. Plane strain fractures are characterized by little ductility as illustrated in Fig. 5.17. In this context, fracture toughness is sometimes assessed by a small, inexpensive test specimen. Because of its small size (thickness), the specimen may not exhibit plane strain conditions and if this is the case, the measured value of toughness will be higher than that which is encountered in a structural prototype of a thicker section. On the other hand, if the thickness of a specimen is identical to that of the structure, but does not exhibit plane strain constraint, a testing requirement to test thicker specimens can result in unduly conservative assessments of the fracture toughness of the structure.

Temperature and Strength Transitions

The fracture toughness of ferritic alloys exhibits significant variations with changes in yield strength level and temperature. The interaction of toughness with strength level and temperature is illustrated by a three-dimensional plot of these variables in Fig. 5.18. Here fracture toughness is presented simply as energy for the fracture of a test specimen; later the correspondence of fracture toughness with energy absorption will become clear.

The "temperature transition" in Fig. 5.18 illustrates the change from brittle to ductile behavior with increasing temperature. The characteristic S-shaped curve reaches a plateau or upper shelf at which the toughness is no longer temperature dependent.

Ultra-high strength steels will often behave in a brittle manner under the appropriate conditions. On the other hand, the more

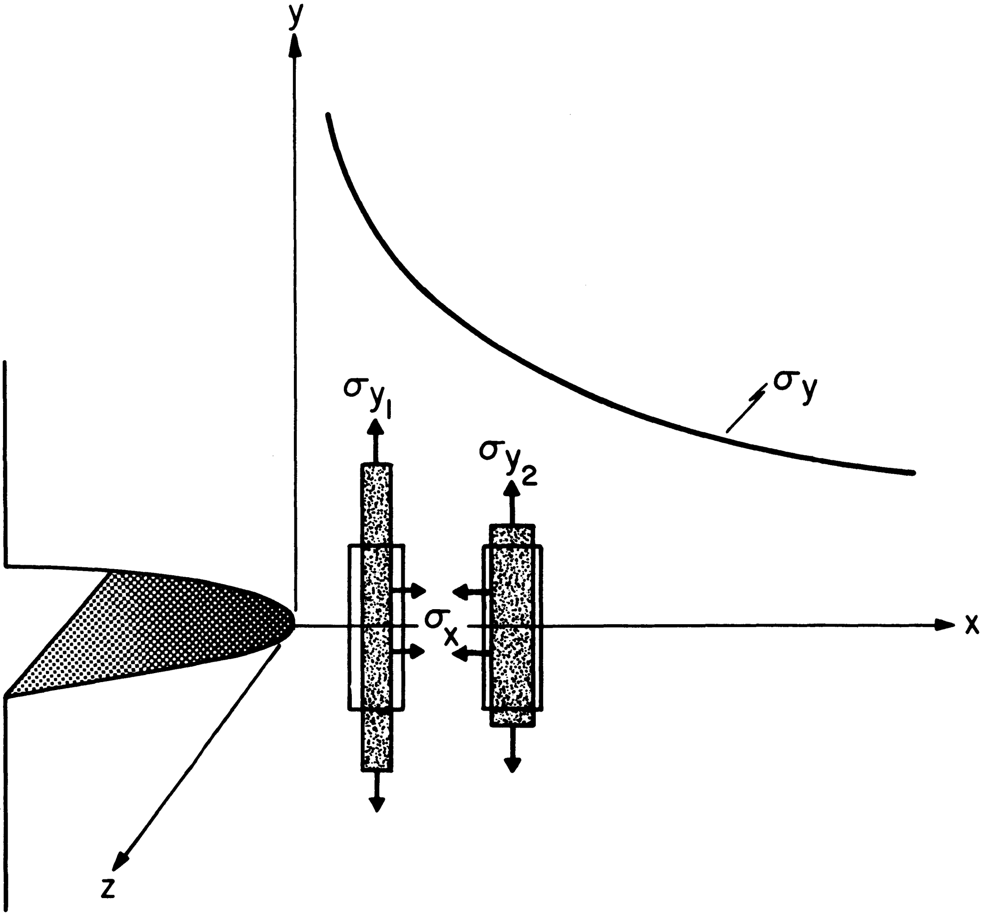


Fig. 5.16—Triaxial stress distribution. Stresses in the x- and z-directions result from a non-uniform elongation of the elements in the direction of applied stress (y-direction).

common structural steels having yield strengths between 210 and 900 MPa (30 and 130 ksi) can exhibit a range of toughnesses dependent on the alloy and the temperature of interest.

Unfortunately, a single method does not exist with which to define all levels of fracture toughness. The alloys falling into the shaded band of Fig. 5.18, labeled "plane strain (brittle)" can best be characterized through LEFM procedures which yield a quantitative relationship between fracture toughness and the critical flaw size and stress level required for brittle fracture. However, LEFM applicability is limited to the toughness levels falling into the brittle fracture zone. The region labeled "ductile fracture" is not considered to lie in the province of the present fracture discussion since alloys at this toughness level generally fail by plastic overload. Thus it can be seen that most of the common tonnage structural steels fall within the nominal ductile range at ordinary service temperatures, and outside the scope of LEFM.

The region between the brittle fracture and ductile fracture areas in Fig. 5.18 is termed the elastic-plastic region. Current research emphasis is on quantitative analysis of fracture toughness in this region, in a manner similar to LEFM, with the hope of evolv-

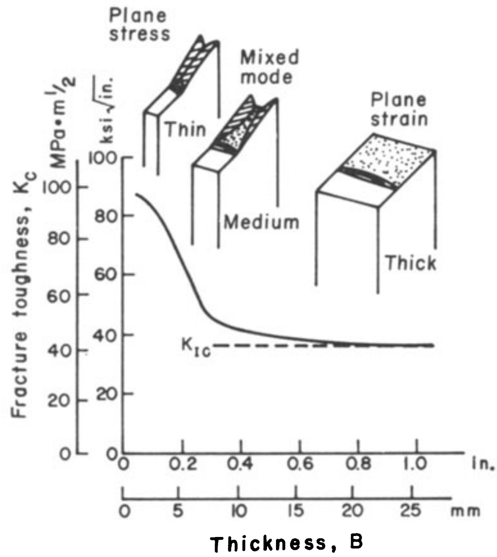


Fig. 5.17—Effect of specimen thickness on fracture toughness. The plane strain toughness, K_{Ic}, represents a minimum value that is exhibited with increasing thickness. For thinner sections, a toughness greater than the plane strain value is exhibited due to through-thickness yielding.

ing new techniques such as the J-integral.[3] However, existing characterizations of elastic-plastic behavior for engineering applications are largely empirical and the methods subject to debate.

Strain Rate Dependence

Figure 5.19 illustrates the sharp change in the crack tip plastic zone (toughness) with temperature referred to earlier on the temperature transition. The fracture toughness variation in this region is complex since it is influenced not only by temperature but also by loading rate, or more specifically, strain rate at the crack tip. In practice the strain rate dependence of fracture toughness can be quite significant. For example, at a given temperature the large plastic zone formed under quasi-static (slow) loading conditions may reduce the mechanical constraint, and therefore improve toughness. On the other hand, dynamic loading may result in a sufficient reduction in ductility (plastic zone) to cause brittle fracture. This phenomenon is believed to result pri-

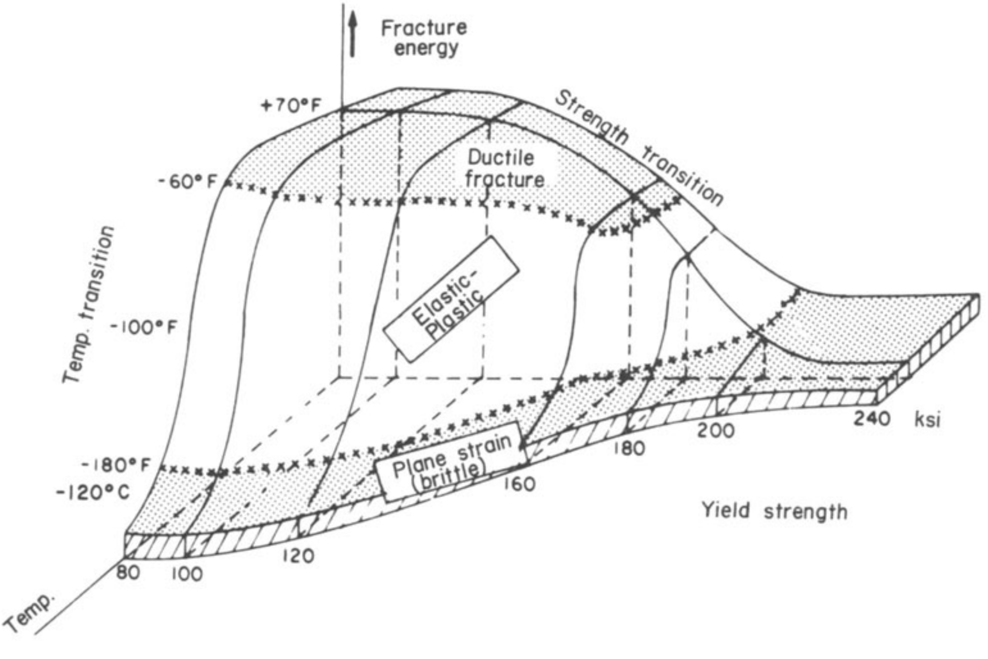


Fig. 5.18—Three dimensional plot showing the interrelationship of fracture energy, temperature, and strength level on fracture behavior. (For SI equivalents of U.S. customary values, see the table on p. 216.)

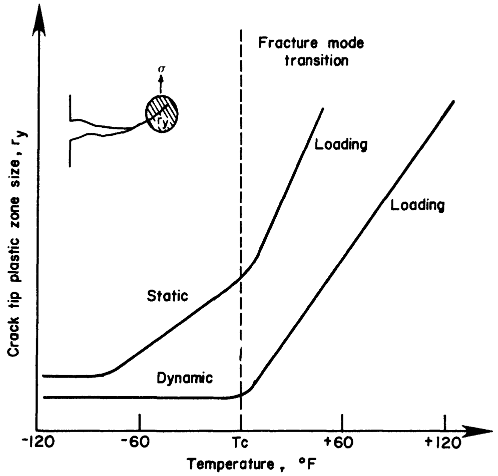


Fig. 5.19—A brittle-ductile transition in toughness with increasing temperature known as the fracture mode transition, exhibited by carbon and low alloy steels. Dynamic loading of these steels may reduce the toughness below the "static" values. (For SI equivalents of U.S. customary values, see the table on p. 216.)

marily from the strain-rate dependence of yield strength for these alloys.

The question has been raised as to what loading rate a fracture toughness specimen should be subjected to simulate structural conditions. Fracture experts disagree on this point. One school feels that the toughness of a statically loaded structure, such as a pressure vessel under constant or slowly changing pressure, is best determined from a notched test specimen loaded slowly as in a conventional tension test. Another school maintains that the toughness of a structure, especially a welded structure, is not uniform throughout because of material inhomogeneities. If a preexisting flaw should grow (by fatigue, stress corrosion, etc.) into such a region of low toughness, the discontinuity could exhibit sudden, unstable propagation over the distance perhaps as small as a few grains (called "popin"). The metal grains at the perimeter of this popin behave as if they are dynamically loaded and therefore exhibit a dynamic toughness value below that of the static toughness; hence a dynamic fracture toughness test may be required.

If static values of toughness are employed, the fracture analyst must be confident that the toughness in his structure is above some minimum value and devoid of major local inhomogeneities that may lead to a popin. This toughness is usually insured by Charpy or other notched dynamic tests of the material at a temperature appropriate to service, plus nondestructive shop inspection to detect and remove defects above an agreed level. Typical practice is described in the ASME Boiler and Pressure Vessel Code, Section 8, Division 1.

If a dynamic analysis is justified, the proper loading rate for the test specimen must be chosen. Again, differences of opinion exist. Some maintain that the relevant strain rate is the average value experienced by the structure. Others claim that the average strain rate of the structure is irrelevant when a popin occurs. In other words, the popin can result in a rapid (localized) strain rate that may bear no relationship to the overall structural loading rate. Partly because of these uncertainties, dynamic fracture toughness tests are very often conducted by impact loading the entire test piece with the hope that this may result in a lower bound value of toughness.

LINEAR ELASTIC FRACTURE MECHANICS

Basic Analytical Relationships

Fracture mechanics, or more correctly, linear elastic fracture mechanics (LEFM), refers only to fracture behavior under conditions of plane strain. As indicated previously, this analysis can only be applied if the plastic zone at the crack tip is small compared with the dimensions of the crack to insure an overall linear behavior. The concept of LEFM can be traced to Griffith who in 1920 developed a means to predict the conditions for fracture of a brittle solid (glass) containing a crack.[4] A balance of the stored elastic strain energy and the energy needed to form new surfaces associated with crack extension yielded a relationship for crack instability. Modern LEFM, however, has abandoned Griffith's energy approach in favor of a stress analysis approach that is more easily related to the language of the designer.

Griffith's approach for glass has been modified to include the notch tip plasticity associated with real metals and to describe the behavior of the material close to the leading edge of a sharp crack in terms of a stress analysis as illustrated in Fig. 5.20.[5,6]

The parameter K_I (Fig. 5.20) is the plane strain stress intensity factor for Mode I or the opening mode (that is, the tensile opening of the crack surfaces). This mode has received the greatest emphasis because if fracture occurs, it is usually by this mode.

K_I provides a single parameter characterization of the stress field near the crack tip. The K_I parameter, in turn, is a function of the geometry of the body, the loads at the boundaries, and the size of the crack. For a given geometry, the value of K_I may be computed through a stress analysis at the crack tip. Expressions for many different loadings and body configurations have been catalogued.[7] All expressions for K_I have the form

$$K_I = \sigma C\sqrt{\pi a} \qquad (5.1)$$

where

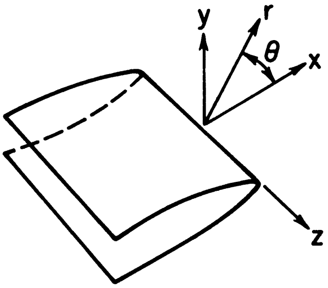
σ = the nominal stress field in which the crack resides, MPa (ksi)

C = a function of the specimen geometry

a = depth of the crack, mm (in.)

The level of K_I at fracture initiation (under plane-strain conditions) is termed K_{Ic}. This quantity is a property of the material in the same sense as the yield stress (σ_{ys}); that is, both quantities vary with temperature, strain rate, and metallurgical structure. The utility of equation (5.1) is readily apparent when one considers that the form or shape of the stress distribution in a notched laboratory specimen

Crack tip stress field approach



$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left[1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right]$$

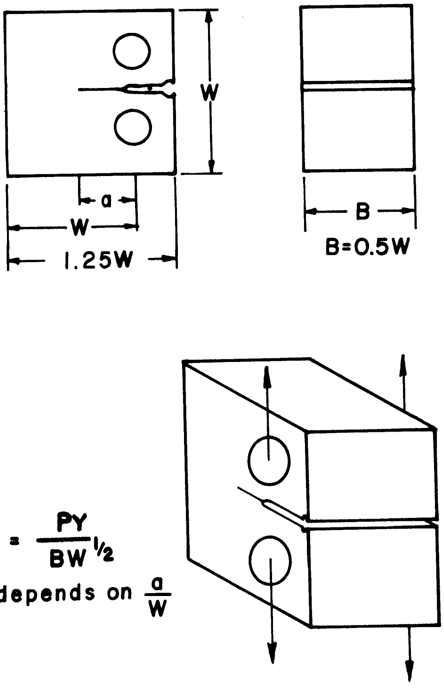
$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left[1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right]$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}$$

$\sigma_z = \nu(\sigma_x + \sigma_y)$ Plane strain

$\sigma_z = 0$ Plane stress

Fig. 5.20—Elastic stresses near the crack tip for a through-thickness crack in a linear elastic, isotropic body subject to Mode I loading.



$$K_I = \frac{PY}{BW^{1/2}}$$

Y depends on $\frac{a}{W}$

Fig. 5.21—Compact tension specimen and displacement gage.

is identical with that in a flawed prototype structure and differs only in intensity as expressed by K_I. The K_{Ic} value determined from equation (5.1) therefore provides the means to relate the critical flaw size and stress level from a simple specimen to a more complex structure.

Static K_{Ic} Measurement Procedures

A standard method for the measurement of K_{Ic} is given in ASTM E 399.[8] Tests performed according to this standard are more complex than tension or Charpy impact tests, and are not applicable to all metals or conditions of service.

Two specimen geometries, a three-point bend specimen, and a compact specimen are described in E 399 (the compact tension specimen is shown in Fig. 5.21). In concept, a K_{Ic} value can be obtained for any geometry for which a stress analysis is available. However, all specimens must have a sharp notch which terminates with a fatigue precrack. The K_{Ic} level is defined experimentally with a laboratory tension specimen record of load versus crack mouth opening (using a displacement or clip gage) by noting the load at which the

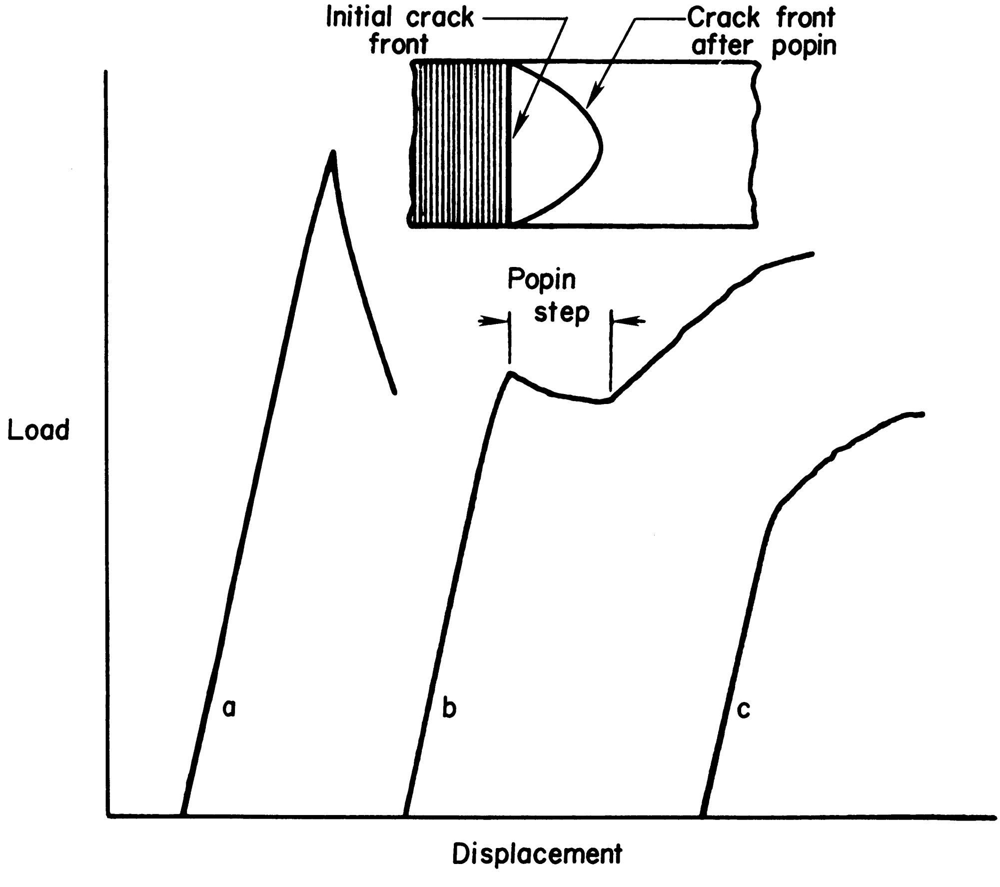


Fig. 5.22—Typical test records of load versus crack mouth opening or displacement of a notched specimen. Type a and b records give unambiguous load points with which to compute K_{Ic}. The type c record, however, is typical of that for ductile behavior; to determine if this record is useful for K_{Ic} calculations requires strict adherence to the ASTM standard method.[7]

crack extends. The equation for calculating K_I for compact tension specimens is illustrated in Fig. 5.21. Typical records of these measurements are illustrated in Fig. 5.22.

Some brittle materials exhibit complete fracture at the maximum load (line a, Fig. 5.22) while others exhibit a rounding (line c, Fig. 5.22) for which the critical load is determined by methods specified in ASTM E 399. The K_{Ic} value is computed from an expression similar to equation (5.1) for the geometry of interest in conjunction with the critical load (or stress) and crack length. The latter quantity is customarily determined from post-test measurements of the completely fractured specimen.

In order to insure plane strain conditions, ASTM E 399 places the following restriction on the thickness, B, and crack depth, a:

$$B \text{ and } a \geq 2.5 \left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 \qquad (5.2)$$

The above requirement is unusual in that it is not possible to assess the "validity" of the result until the completion of the test and a computation of a "tentative" K_{Ic} value.

Failure to meet the requirements of equation (5.2) may result in fracture values that are larger than the true K_{Ic} values as illustrated in Fig. 5.17. These values are usually referred to as K_c and occur because the constraint in the specimen is insufficient. The increase in K_c from the K_{Ic} level represents a geometry dependence; this phenomenon masks the K_{Ic} value and prevents the translation of the stress intensity from a specimen to a structure of different geometry.

A common flaw geometry encountered in service is the surface flaw or discontinuity. The equation for this geometry is given in Fig. 5.23 for a plate in tension where σ is the nominal stress and Q is a geometry factor that depends on the flaw's aspect ratio or ratio of depth to length. Critical crack depths are plotted in terms of the K_{Ic}/σ_{ys} ratio which determines the specimen thickness required for that level of toughness in accordance with ASTM E 399 (equation [5.2]). The K_{Ic}/σ_{ys} ratio is the more appropriate expression of toughness than is K_{Ic} by itself since the former is a measure of the plastic zone size—that is, the amount of plasticity that determines the level of fracture toughness.

Given the K_{Ic} of the material at the specific temperature and strain rate, and the nominal stress at the point of interest, it is possible to judge the critical flaw size from Fig. 5.23 and to ascertain from it the appropriate levels of nondestructive inspection required to prevent fracture. However, an important limitation of LEFM becomes apparent in this exercise. If a 25 mm (1 in.) flaw exists in a region which approaches yield stress loading, the material must exhibit a toughness ratio between 7 and $11\sqrt{\text{mm}}$ (1.4 and 2.2 $\sqrt{\text{in.}}$) depending on the aspect ratio. Furthermore, a section size of 125 to 300 mm (5 to 12 in.) is required to measure this level of toughness. If, on the other hand, the structural thickness is less than that required, plane strain conditions would not be achieved, thereby preventing the use of LEFM except as a conservative lower bound that could preclude the use of the material. In the absence of plane strain, the analysis must be treated by more sophisticated elastic-plastic techniques that are currently in the research stage. As an alternative, empirical methods of lesser quantitative accuracy (described in the following section) may be employed.

Another limitation to the practical application of LEFM is illustrated by Fig. 5.23. For commonly used section thicknesses of 50 mm (2 in.) and less subjected yield stress loading, the critical depth for a fully constrained flaw (that is, one meeting the requirements of equation [5.2]) is only a few millimetres. Larger discontinuities can be tolerated only when the stress levels are appropriately reduced. This limitation must be given serious consideration since most structures have regions of stress concentration where the stresses reach the yield level. It is apparent that LEFM must be approached with caution for these regions where it is most needed. It follows that the application of LEFM to areas of high stress may require the elimination of even the very small discontinuities—that is, the ones that may escape nondestructive inspection.

Dynamic K_{Id} Characterization

Up to this point, LEFM methods have been described in terms of static loading. Because the toughness of ferritic structural steels decreases with elevation in strain rate, dynamic (K_{Id}) analyses are important to conservative assessments of structural reliability. Unfortunately, a standard test method for dynamic K_{Id} testing, similar to that of ASTM E 399 for static testing, has not yet been established. Therefore, investigators of the K_{Id} toughness trends have generally applied the concepts and restrictions of E 399.[9,10]

One difficulty with dynamic testing lies in defining the load at fracture initiation. Under rapid loading, the mass of the test specimen creates "inertial loads" which are transmitted to a transducer (load cell) in the loading train.[11] The inertial load does not represent a true load on the specimen and, in general, cannot be used to compute K_{Id}. For relatively slow loading rates, say less than 10 000 MPa • $\text{m}^{1/2}\,\text{s}^{-1}$ (9100 *ksi* • $\sqrt{\text{in.}}^{1/2}\,\text{s}^{-1}$), the dynamic effects are not large and the load cell appears to give an acceptable representation of the specimen load. For these "slow" dynamic tests, K_{Id} is determined from the maximum load in conjunction with the statically derived

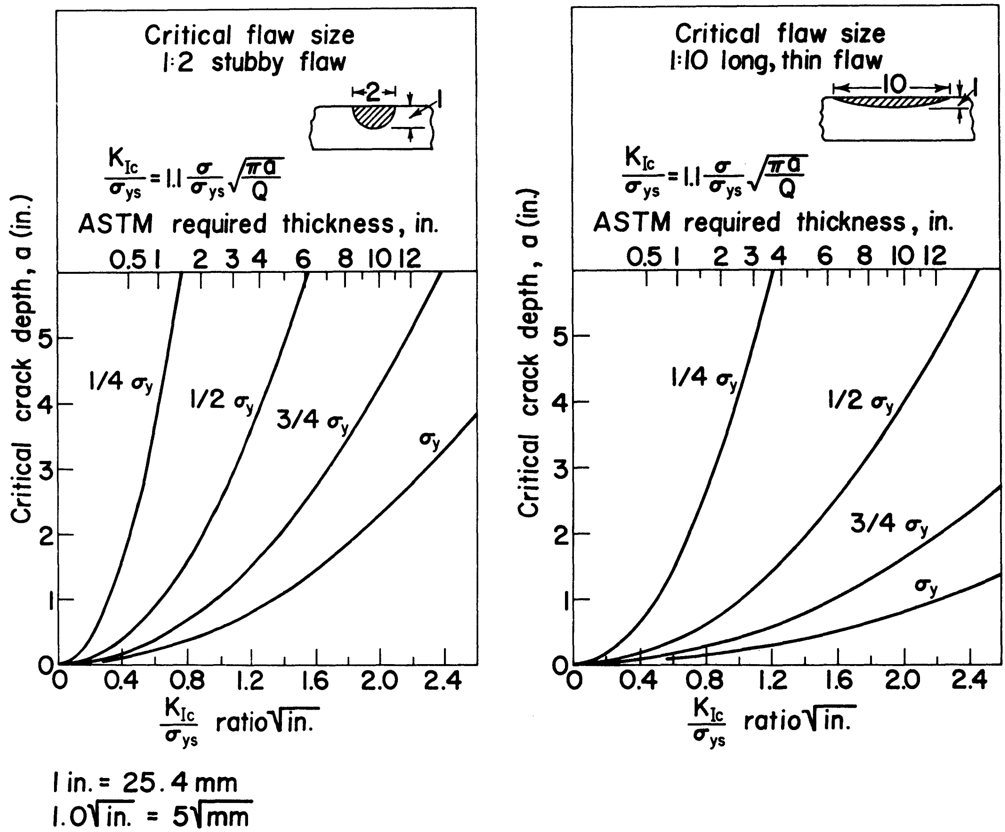


Fig. 5.23—Critical crack depths for a plate containing a surface discontinuity and subject to a nominal tensile stress, σ. The family of curves represents the values of σ for two different flaw geometries. (For SI equivalents of U.S. customary values, see the table on p. 216.)

K-equation (equation [5.1]). This method is expected to be of engineering value, but may not achieve the same accuracy limits as those for static tests conducted in compliance with ASTM E 399.

A second difficulty with dynamic testing rests in the determination of the crack length at fracture initiation. This length is determined from post-test measurements to the tip of the fatigue precrack. Near the upper levels of the plane strain region and into the elastic-plastic region, it appears that crack extension can occur prior to maximum load. In this case, the use of the maximum load is not consistent with the crack length at fracture initiation and could result in high K_{Id} values.

ENGINEERING PROCEDURES FOR ELASTIC-PLASTIC TOUGHNESS

It was pointed out using Fig. 5.18 that LEFM applies only to a limited toughness region where plane strain conditions can be achieved. For this region, LEFM presents a reliable, quantitative method with which to assess critical flaw size levels. Similar quantitative analysis procedures for the elastic-plastic region are in the research stage and not yet available for general engineering application.[12,13] As a result, present engineering methods for characterization of elastic-plastic fracture behavior are largely empirical and rely on either experience or service failure correlations.

A variety of fracture toughness procedures are used throughout the world, but in the interest of brevity, only four procedures will be discussed here: the crack opening displacement (COD) test, the Charpy V-notch (C_V) test,[14] the dynamic tear (DT) test,[15] and the drop weight-NDT test.[16] Both the C_V and drop weight tests are ASTM standard methods; the DT test is a military standard. The COD test is a tentative British Standards Institution test.

The Crack Opening Displacement (COD) Test

One of the tests which has been developed to measure toughness primarily for elastic-plastic conditions is the crack opening displacement test. This test procedure permits fracture toughness assessments to be made from specimens which do not meet the requirements for linear elastic fracture toughness. The specimen used for these tests need not be different in configuration or size from those used in LEFM tests, but may merely utilize different toughness criteria than those applied to the test data in LEFM tests. For example, when making tests of fracture toughness using the K_{Ic} approach, the load on the specimen is used to determine the K_I value at fracture. In COD tests, the clip gage opening (crack mouth opening displacement) at onset of fracture is measured and used to calculate the crack opening displacement at the crack tip, COD. The critical value of COD at fracture, known as Δ_c, is a critical strain parameter analogous to the critical stress intensity parameter, K_{Ic}. The value of Δ_c is calculated from the COD and specimen geometry.[17] It should be noted that in both these types of tests the fracture toughness specimen has a fatigue-crack sharpened notch to serve as the sharp-ended flaw required by the analysis.

The crack opening displacement concept assumes that prior to fracture, the material at the crack tip plastically strains to a blunt crack. Thus, Δ_c can be considered a measure of crack toughness in terms of the amount of plastic strain that a material will tolerate at a crack tip before failure. Like K_c, Δ_c can be related to stress and flaw size, and can thus provide a quantitative measure of allowable stress for each flaw size. In order to provide applicable data, the specimen thickness should be the same as the structure for which the data are intended.

Charpy V-Notch Test

The C_V test was developed in 1905 to make qualitative assessments of the influence of notches on the fracture behavior of steels in the transition temperature range. Since that time, this test procedure has gained worldwide acceptance and today is used routinely for steel specification and quality assurance. The test is used to determine the energy absorption in fracturing a specimen and consists of impact loading a three-point bend bar which contains a relatively blunt notch. The energy absorbed is considered to be a measure of fracture toughness.

In the 1940's, correlations were evolved to relate the maximum C_V energy to the fracture behavior of ship plates.[18] Specifically, it was discovered that fractures would initiate from small cracks when the C_V energy at the service temperature was below 13.6 J (10 ft•lbf). These fractures continued to propagate in plates having a maximum energy of 27 J (20 ft•lbf) at the fracture temperature but arrested in plates having a maximum C_V energy in excess of 27 J. By 1952, a 20 J (15 ft•lbf) C_V energy was accepted as a criterion for purposes of design and metallurgical improvement.[19] Unfortunately, it was demonstrated that for steels whose chemistry and steelmaking practice differed from that comprising the original ship fracture correlations, the critical value of C_V energy for fracture-safe assurance was not a unique value of 20 J.[20] Consequently, a particular C_V energy predicting structural integrity first required a correlation of service failures using the specific steel of interest.

To derive a more useful interpretation of C_V behavior, fracture toughness can also be defined in terms of the lateral expansion (LE) of the specimen at the point where it is impacted by a hammer. Lateral expansion is considered by some to be a ductility parameter that guarantees a certain amount of plastic deformation regardless of the energy absorption values.[21] Consequently, LE values have been incorporated in the ASME Boiler and Pressure Vessel Code and in certain ASTM steel specifications. However, the supposition that a lateral expansion criterion offers an advantage over a C_V energy criterion is considered doubtful by others.[22]

Some investigators and designers do not believe that the C_V test is a reliable measure of fracture behavior in a real structure. They point out that the dull and shallow notch, the small specimen size, and the short unbroken ligament under the notch do not adequately represent the sharp, highly constrained discontinuites in a large structure. Other designers believe that satisfactory empirical correlations of C_V test behavior and the fracture behavior in structures have been developed and employed for fracture control.

Drop Weight—NDT Test

The drop weight test design, developed starting in 1953, was based on service failures resulting from a brittle fracture initiation at a small flaw located in a region of high stress. To simulate this behavior, a specimen consisting of a small plate section containing a brittle weld region was devised. The specimen (Fig. 5.24) is dynamically loaded in bending by a falling weight which causes the specimen to deflect a fixed distance (restricted by "stops"). During the test the weld is fractured and the plate is subject to a strain of several percent if the base metal does not fracture.

The fractures illustrated in Fig. 5.24 (top) show a change from break to no-break performance that evolves sharply within a 6 to 11 °C (10 to 20 °F) temperature increment. The highest temperature at which the specimen breaks is termed the nil-ductility transition (NDT) temperature. The sharp change between break and no-break performance is an indication of the brittle-ductile transition phenomenon exhibited by the mild steels. It should be apparent, however, that an NDT temperature can be obtained only for steels that do exhibit a sharp temperature transition behavior, thereby excluding the high strength steels. Also excluded from the test method are steels that develop a tough heat-affected zone resulting from the brittle weld deposit. In other words, a tough heat-affected zone would result in an erroneously low value for NDT.

The NDT temperature has provided a means for correlating ship fractures and other service failures. On the basis of such service failures, a fracture analysis diagram was developed for the correlation of critical flaw lengths and stress levels with temperature above the NDT temperature.[23]

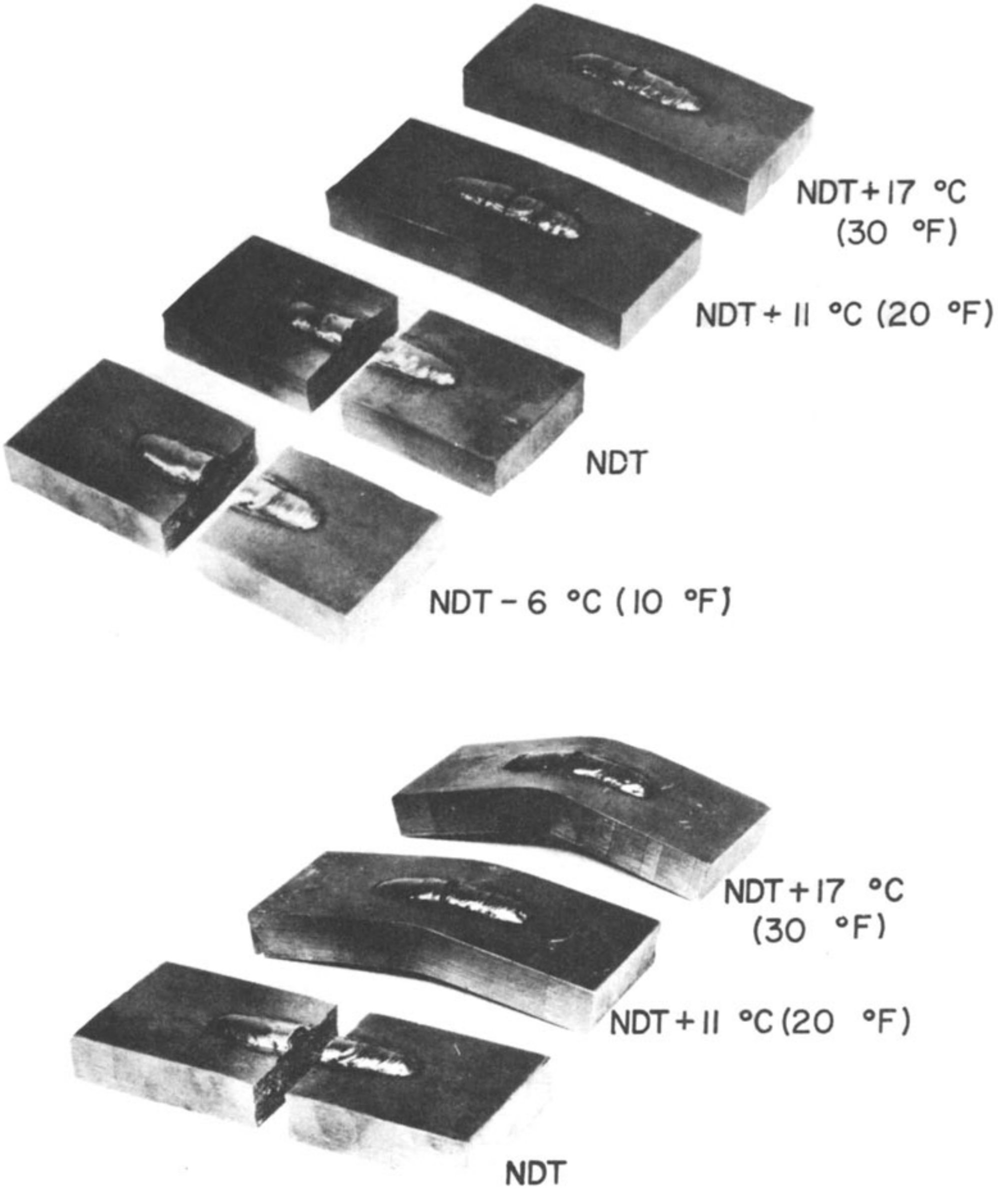


Fig. 5.24—Fracture appearance of drop weight-NDT specimens. The upper series of specimens represents those conducted in accordance with ASTM E 208. In the lower series the specimen deflection stops have been removed to demonstrate the sharp increase in plastic deformation exhibited by the material within 11 °C (20 °F) above the NDT temperature. The specimen size is 50 x 125 x 16 mm (2 x 5 x 5/8 in.).

Dynamic Tear Test (DT)

As just discussed, the drop weight test serves to define the beginning of the brittle-ductile temperature transition region and can be used to predict structural integrity. In the early 1960's, it became apparent that a new fracture test procedure was required to characterize the properties of the ultra-high strength steels as well as aluminum and titanium alloys that do not exhibit a temperature transition behavior and the steels of intermediate strength which feature a low value of upper shelf (above the transition range) energy.

To fulfill the above needs, the DT specimen (Fig. 5.25) was designed to simulate the critical structural features that affect fracture toughness.[18] The specimen thickness may be adjusted to match that of the structure and thus achieve the proper mechanical constraint. However, the standard specimen (Fig. 5.25, top) is of a 16 mm (5/8 [0.625] in.) thickness.[13] The DT specimens feature a deep, machined notch with a knife sharpened tip so

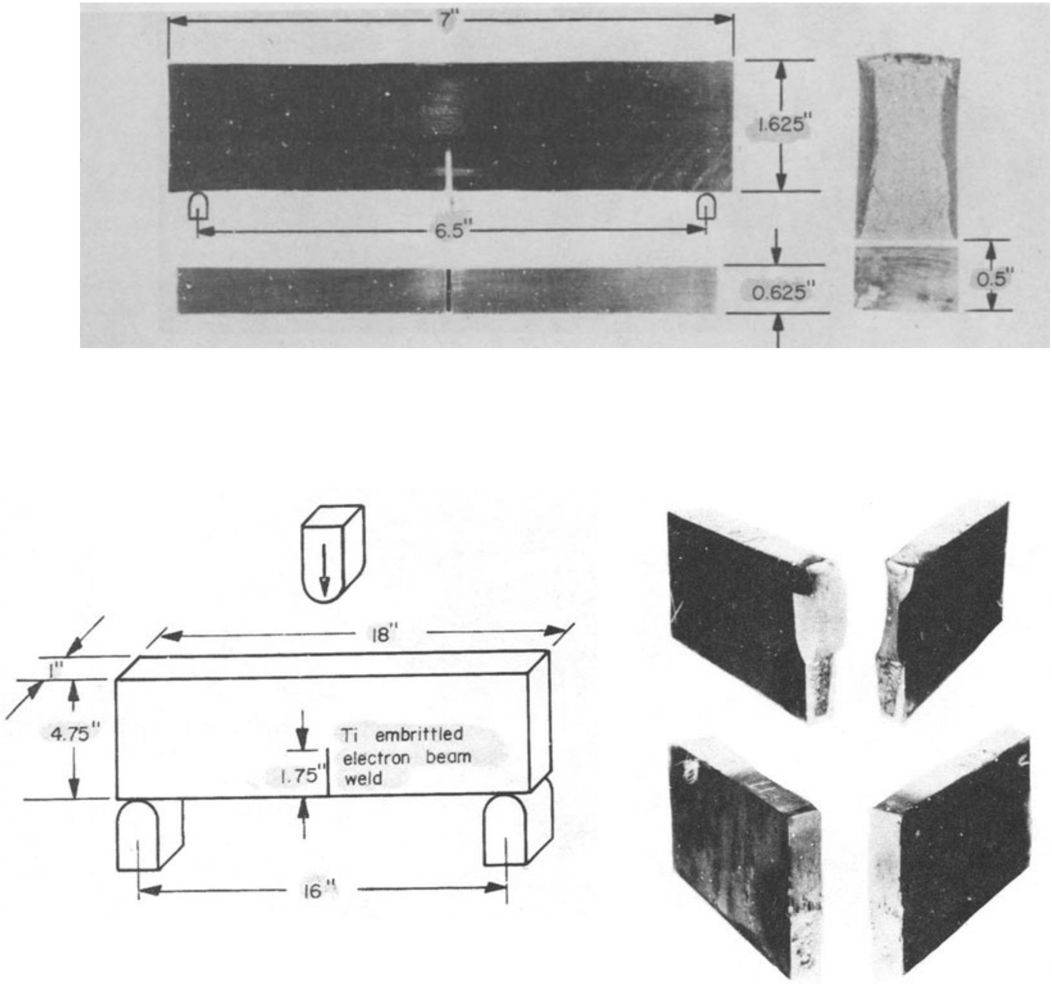


Fig. 5.25—Dynamic tear (DT) test specimen configuration. The standard specimen (top) features a machined notch with knife-pressed tip.[18] *Other specimens (bottom) employ a brittle crack starter region in place of the machined notch. (For SI equivalents of U.S. customary values, see the table on p. 216.)*

as to achieve maximum constraint for a given thickness.* The unbroken ligament is of sufficient length to simulate a fully developed fracture. The specimen is tested by impact loading to account for the strain rate sensitivity of some metals, and the absorbed energy is recorded. The features combine to produce a test of high severity.

The important features of the DT test performance are illustrated in Fig. 5.26 for a steel which exhibits a temperature transition behavior. For steels such as these which have high upper shelf energies, the DT energy exhibits a sharp increase above the NDT temperature. It is important to note that the NDT temperature is consistently indexed by the lower toe region of the 16 mm (5/8 in.) DT curves.

The correspondence of the DT trends with those of the Robertson crack arrest test (CAT) is also illustrated in Fig. 5.26. The Robertson specimen consists of a tension-loaded plate in which a running crack is introduced. Depending on the applied stress level and temperature, the initial crack will arrest in the test plate or result in a complete break. The curve of "run" versus "stop" behavior as a function of temperature is called the CAT curve. The correspondence of the DT and CAT curves illustrated in Fig. 5.26 gives the former a structural significance (since the Robertson test is, in effect, a structural member). Also note that the mid-energy range of the DT curve relates to yield stress loading of the Robertson test. Hence the energy level of the DT test can be related to nominal stress level in a structure.

The results of the test can also be directly correlated with fracture toughness concepts. This is done through a series of semi-empirical relationships developed from data or plates for which K_{Id}, DT impact energy, and K_{Ic} data were available. The procedure, although complicated can be simply stated. The basic premise is that the midpoint in energy of the test curve occurs at a condition where a through-thickness crack in the section size tested would have to reach dynamic yield point stresses to propagate. This is interpreted to mean that the following condition is fulfilled:

$$B = 1.0 \frac{K_{Id}}{\sigma_{yd}} \tag{5.3}$$

where B is the section thickness and K_{Id} and σ_{yd} are the dynamic fracture toughness and dynamic yield point, respectively. The dynamic yield point is estimated by adding 210 MPa (30 ksi) to the static yield point. The energy midpoint (mentioned above), called the YC or yield criterion point is then a fracture mechanics parameter from which the K_{Id} may be estimated.

SPECIAL PROBLEMS OF WELDED JOINTS

The welded joint presents a special problem in evaluating fracture toughness because it contains a wide gamut of microstructures oriented as thin layers adjacent to the weld metal. Any test for evaluating the toughness of welded joints therefore should assess the effect of these varied microstructures and, if possible, assign a toughness index to each. This has the value of establishing which of these structures is the most critical, the "weak link," and what the relative behavior of each zone is. It is, however, not at all certain that a "weak link" will fail in actual service. For example, in some steels the heat-affected zone is known to be less tough than the base metal or weld metal. However this zone may be rather narrow and irregular and the fracture may not be restricted to it. As a result, fracture behavior may not reflect the toughness of this zone alone but may be affected by the portion of the crack front which passes through tougher regions. The fracture toughness test specimens are, in some ways, more suited to testing a

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*Alternate specimen designs employ a brittle weld region in place of the machined notch. For steels with a hardness above HRC 36, a knife blade will no longer sharpen the machined notch tip and a fatigue precrack is often used.

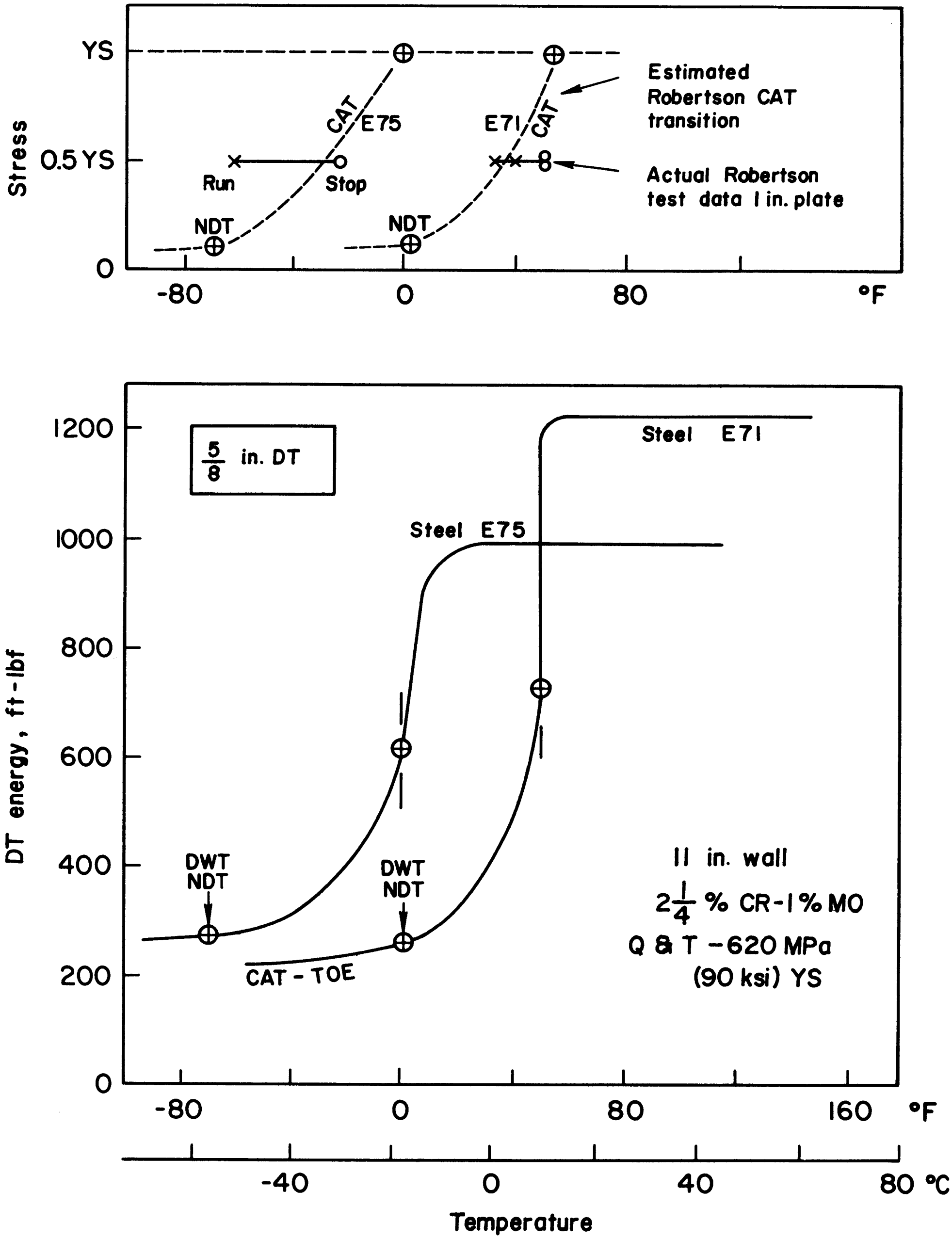

Fig. 5.26—Dynamic tear (DT) energy trends for steels which exhibit a temperature transition behavior.

specific zone than many of the more conventional fracture tests. Since it is a requirement that the notch or crack in the specimen be in a specific zone, that zone should therefore tend to dominate the fracture properties that are measured.

Fatigue cracking of the specimens may cause difficulty in preparing LEFM or COD test specimens. Although the initial notch may be located in a specific zone, it has been observed that the fatigue cracks may tend to curve away from this zone again, and the fracture may not run in this zone. Thus a test intended for the heat-affected zone may eventually end up failing in the weld metal or the base metal and data intended to represent the heat-affected zone may, in fact, not represent this zone at all. In spite of precautions against this phenomenon (for example, prior compression of the specimen to establish favorable residual stress patterns), [24] it has been found that in some combinations of weld metal, base metal, and heat-affected zone, the locus of a crack directed into one of the specific zones, especially the heat-affected zone, is very hard to control.

Another problem in these tests is the complex nature of the zones themselves. The heat-affected zone in reality encompasses a series of zones. Therefore a judgment must be made as to which part of this zone to test. Most engineers prefer to test the zone in its least favorable region—the coarse-grained zone near the fusion line.

The heat-affected zone also differs from the others in another significant respect: it does not exist by itself in a specimen and is usually too small to test alone. Weld metal and base metal may be tested by cutting a specimen from the regions of interest. If the weld metal itself is too small a region to test, it may be built up with additional passes to make a weld metal pad to use for testing. This is not possible with the heat-affected zone. This zone must either be tested in position, or as an artificial zone created by use of thermal cycle simulation. Simulated heat-affected zones are currently available only in small sizes (Charpy specimen size) and are thus not suitable for other tests.

In any case, removing small specimens from welded joints tends to relieve residual stresses and thus change the fracture characteristics.* The best test is one that retains the residual stress pattern around the weld and such a test usually requires a large weld specimen. The larger specimen also preserves the elastic constraint of one zone, such as a hard heat-affected zone, on surrounding zones and this feature may be important in welded joint behavior.

The geometry problem in testing welded joints is usually overcome by use of special weld groove preparations, especially with respect to the weld heat-affected zone. One of the more common methods is to prepare a "K" type of joint, with one side cut straight and the other containing a double bevel. This joint provides a straight sided heat-affected zone for notching and testing.

In this case, however, the joint is not a realistic one from the standpoint of service joints, which do not often contain a straight heat-affected zone. The testing of a weld composite, it can be argued, must include the geometry that truly represents the service joint. For this reason, there are also a number of tests that are conducted on specimens cut from actual, rather than artificial, joints so that failure is not prejudiced by arbitrary joint design. In many respects this is a more realistic test since failures that occur in specific joint locations, say in the heat-affected zone at a weld toe, must always traverse some base metal, and perhaps even weld metal, to propagate through the joint.

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*The relationship between residual stresses and unstable fracture is discussed on pp. 231-234 in Chapter 6.

FATIGUE PROPERTIES OF WELDED STRUCTURAL JOINTS

When subjected to repeated cyclic stress, metals have a tendency to break at a stress considerably below their ultimate tensile strength. The term fatigue failure commonly denotes failure under many repetitions of load. This load would be insufficient to cause failure if applied slowly and repeated less frequently. Fatigue failure is progressive. It originates in a highly localized region of stress concentration, at design or fabrication discontinuities which act as crack initiators. The net result is the development or extension of the initial crack condition under cyclic load until the member fails due to reduction in the effective load-carrying area of the cross section.

The fatigue strength of a part or member is much more dependent on the localized state of stress than is the static strength. The difference between fatigue and static strength varies with design and fabrication methods. For example, in machine design very high fatigue strengths have been developed by providing streamline section transitions and smooth machining-stressed surfaces and by introducing compression residual stresses through shop peening or other methods. Comparable methods have also been used in aircraft structures.

However, in bridge and building fabrication, such operations may be costly for most applications. As a result the fatigue strength of a part or member is much more dependent on abrupt changes in section, rivet and bolt holes, undercutting at the toes or edges of welds, incomplete fusion, slag inclusions, porosity, and other miscellaneous discontinuities.* Other factors such as sharp re-entrant corners, grooves, screw threads and other notch-like details of design or workmanship are more likely to exist. These result in fatigue strengths which in many cases can be substantially less than the static strength of the member. Fatigue failure also depends on the number of repetitions of stress and the nature and range of the stress. When the number of repetitions of stress is decreased, the fatigue strength approaches the static strength.

When the number of cycles is lower than about 10^4 to 10^5 cycles (which depends on the type of design detail), the term "low cycle fatigue" is sometimes used. This section describes methods of fatigue testing welded steel components. Emphasis is placed on the as-welded behavior more common to buildings and bridges.

DESCRIPTION OF PHENOMENON

Fatigue has been basically an empirical problem from a design point of view. A number of theories and explanations have been advanced based on phenomenological occurrences, deviations of stresses on the slip planes of the molecular structure, unbonding, and so forth. Attempts have been made to find general mathematical laws for the relationship between load and life with little or no success. In more recent years, the concept of fatigue damage as being the growth of cracks from preexisting discontinuities has shown considerable promise.[25]

As was stated in the previous section on fracture toughness, all welding processes introduce small discontinuities in or near the weld. Irregular oxygen-cut edges and steel-stamped part numbers also introduce discontinuities. Good welding practice will minimize the number and size of these discontinuities thus increasing fatigue life. They cannot be eliminated however. They exist and good design practice must reflect the fact.

In general, initiation and growth of

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*See section on weld discontinuities, pp. 209-215.

fatigue cracks are most likely to occur in areas subjected to a high tensile stress range and where initial discontinuities exist. The higher the stress range and the larger the initial flaw, the faster fatigue cracks will propagate. For example, stress concentrations and initial discontinuities may exist along the toe of the fillet welds connecting stiffeners, attachments, or cover plates to the tension flanges of girders and provide conditions favorable for crack growth.

Under cyclic stresses of sufficient magnitude, cracks can initiate and grow.[26] A typical fatigue crack causing failure at a stiffener detail is shown in Fig. 5.27. The detail was subjected to a 100 MPa (14.4 ksi) stress range and sustained 2 616 000 cycles.[27] The crack initiated and grew at several points along the toe of the fillet weld connecting the stiffener to the tension flange. Crack growth was characterized by stages. During the first stage, each individual crack propagated in a semi-elliptical shape as shown in Fig. 5.28. As the small cracks grew larger, they joined each other and eventually assumed the shape of a larger semi-elliptical crack as illustrated in Fig. 5.29 (cover-plated beam). Before the crack front reached the extreme fiber of the tension flange, the crack width had spread over most of the transverse weld length for the details shown in Figs. 5.27 and 5.28.

In joint designs which have relatively small stress concentrations, a much higher fatigue strength results and crack growth may originate at internal discontinuities in both fillet and groove welded joints.[28, 29] For example, in welded girders, discontinuities in the web-to-flange connection can propagate into fatigue cracks under high repetitions of a high stress range.

Cracks starting at discontinuities like gas pockets or blow holes can take the shape of a disc and, at first, are completely inside the weld, as shown in Fig. 5.30. The discontinuity then initiates a fatigue crack that propagates out to the fillet weld surface and continues to grow in the flange-to-web junction in a region of high tension residual stress until it reaches the surface of the opposite fillet weld. It then penetrates the outside fibers of the flange maintaining a penny shape throughout this process. The crack continues to grow on two fronts toward the flange tips until the flange fractures. When the discontinuities and geometrical stress concentration conditions are minimized, very high fatigue strengths result. Plastic strains may be necessary before fatigue damage occurs in such cases.

When cyclic stresses are low enough, all design details appear to exhibit a crack growth threshold below which a crack will not propagate. Studies have indicated that this behavior is apparently related to the crack

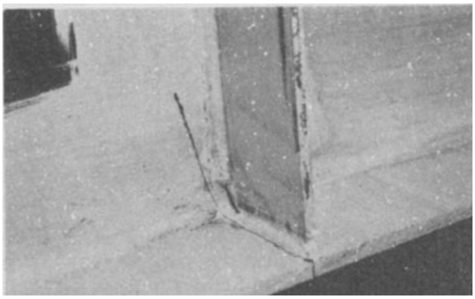

Fig. 5.27—Fatigue crack at a welded stiffener detail.

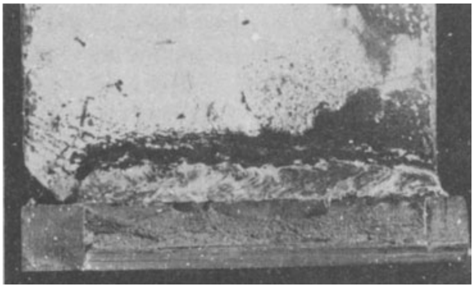

Fig. 5.28—Small semi-elliptical fatigue cracks of a stiffener weld toe.

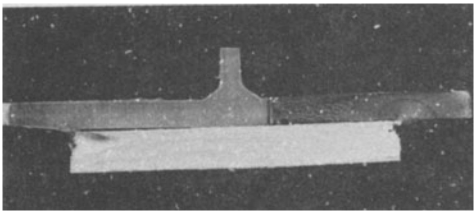

Fig. 5.29—Fatigue crack at the end of a longitudinal weld of a cover plate to beam showing a semi-elliptical shape up to the penetration of the flange.

ron, usually with less than 0.5 percent carbon and varying, but minor amounts of manganese, phosphorous, sulfur, and silicon. The properties and weldability of these steels depend mainly on their carbon content, although the other elements do influence these properties to a limited extent. Plain carbon steels frequently are categorized in relation to their carbon content as indicated in Table 4.3.

*Low Alloy Steels.** The carbon content of these steels usually is less than 0.25 percent and frequently is below 0.15 percent. Other alloying elements (nickel, chromium, molybdenum, manganese, silicon) are added to increase the strength of these steels at room temperature and at elevated temperatures, as well as to impart better notch toughness at low temperatures. These elements also alter the response of the steels to heat treatment, and can improve their corrosion resistance. Sometimes these additions reduce the ease with which the steels can be welded.

Modern design requires steels that have higher strength and toughness than the plain carbon and structural steels. A yield strength of 345 MPa (50 000 psi) and a tensile strength of 480 MPa (70 000 psi) are achieved in the as-rolled condition by adding two or more alloying elements; adequate weldability is maintained by restricting the carbon to 0.20 percent maximum. Some of these steels are heat treated up to 690 MPa (100 000 psi) yield strength and they have better notch toughness than the ordinary carbon steel grades. Proper choice of filler metal and welding procedures will develop comparable properties in welded joints in these steels.

A wide variety of steels has been developed for use in machinery parts. These steels, many of which are eminently weldable, have been classified according to chemical composition by the AISI-ASME classification system. Other steels have been developed to meet the needs of the cryogenic industry. Those steels have good notch toughness at temperatures well below zero. Fine-grained aluminum-killed steels with up to ten percent nickel are frequently used for cryogenic service.

Low alloy steels have also been developed for high temperature service in welded structures such as steam boilers, oil refining towers, and chemical processing retorts. Additions of chromium and molybdenum give these steels structural stability and provide high creep and stress rupture values at temperatures up to 595 °C (1100 °F).

*High Alloy Steels.*** This group of steels consists of high quality, expensive steels with outstanding mechanical properties, corrosion resistance, oxidation resistance, and elevated temperature strength and ductility.

Dies, punches, shears, etc. are made from high carbon tool steels that also contain moderate amounts of other alloying elements. These steels have outstanding hardness at room temperature and some of them retain their hardness at elevated temperatures. These steels generally are difficult to work with and require considerable care in welding.

Most of the high alloy steels are stainless steels. Stainless steels resist attack by many corrosive media at atmospheric or elevated temperatures. They contain at least twelve percent chromium and many of the grades have substantial amounts of nickel. Other alloying elements are added for special purposes.

There are three basic types of stainless steel: austenitic, ferritic, and martensitic. Some of these steels are precipitation hardenable. The martensitic stainless steels contain the smallest amount of chromium and they can be quite hardenable. One classic example is the cutlery grades, which are included in this group.

Care must be taken when welding the martensitic steels since martensite tends to be produced in the heat-affected zone, and can be very hard. Preheating and a postheat treatment are necessary to prevent cracking.

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*Chapter 63 in Section 4 of the *Welding Handbook*, Sixth Edition covers these steels in detail. In the Seventh Edi-

**High alloy (stainless) steels are covered in Chapters 64 and 65 of Section 4 of the *Welding Handbook*, Sixth Edition. Stainless steels tentatively will be covered in Volume 4

MEASUREMENT OF FATIGUE PROPERTIES

High Cycle Fatigue (more than 10^5 cycles)

As has already been indicated, the major variables thát influence the fatigue strength of welded joints are the stress range and the type of design detail. The major effect of the type of design detail is the geometric stress concentration that it produces. The smaller the geometric stress concentration, the longer the fatigue life. Hence care should be exercised in the fabrication of test specimens so that they properly reflect the conditions that will exist in the actual structure.

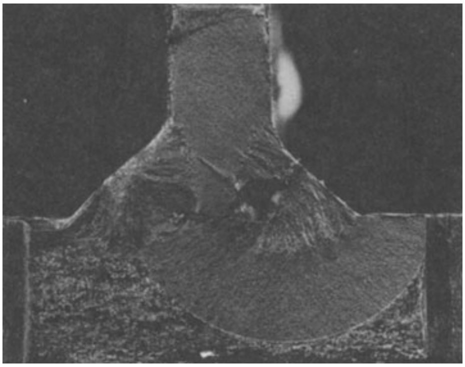

Fig. 5.30—Disk-like crack in a flange-to-web fillet weld.

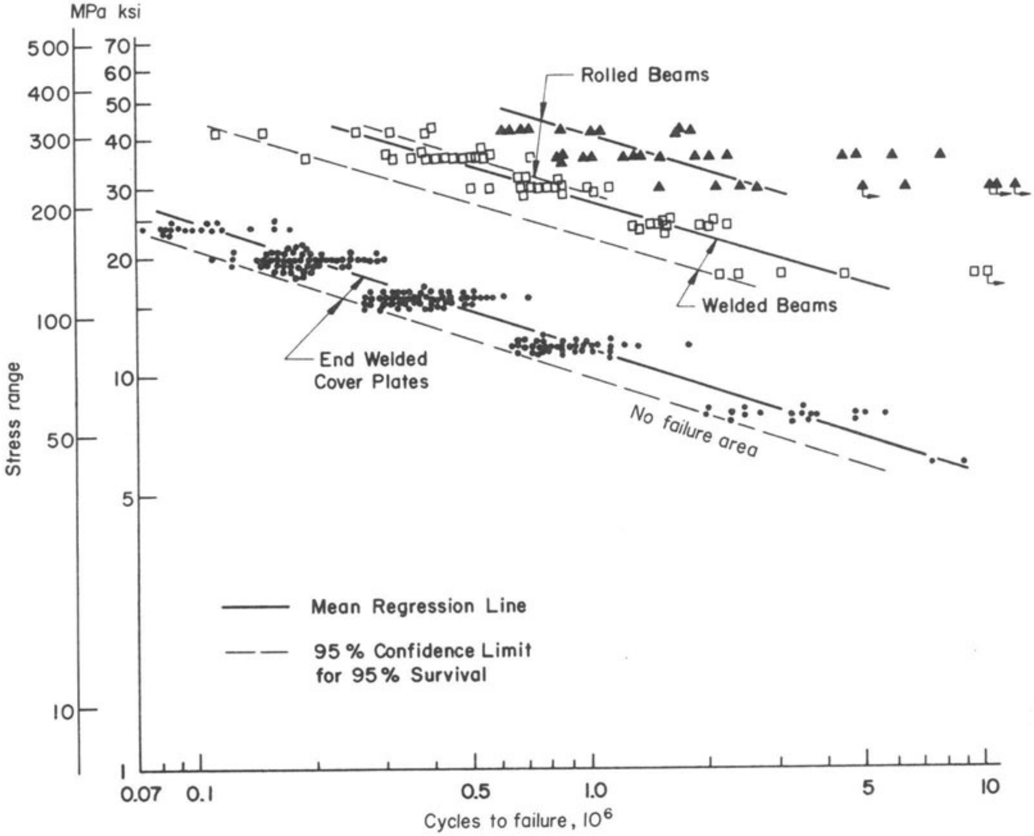

Fig. 5.31—Stress range-cycle life relationship for several welded details compared to rolled beams.

The experimental determination of a stress range-cycle life relationship is related to the rate of crack propagation. Generally this relationship defines the fatigue strength between 10 000 and 10 000 000 cycles of loading. The crack growth threshold starts somewhere between two and ten million cycles in several design details. It corresponds to a limiting value of stress range below which the detail can endure extremely large numbers of cyclic loading with no apparent crack growth. This threshold is often called the fatigue limit.

The data obtained from more than 200 tests of cover-plated beams which were loaded with different stress cycles are generally summarized in a stress range-cycle life plot as illustrated in Fig. 5.31.[29] Between 70 000 and 5 000 000 cycles, the resulting curve has a slope directly related to the exponent in equation (5.5). It is also apparent that a lower limit to the fatigue strength is being approached as the stress range decreases to about 34 MPa (5 ksi). When a large quantity of experimental data is available, the slope of the SN (stress versus number of cycles) curve can be made more compatible with the crack growth exponent. This result illustrates the desirability of conducting a sufficient number of tests, so that uncontrolled variables such as weld profile and initial discontinuities are properly accounted for.

Low Cycle Fatigue (less than 10^4 to 10^5 cycles depending on design detail)

Unless large discontinuities or cracks exist in a structural component, low cycle fatigue requires large strains to be introduced into the component. These strains often produce changes in the geometry and material properties which complicate the analysis and evaluation of the problem. These factors also make it difficult to refer to actual stresses or strain distributions and results are often related to initial conditions.

The information available on low cycle fatigue is not as extensive as it is for high cycle fatigue.[34] Often it is possible to relate the number of cycles for failure to the magnitude of the cyclic strain.[35] In extreme cases, only a few cycles of load may result in failure if sharp notches exist due to flaws or geometric discontinuities.

Low cycle fatigue may occur in structures or components which remain stable under large cyclic plastic strains.[36] Large strains due to overloads or thermal conditions can occur in such structures. Tests on simple specimens or on welded joints have all demonstrated that severe cyclic loading into the inelastic range is necessary to cause low cycle fatigue.[37]

TEST SPECIMENS

One very important aspect of structural details that is often overlooked is the presence of residual stresses.* They are a major factor in the behavior of welded built-up connections.[28, 38] The welding process results in high tensile residual stresses which approach yield point magnitude as a limit in the weld metal and base metal adjacent to it. This result is due to the shrinkage of the weld on cooling. Thus, at least the early stages of fatigue crack growth in an as-welded structure occur in regions of high tensile residual stress. Under applied cyclic loading, therefore, the actual stress cycle to which the material adjacent to the weld will be subjected will generally vary from yield stress tension downwards, regardless of the nominal stress cycle. For example, if the nominal stress cycle is $+\sigma_1$ to $-\sigma_2$, giving a total range of $(\sigma_1 + \sigma_2)$, the actual stress cycle will vary from $+\sigma_y$ to $\sigma_y - (\sigma_1 + \sigma_2)$, where σ_y is the yielded stress. This condition explains why one would expect the fatigue behavior of a welded joint to be capable of expression merely in terms of stress range.

Tests of welded beams with a variety of design details have confirmed the growth of flaws in tensile residual stress zones. Crack growth was observed in both tensile and compression flanges of welded beams. When no reversal of loading was applied to the compression flange, the crack arrested when it

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*The origin of these stresses is described further in Chapter 6, p. 221.

grew out of the region of tensile residual stress.

However, a somewhat different situation exists in many of the axially loaded specimens which are tested in the laboratory. Owing to limitations of testing machine capacity, specimens are usually of relatively small cross section; for example, 100 or 125 x 13 mm (4 or 5 x 1/2 in.) thick is a fairly typical size. Thus, in the case of specimens with transverse welds, lateral weld shrinkage can be relieved by movement of the parts being joined, and longitudinal stresses are low because the weld is short. The removal of a small test specimen relieves much of the remaining residual weld stress. This indicates that few specimens with transverse welds containing the high tensile residual stresses existing in most structures have been tested.

The situation just described implies that test results are quite misleading in defining the fatigue strength of a real structure, at least for specimens with transverse welds and with loads that alternated between tension and compression. In these specimens, the compressive part of the cycle will be partly nondamaging whereas in a real structure, with high tensile residual stresses, it would be damaging. This problem does not arise in the case of specimens tested under full tensile loading.[38]

A related variable is the size and distribution of the initial discontinuity in or near the welds. In welded built-up members, these discontinuities occur in regions of tensile residual stress and form the source of crack nucleation and growth.[27, 29, 38] Consideration of these factors should be taken into account during the design of the test specimens and experiment design.

Crack growth in welded details is governed by stresses that are applied perpendicular to the plane of the discontinuity or the projection of the discontinuity on that plane. In details that are subjected to combined shear and moment, the crack will propagate perpendicular to the principal tensile stress. In most details, shear stresses are not as significant as the axial stress component. For example, transverse stiffener details are reasonably described by bending stresses alone even though the principal stress provides a theoretically correct correlation.

Care should also be exercised in the choice of maximum stress in the stress cycle. It has been common practice in many experiments to control the ratio of minimum and maximum stress. This has resulted in maximum stresses that exceed the yield point and often approach the tensile capacity. Such conditions are not applicable to the structure and detail they are intended to simulate and should not be used.

FATIGUE STRENGTH OF WELDED JOINTS

In the past, only approximate general design relationships in fatigue have been possible because of the limited experimental data available. Recent studies at Lehigh University on some 531 steel beams and girders have shown that stress range is the most significant stress factor in fatigue design. The tests included rolled beams, welded beams, groove welded splices with the reinforcement removed at transitions in width, square ended cover plates with and without transverse end welds, cover plate width and thickness transitions, multiple cover plates, and beams with stiffeners and attachments.[27, 29]

Design Details that Experience Crack Growth from Internal Discontinuities

In welded built-up beams, the crack causing failure initiated at a discontinuity in the fillet weld at the flange-to-web junction. In beams with groove welded flange splices at transition in width with the weld reinforcement removed, fatigue crack propagation generally occurred as follows: (1) from a weld discontinuity in the longitudinal fillet weld at the flange-to-web junction in a manner similar to the plain welded beams, or (2) in the ground groove weld detail near a discontinuity or mechanical notch. A relatively high fatigue strength resulted and the test results for the flange transition at a groove weld with the

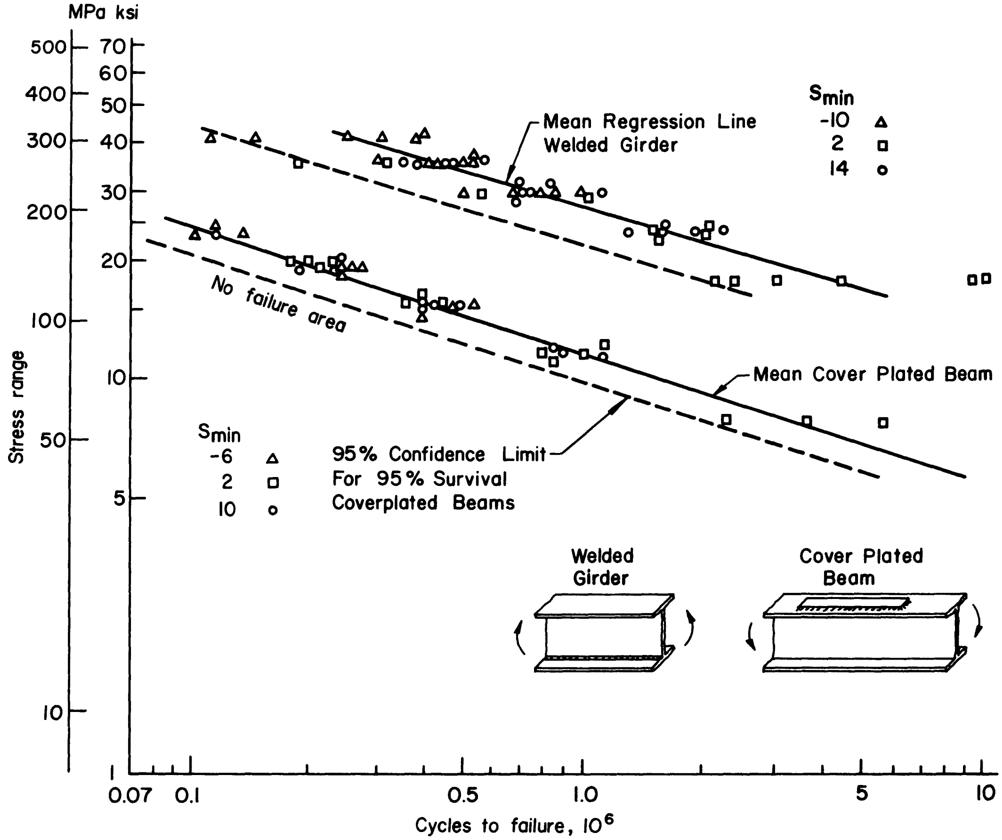


Fig. 5.32—Effect of minimum stress on stress range-cycle life relationship.

reinforcement removed provided a fatigue strength that was identical to the welded beam.

The test data for the welded beam and cover-plated beams are summarized in Fig. 5.32.[27, 29] Stress range is plotted as a function of cyclic life for several different levels of minimum stress on a log-log scale. It is visually apparent that stress range accounted for the fatigue strength for both structural details; that is, the minimum or maximum stress showed no consistent influence on the fatigue behavior.

The tensile property differences of the structural steel grades were overshadowed in these tests by design configuration. Figure 5.33 shows the individual fatigue values for welded beams of ASTM A36, A441, and A514 steel (nominal yield point 250 MPa [36 ksi], 345 MPa [50 ksi], and 700 MPa [100 ksi], respectively). For a given stress range, there is a scatter in fatigue life, probably due to inherent variation in weld surface irregularities, soundness, and penetration.

Design Details that Experience Crack Growth from Weld Toe

Evidence indicates that the termination of groove and fillet welds provides a more critical fatigue condition than internal discontinuities. This is illustrated in Figs. 5.32 and 5.34 where beam test data for cover plates, and a transverse member attachment to the flange are summarized. The welded connection with the highest fatigue strength is the welded beam without attachments. In the

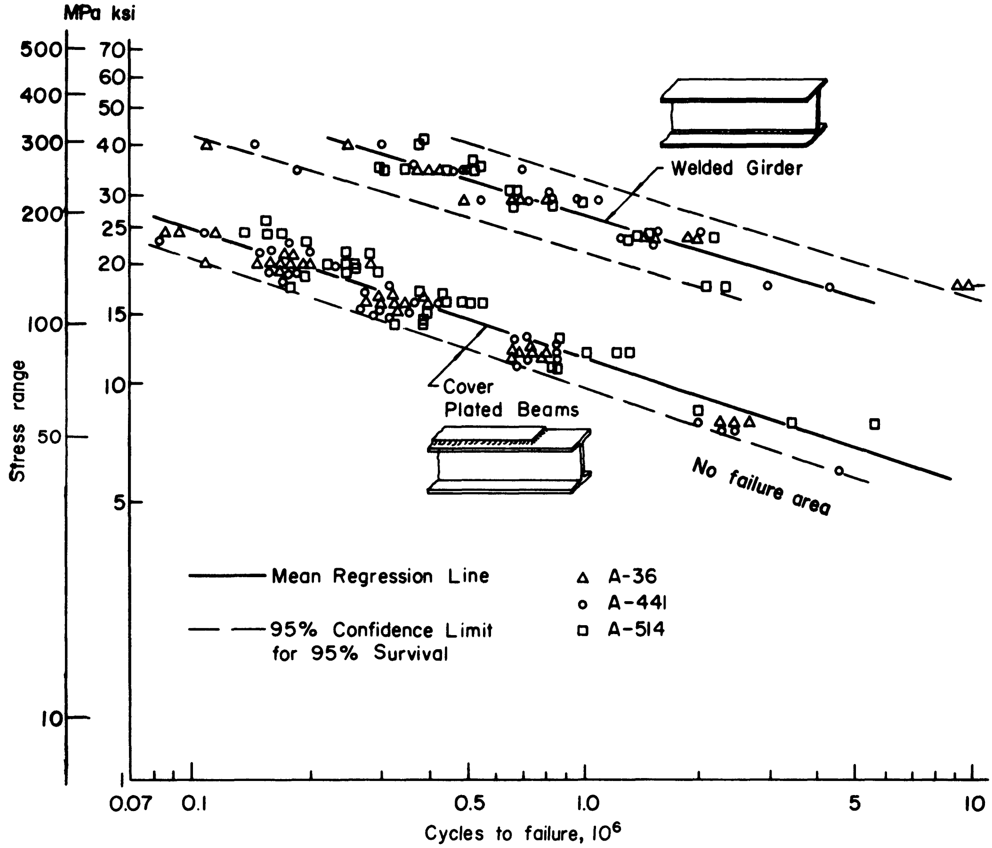


Fig. 5.33—Effect of type of steel on stress range-cycle life relationship.

cover-plated beam, cracks nucleated and propagated from the toe of the fillet welds at the end of the cover plate. In general, the growth of fatigue cracks at such locations are most likely to occur because the area is a region of high stress concentration and tensile residual stress.

The reduction in fatigue strength at a transverse stiffener (Fig. 5.35b) is approximately 50 to 55 percent of the strength for base metal or rolled beam. About the same strength is also provided by short attachments up to 50 mm (2 in.) in length in the direction of the applied stress. Transverse attachments which provide a minimum length of weld in the direction of the primary bending stress provide the least decrease in fatigue strength. In general, the discontinuity results in crack growth in the form of a semi-elliptical shape until the crack has penetrated the thickness of the load-carrying element. Thereafter very rapid growth occurs and relatively little life remains in the structural detail.

As the attachment length is increased, the forces developed in the attachment increase. This causes an increase in the stress concentration effect which in turn decreases the fatigue strength. For fillet or groove welded attachments up to 100 mm (4 in.) in length, an additional ten percent decrease in fatigue strength results.[27] (See Fig. 5.34.)

A reduction in fatigue strength of 60 to 70 percent from the rolled beam is ex-

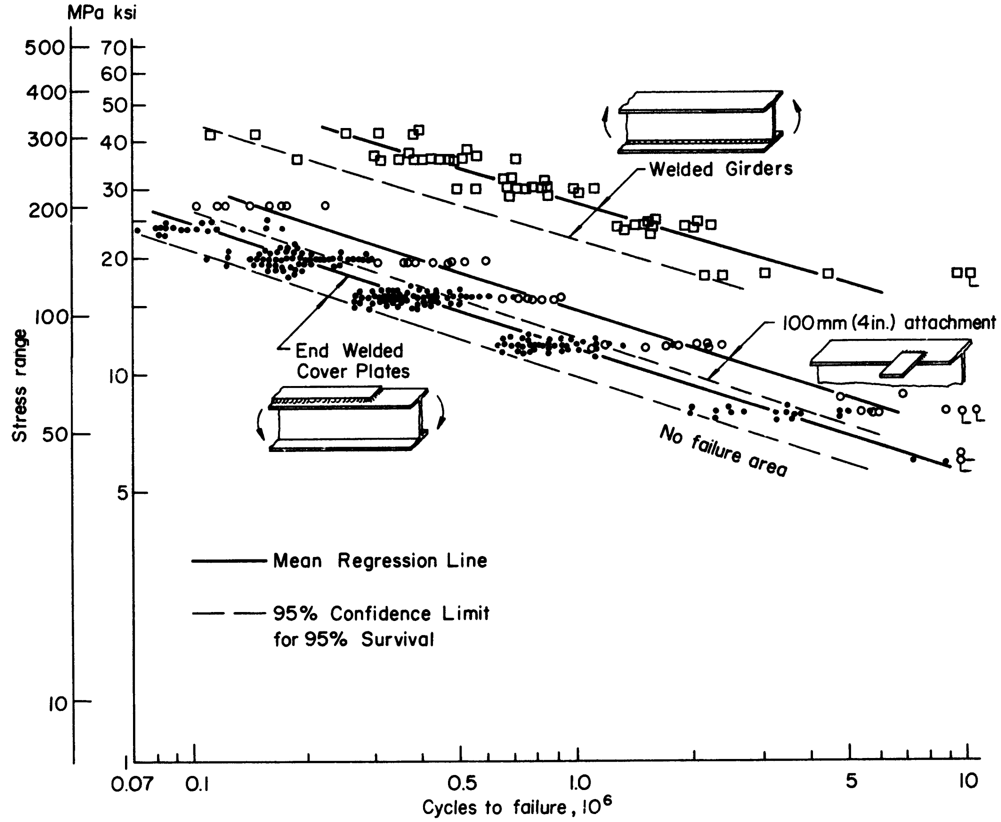


Fig. 5.34—The effect of attachment length.

perienced at the lower bound cover-plated beam condition. The increasing length results in the development of greater forces in the attachment which in turn cause a more severe condition at the termination of a weld. Experimental evidence on fillet and groove welded connections verify the reduction in fatigue strength with increasing attachment length. Studies show that a cover-plated section reached conformance with the theory of flexure at a distance from the end of the cover plate equal to approximately twice the cover plate width. This result applied to beams with end welds across the cover plate and at a distance equal to approximately three times the cover plate width without end welds.

Fatigue Strength of Welded Aluminum Joints

The preceding discussion has been devoted to the fatigue strength of welded steel joints. Available information on welded aluminum joints shows that the same factors influence their fatigue strength.[39] The type of detail with its resulting stress concentration was particularly important for those details experiencing crack growth from the weld toe. When growth occurred from internal discontinuities, the size of internal discontinuities was a governing factor. Although the test data are described in terms of maximum stress in Reference 38, stress range is the most significant stress factor in the data summary.

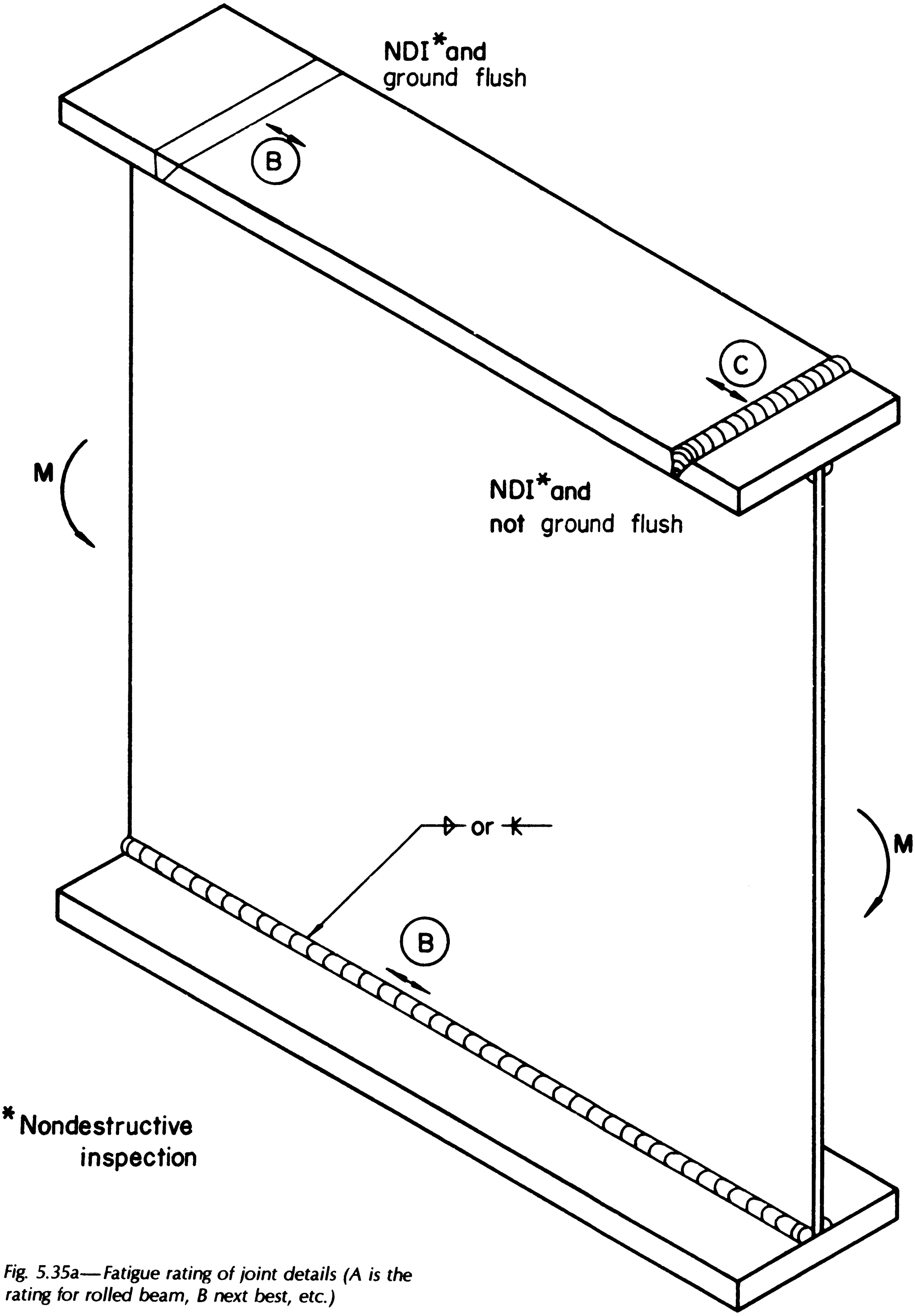


Fig. 5.35a—Fatigue rating of joint details (A is the rating for rolled beam, B next best, etc.)

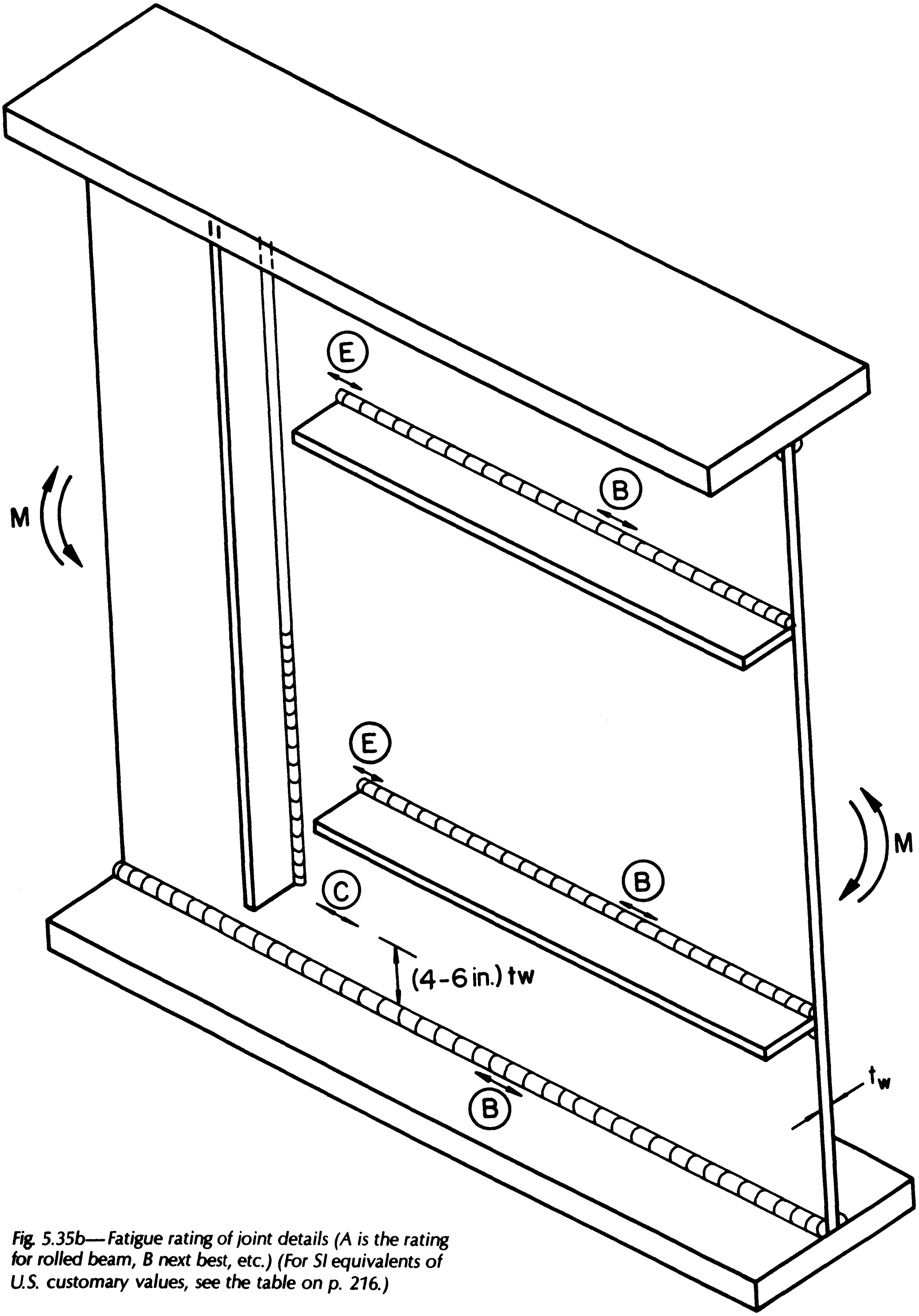


Fig. 5.35b—Fatigue rating of joint details (A is the rating for rolled beam, B next best, etc.) (For SI equivalents of U.S. customary values, see the table on p. 216.)

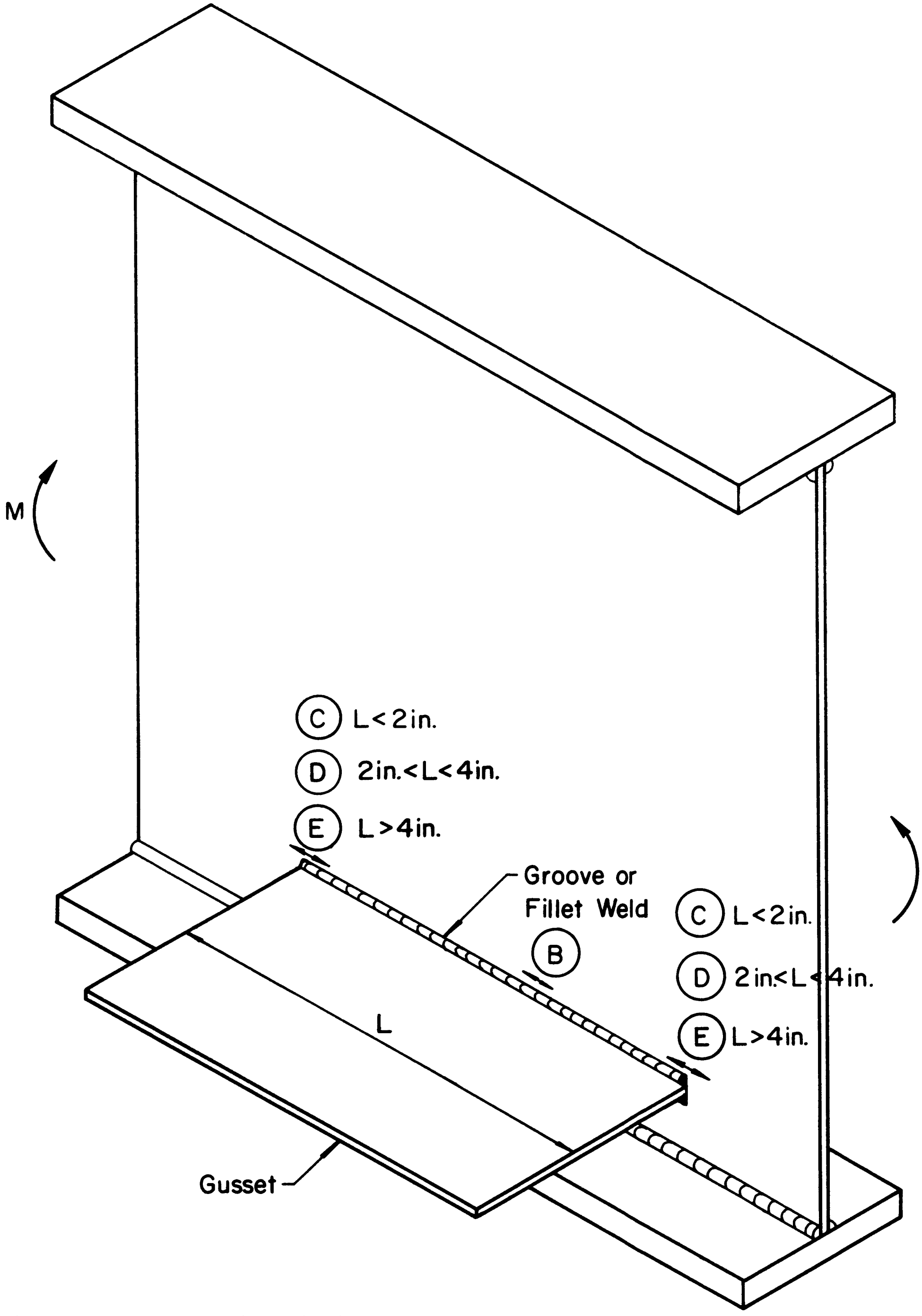
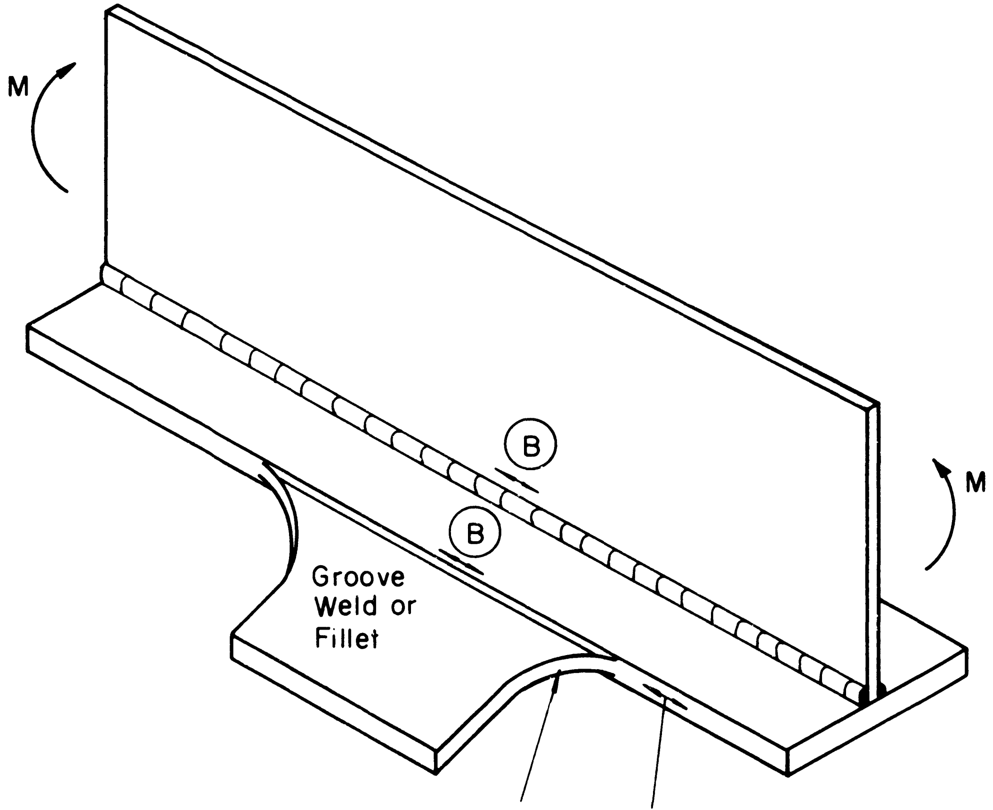


Fig. 5.35c—Fatigue rating of joint details (A is the rating for rolled beam, B next best, etc.) (For SI equivalents of U.S. customary values, see the table on p. 216.)



R	Category
R ≥ 24 in.	B
24 > R > 6 in.	C
0	E

Fig. 5.35d—Fatigue rating of joint details (A is the rating for rolled beam, B next best, etc.) (For SI equivalents of U.S. customary values, see the table on p. 216.)

SUMMARY OF FATIGUE DATA

Available literature on many girder connection fatigue tests are given in Table 5.3. All the results were obtained after 1950 and relate to specimens tested under tensile loading. The analysis represents data on steel with a yield point between 210 and 760 MPa (30 and 110 ksi). Table 5.3 shows a summary of the strengths for 10^5 and 2 x 10^6 cycles corresponding to the mean and 95 percent confidence limits.[38]

It should be noted that the results in Table 5.3 refer to the "raw data" analysis. Detailed discussions of the test data are provided in the Reference List.

Satisfactory control of fatigue life is most likely to be achieved by avoidance of stress elevating features in design or fabrication and by uniform high quality welding. Table 5.3 and the following example show connections that can be designed to provide high fatigue strength. They also demonstrate where critical conditions may occur in a welded connection.

Table 5.3—Summary of fatigue strength: cyclic tensile or bending tests from world literature after 1950

Type of joint	Number of results	Standard deviation of $\log_e N$	Fatigue strengths MPa (ksi)			
			10^5 cycles		2×10^6 cycles	
			Mean	Lower 95% confidence limits	Mean	Lower 95% confidence limits
Continuous automatic longitudinal butt weld	20	0.196	330 (47.9)	312 (45.2)	196 (28.4)	183 (26.6)
Continuous automatic longitudinal fillet weld	120	0.436	407 (59.1)	309 (44.8)	156 (22.6)	121 (17.5)
Continuous manual longitudinal fillet weld	60	0.429	403 (58.5)	294 (42.6)	136 (19.7)	99 (14.3)
Shear stud attached to stressed plate	63	0.265	312 (45.2)	252 (36.5)	102 (14.8)	85 (12.3)
Stiffener fillet welded to girder web or flange	107	0.364	310 (45.0)	221 (32.0)	108 (15.7)	90 (13.0)
Transverse butt weld (submerged arc)	95	0.667	265 (38.5)	185 (26.9)	118 (17.1)	83 (12.1)
Transverse butt weld on permanent backing bar	9	0.317	232 (33.6)	193 (28.0)	101 (14.6)	84 (12.2)
Transverse load-carrying butt weld, cruciform	24	0.363	255 (37.0)	205 (29.7)	107 (15.5)	86 (12.5)
Intermittent longitudinal fillet weld	44	0.676	241 (34.9)	172 (24.9)	113 (16.4)	80 (11.6)
Longitudinal non-load-carrying fillet weld	172	0.337	255 (37.0)	201 (29.1)	89 (12.9)	70 (10.1)
Transverse non-load-carrying fillet weld	333	0.675	334 (48.4)	195 (28.3)	102 (14.8)	59 (8.5)
Transverse load-carrying fillet weld, cruciform	66	0.6104	321 (46.6)	201 (29.1)	97 (14.0)	60 (8.7)
Transverse load-carrying fillet weld, lap joint	79	0.518	256 (37.2)	193 (28.0)	113 (16.4)	85 (12.3)
Longitudinal non-load-carrying gusset on plate edge	52	0.508	179 (26.0)	128 (18.6)	76 (11.0)	54 (7.8)
Longitudinal load-carrying fillet weld, cover-plate failure	62	0.63	201 (29.1)	125 (18.1)	66 (9.5)	41 (5.9)
Cover-plate beam flange, welded across plate ends	190	0.232	168 (24.4)	145 (21.1)	63 (9.2)	56 (8.1)
Cover-plate beam flange, not welded across plate ends	99	0.25	201 (29.1)	167 (24.2)	63 (9.2)	52 (7.6)
Beam flange with wide cover plate, not welded across plate ends	30	0.24	143 (20.8)	121 (17.5)	48 (6.9)	40 (5.8)

For instance, groove welded butt joints with the reinforcement removed and the weld soundness established by nondestructive inspection have high fatigue strength. However, groove welded connections perpendicular to the applied stress with the reinforcement left in place and the weld soundness established by nondestructive inspection fall into a lower fatigue strength category (see Table 5.3 and Fig. 5.35a-d).

An approximation of the fatigue strength of different weld details is shown by the circled letters in Figs. 5.35a-d, with A the plain plate, and B, C, etc. progressively lower fatigue strength details. (A represents a rolled beam.) Weld toe terminations of longitudinal stiffeners have low fatigue strength, as shown in Fig. 5.35b and attachments to the web or flange greater than 100 mm (4 in.) in length in the direction of the applied stress (see Fig. 5.35c).

If attachments are fillet or groove welded to the edge of the flange, as indicated in Fig. 5.35d, the stress category at the weld termination is dependent on the transition radius. If the transition radius is sharp ($R \sim 0$), a fillet or groove weld provides a right angle attachment similar to the flange attachment in Fig. 5.35c and stress Category E is applicable. If the transition radius is less than 600 mm (24 in.) but greater than 150 mm (6 in.), Category C is applicable. The improvement in fatigue strength is caused by a decrease in the stress concentration condition with an increase in the transition radius, *R*, and the removal of the weld ends by grinding. The categories shown in Fig. 5.35d also apply to web attachments.

High fatigue strength can also be achieved by bolting attachments to the flange or web of beams and girders. Welded connections located in compression stress regions are not fatigue critical unless there is a possibility of some stress reversal.

IMPROVEMENT TECHNIQUES

Improvements in fatigue strength can be achieved by contouring the end of the welds to decrease the stress concentration and by grinding the weld toe to reduce or minimize the discontinuity. Available studies indicate that the results are variable unless great care is taken to provide a smooth weld transition and remove the discontinuity at the weld toe. Some recent studies indicate that peening or providing a gas tungsten arc remelt pass along the toe of the weld may improve fatigue strength.[40, 41] These treatments are costly and it is often cheaper to change the design or place the welded connection in a lower stress region.

"Streamlining" contours by smooth radiused transitions will provide significant improvements in fatigue strength.

CORROSION FATIGUE

Corrosion fatigue is the result of the simultaneous operation of fatigue stress and an active corrodent upon a metal. The usual outcome is an acceleration of fracture. Most corrosion fatigue studies have been conducted on high (greater than 345 MPa [50 ksi]) yield strength steels. These studies have indicated that the rate of fatigue crack growth has been accelerated in sodium chloride solutions. The magnitude of this acceleration was dependent on the stress frequency.[32]

A recent study on ferrite-pearlite low yield strength steels has indicated that they are not greatly affected by atmospheric corrosion effects as far as the *rate* of fatigue crack growth is concerned.[42]

Extremely corrosive environments can result in dissolution of the metal at the crack tip and will accelerate the rate of crack growth particularly for higher strength steels.[43]

THERMAL FATIGUE

Repetitive stresses which are thermal in origin are often responsible for thermal fatigue, a type of failure experienced in thermally cycled component applications. Thermal stresses arise because the inherent expansion or contraction of a component during heating or cooling is hindered or restrained. The cause of thermal fatigue is attributed to localized plastic flow resulting from the expansion and contraction forces during heating and cooling cycles. Thermal fatigue problems exist when failure occurs after a time period significantly shorter than the predicted life of the component or structure. Cumulative effects of cyclic thermal stresses can cause either excessive distortion or thermal fatigue cracking. The life of the component is terminated when the change of shape due to distortion is more than can be tolerated, or when the fatigue cracks have propagated to a critical extent.

Those applications in which thermal fatigue problems have been diagnosed and studied include oil pipelines which experience a periodic flow of hot and cold oil, steam pipelines, gas turbines, nuclear reactors, incinerators, boilers, and heat exchangers.

Thermal fatigue has been observed in welded components. Welds and weld heat-affected zones are potential regions of failure since welding is often used to join dissimilar thicknesses of materials, as well as dissimilar materials. Notch effects such as undercut, cracks such as crater cracks, weld contour, large grain size (in the heat-affected zone), residual stresses, discontinuities, and thermal gaps are among the factors which promote thermal fatigue problems in welded joints.

Many precautions have been taken to prevent thermal fatigue. Each specific application requires individual analysis. The overall subject has been dealt with adequately in the literature which should be studied for a thorough understanding of thermal fatigue phenomena.* Although no general solutions can be offered here, the following measures may prevent or solve specific thermal fatigue problems:

(1) Allowing the structure to have the maximum possible freedom of movement.

(2) Utilizing uniform section thickness wherever possible.

(3) Avoiding the placement of welds in regions of high thermal stresses.

(4) Avoiding thermal gaps and crevices.

(5) Avoiding defects which act as stress risers such as undercut, cracks, etc.

(6) Improvement of mechanical and welded joint design to reduce or eliminate thermal stresses.

(7) Consideration of alternate materials.

CORROSION FACTORS AFFECTING THE TESTING AND PERFORMANCE OF WELDED JOINTS

A welded joint will normally resist corrosion the same as the metal being joined. However, there will sometimes be exceptions, either because of variations in composition or as a result of metallurgical or mechanical changes brought about by the welding process itself. In the latter cases, the welding process can generally be selected and controlled to optimize corrosion resistance.

Before discussing the various methods of testing and evaluation it is important to realize that there are many different forms of corrosion.

TYPES OF CORROSION

In addition to the well-known uniform attack, there are a variety of localized forms of corrosion as shown in Fig. 5.36. Since several of these are particularly relevant to welded joints, their cause and remedy will be discussed briefly.

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*See the appropriate entries in the Supplementary Reading List, p. 219.

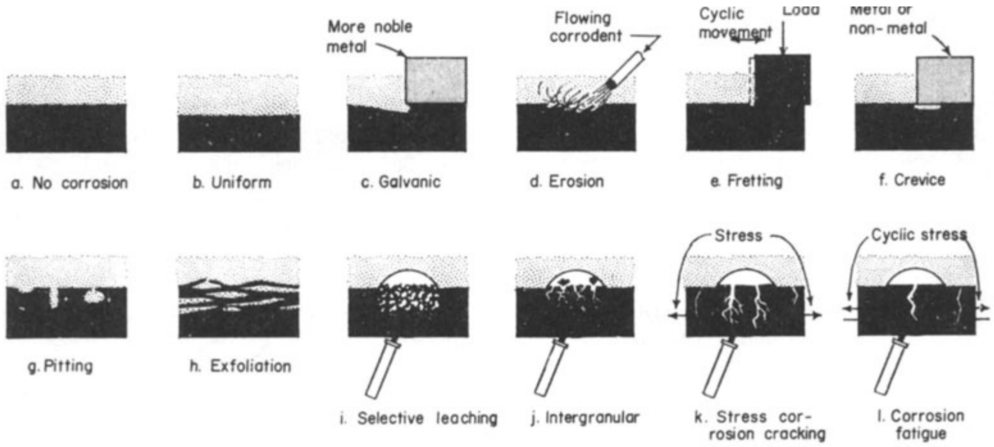

Fig. 5.36—Types of corrosion found in metals and metal alloys.

Galvanic Corrosion

This type of corrosion may occur when two different metals in contact (or connected by an electrical conductor) are exposed to a conductive solution. A difference in electrical potential exists between different metals and serves as the driving force to pass current through the corrodent. This current flow results in corrosion of one of the metals in the couple.

The larger the potential difference between the two metals, the greater the probability of galvanic corrosion. It should be noted that galvanic corrosion only causes increased deterioration of one of the metals. That is the one that would have corroded the most even if immersed just by itself (it is called the more "active" metal). It now corrodes even more, while the other metal in the couple corrodes less than it would by itself (it is called the more "noble" metal).

Galvanic corrosion can occur when a weld filler metal is of significantly different composition than the base metal and occasionally might occur as a result of differences in behavior between cast weld metal and the wrought base metal.

The relative areas of the two metals are also important in galvanic corrosion. A much larger area of the noble, compared to the active metal, will accelerate the attack, and vice versa. This has special significance for weldments as shown in Fig. 5.37. The situation in Fig. 5.37a is the one most likely to cause weld corrosion problems.

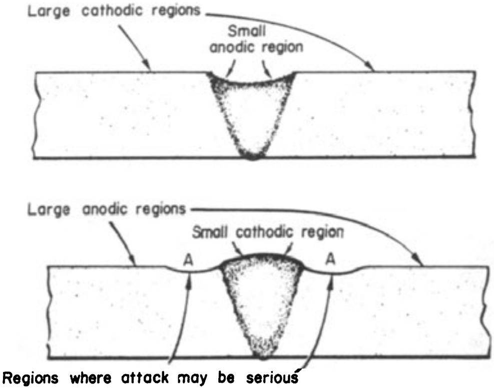

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Fig. 5.37—Galvanic corrosion in a welded joint. Top: Weld metal less noble than base metal. Bottom: Weld metal more noble than base metal.

Crevice Corrosion

With time, the environmental conditions in a crevice can become quite different from those on a nearby clean, open surface. A more

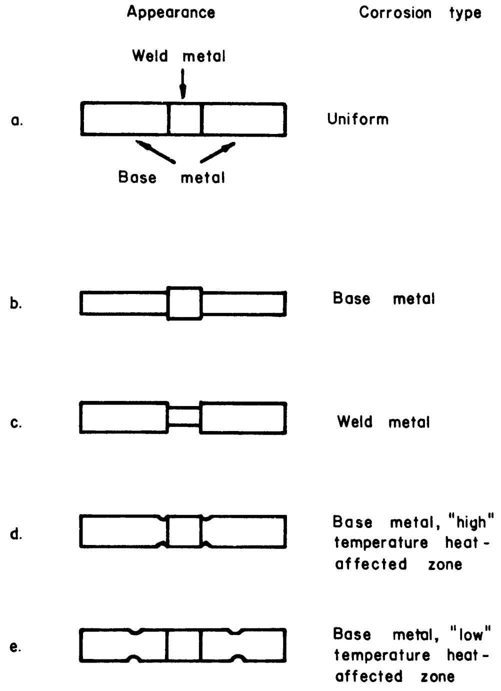


Fig. 5.38—Types of corrosion in a welded joint.

aggressive environment may develop and cause local attack in the crevice. Crevices in welded joints occur in a variety of ways—surface porosity or cracking, slag or weld scale deposits, inadequate joint penetration, undercut, and design defects.

Like all forms of localized attack, crevice corrosion does not occur in all metal-corrodent combinations. Some materials are more susceptible to it than others; namely those that depend on an air-formed oxide film for protection, such as stainless steel and aluminum. These materials can be alloyed to improve their resistance and this approach, together with designing to minimize crevices and maintenance to keep surfaces clean, are used to combat the problem.

Intergranular Corrosion

Grain boundaries are sometimes preferentially attacked by a corrodent. The attack is usually related to the segregation of specific elements or the formation of a compound in the boundary (the atomic mismatch makes this a favored place for segregation and precipitation). Corrosion generally occurs because the corrodent preferentially attacks the grain-boundary phase or a zone adjacent to it that has lost an element necessary for adequate corrosion resistance.

The grain-boundary phenomena that cause intergranular corrosion are sensitive to heat. Susceptibility to intergranular attack is usually a byproduct of a heat treatment (such as a welding or stress relieving operation) and can be corrected by another heat treatment or the use of a modified alloy.

Austenitic stainless steels can exhibit this problem. Chromium carbides precipitate at the grain boundaries when the steel is heated in the region of 650 °C (1200 °F). In some media this results in intergranular corrosion in a band remote from the weld (that is, the band of material that reached 650 °C). Fortunately, the problem is readily avoided by postweld annealing or by the use of low carbon or stabilized steels. The problem of intergranular corrosion can be avoided by using heat treated aluminum alloys in applicable situations.

Stress Corrosion

The conjoint action of a tensile stress and a corrodent will in some instances result in the cracking of a metal alloy. Most alloys are susceptible to this problem, but fortunately the number of alloy-corrodent combinations that cause it are relatively few. However, it is still the most serious unsolved metallurgical problem of the day. Stresses that cause cracking arise from residual cold work, welding, or thermal treatment, or they may be externally applied during service.

The cracks can follow intergranular or transgranular paths, and there is often a tendency for crack branching. The following list contains some characteristics of stress corrosion cracking:

(1) Stress corrosion requires a tensile stress. Below a threshold stress, cracking does not occur.

(2) Cracking appears macroscopically

brittle, whereas mechanical failure of the same alloy, in the absence of a specific corrodent, would generally appear ductile.

(3) Stress corrosion depends on the metallurgical condition of the alloy.

(4) A few specific environments usually cause cracking in a given alloy. Frequently, the same environments do not cause cracking in other alloys.

(5) Stress corrosion can occur in environments that would otherwise be considered mild for the given alloy; that is, the rate of uniform corrosion is low when cracking occurs.

(6) Long periods of time (often years) may pass before cracks become visible. The cracks then propagate quite rapidly and result in unexpected failures.

(7) Stress corrosion is not really understood in most cases, although there are now large amounts of data to help the engineer avoid the problem.

Methods of combatting stress corrosion cracking include stress relieving, removing the critical environmental species, or selecting a more resistant material.

CORROSION TESTING OF WELDED JOINTS

A welded joint may corrode uniformly over its entire surface or may be susceptible to varying degrees of preferential attack as shown in Fig. 5.38. The weld metal may corrode more (Fig. 5.38c) or less (Fig. 5.38b) than the base metal as a result of differences in composition or metallurgical condition (that is, structure or precipitation of second phases, etc.). In addition, the base metal heated during welding may corrode (Figs. 5.38d and e) as a result of metallurgical changes caused by the heating cycle (or cycles if there is more than one welding pass).

More than one of the several forms of attack shown in Fig. 5.38 can occur in the same welded joint. Also, it is important to realize that Fig. 5.38 represents a macroscopic view and that within the zones of attack shown in, for example, Fig. 5.38e, the corrosion may be further localized (that is, intergranular).

Some of the factors that can influence the corrosion resistance of welded joints are included in the following list:

(1) Composition and structure of base metal and weld metal.

(2) Metallurgical condition of base metal before welding (prior thermal and mechanical working history).

(3) Welding process.

(4) Welding procedure—manual or automatic, number of passes, rate of welding, current, and voltage.

(5) Shielding gas—composition and flow rate.

(6) Size of material welded (that is, plate thickness) and size and geometry of weld deposit.

When reporting corrosion data for a welded joint, the items in the preceding list should generally be reported also.

The most common method of evaluating corrosion resistance is to measure the weight lost during exposure to the corrodent and convert this to an average corrosion rate using the formula:

$$R = \frac{KW}{ADT} \tag{5.7}$$

where

R = the corrosion rate in depth of attack per unit time

K = a constant, the value of which depends upon the units used

W = the weight lost by the specimen during the test

A = the total surface area of the test specimen

D = the density of the specimen material

T = the duration of the test

The use of this formula is ideally suited to the conditions shown in Fig. 5.38, but it is obvious that selective corrosion, such as shown in Figs. 5.38d and e, can be severe without resulting in a large enough weight loss to significantly increase the average corrosion rate for the entire specimen.

In some instances, the errors inherent in an average corrosion rate determination can be minimized by also testing a sample which is the same size as the welded joint, but which does not contain a weld. A ratio of the weight losses of the two samples may then indicate any localized attack in the welded joint. This method is satisfactory provided the welded joint does not (in addition to containing a region susceptible to localized attack) also contain a region which shows a lower rate of corrosion than the base metal. For example, a combination of Figs. 5.38b and e would cancel out some or all of the weight loss due to Fig. 5.38e.

Test Specimens

Specimen Geometry. The test specimen used will vary with the size and type of product being welded and the type and size of the weld. The simplest test specimen shape is that shown in Fig. 5.39.

In Fig. 5.39, suitable dimensions for X, Y, and Z are based on several factors. In general, Y will be determined by the availability of test material and the size of the container holding the corrodent, but it must be sufficiently long so that section AB is representative of a longer weld. The length of X is more critical especially if weight loss measurements are to be intelligently used. The dimension X must be sufficiently long to insure that material at C has corrosion resistance identical to unwelded base metal. However, to isolate weight loss changes in the welded joint effectively, the amount of base metal unaffected by the welding should be kept to a minimum. The thickness, Z, influences the heat input necessary during welding and so will affect the size and location of the heat-affected zone. Generally, the smaller Z is, the larger will be the heat-affected zone and hence the larger X must be in the test specimen. It should also be noted that the larger the Z dimension, the greater the amount of end grain exposed. In

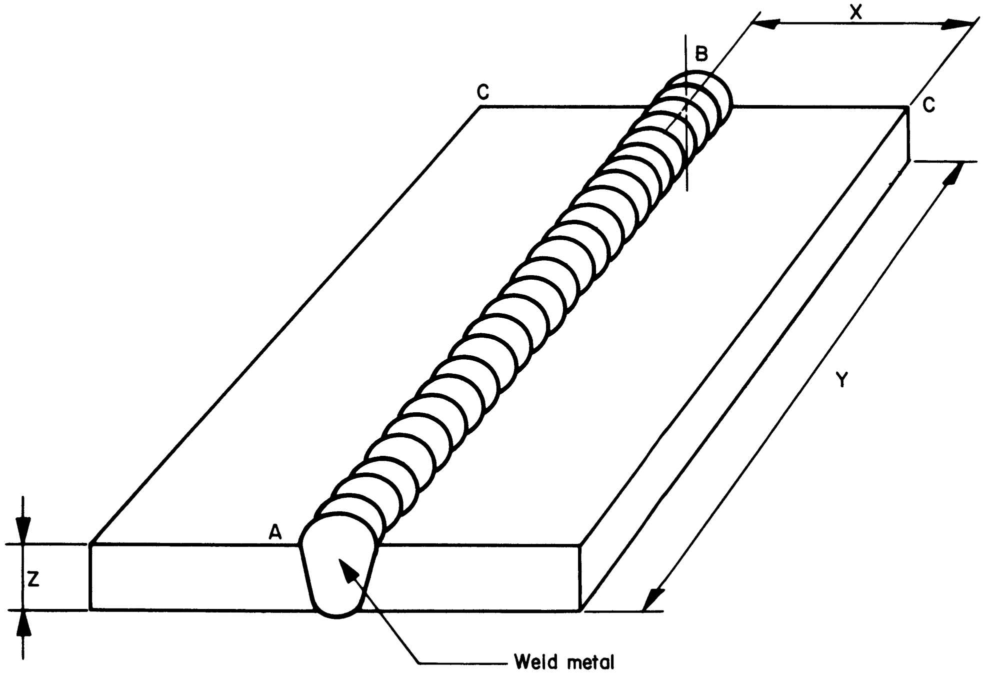


Fig. 5.39—Typical welded joint.

some cases the latter may result in end grain corrosion which introduces an additional error into average corrosion rates calculated from weight loss measurements. This can be prevented by coating the edges with a special corrosion resisting paint, usually rubber-based.

Cross welds may be tested also. In some cases, it may be desirable to cut and test a sample from the weld metal only.

Although minimizing the amount of base metal increases the usefulness of weight loss measurements, it may cause problems when galvanic corrosion between the base metal and a less noble weld metal is a possibility. In such a case, the larger the X dimension (in Fig. 5.39), the greater would be the galvanic corrosion, and the size of the finished article would have to be considered when selecting the sample geometry. Alternatively, an extremely noble weld could accelerate attack in the immediately adjacent base metal (see Fig. 5.37).

Surface Preparation. The surface preparation of the test specimen will depend upon the purpose of the test and the technique of evaluating the corrosion damage after the test. These steps should be followed:

(1) Test in the as-welded condition with no attempt to remove metal or welding scale. This is recommended only if the weld must be used this way in service and if the test environment is the same or similar to that which the weld would experience in service.

(2) Keep the amount of base metal outside the heat-affected zone to a minimum unless galvanic corrosion is suspected in the weld.

(3) Machine or grind all surfaces flush, leaving no undercut or surface imperfections, and polish to a 120 grit finish. Avoid overheating. This method is recommended if surface examination is to be used in the evaluation stage. However, it is important to realize that the removal of large amounts of weld metal can significantly affect corrosion rates particularly in the case of large sections and multipass welds.

In some cases where two faces of a weld are exposed to the test, a compromise method is to grind one side of the weld bead flush, but leave the other side as-welded and cleaned by one of the following methods:

(1) Clean the weld by mechanical means, such as by shot or vapor blasting, but do not remove the weld bead.

(2) Clean the weld by chemical means. This method may involve a descaling operation only or a pickling operation in which scale and metal are removed. Care must be taken to insure that the chemical used does not attack the weld preferentially. For instance, hot HNO_3-HF pickling solutions could cause significant intergranular attack of some stainless and nickel-base alloy welds.

Normal corrosion test procedures prior to testing, such as degreasing, should be followed.

EVALUATION OF CORRODED WELDMENTS

If localized attack occurs during the corrosion of a weld, special techniques are usually needed to evaluate the attack because weight loss measurements can be misleading as noted earlier. (It should be noted that after all corrosion tests, it may be necessary to remove the corrosion products.)

Methods of Evaluation

Weight Loss Measurements. Allowing for their previously discussed limitations, weight loss measurements are still considered useful because they are generally easy to perform. In addition, they screen out high corrosion rate material if the specimen geometry is carefully selected for this purpose or if control samples (without welds) are also tested.

Macroscopic Examination. Low magnification (1-20X) examination of the tested sample is generally adequate to determine the existance of significant localized attack. Higher magnifications, that is, up to 100X, may also be used to advantage provided the original surface finish of the test specimen permits this. Standard photographs may be used as a reference for a rating system.

Electrical Resistance. Observing the change in electrical resistance across a weld as a result of corrosion is an accurate and effective method of detecting general and intergranular corrosion. Unfortunately, it is desirable to use long, thin sections (preferably wires or strips) to detect small amounts of attack satisfactorily.

Measurement of Depth of Attack. Several devices are available to measure the depth of preferential attack in a corroded weld. They include (1) a fine-tipped micrometer which may be suitable for measuring a severe attack such as shown in Fig. 5.38c, (2) a microscope with calibrated vertical movement (the distance between the focal point of the top and bottom of a locally corroded zone such as shown in Fig. 5.38e can be measured); and (3) a profilometer. Profilometers, which can be used to scan the surface of a tested sample, are available and have possible application in the evaluation of welded joints. With this device, a fine needle moves over the surface of the tested sample and a transducer measures the movement of the needle relative to a flat-tipped shoe.

Ultrasonics. Ultrasonic techniques are applicable to the measurement of localized surface discontinuities and have been used to evaluate intergranular attack.

Electrochemical Tests. In all of the preceding it has been assumed that a bulk sample containing a weld has been exposed to a corrodent and that the main difficulty is in evaluating the corroded specimen. An alternative approach is to use electrochemical tests to evaluate (that is, predict) susceptibility to attack.

ELEVATED TEMPERATURE BEHAVIOR

CREEP-RUPTURE PHENOMENA

When a load, less than that required to produce immediate fracture, is applied to a material at an elevated temperature, the material will experience gradual elongation and will ultimately fracture. The gradual elongation or plastic deformation is called creep, while the eventual fracture is called rupture. This time-temperature phenomenon is shown schematically in Fig. 5.40. Elongation progresses, at a constant temperature, in roughly three stages. On initial application of the load, the creep or elongation rate is relatively high but continually decreases with time. This is termed the period of primary or first stage creep. The second stage of creep is generally an extended period during which a constant and minimum creep rate occurs. In the third stage, the creep rate again increases, generally as a result of the onset of necking, and culminates in rupture of the material. Increasing load or temperature shortens the time for each stage and reduces the rupture life.

TEST METHOD

The test specimen used to determine creep-rupture strength is similar to that used for the previously described tension test. It may be either all-weld-metal or a specimen taken transverse to the welded joint axis containing some or all of the structural components of the joint. The advantages, disadvantages, and limitations of each orientation are similar to that of the tension test. However,

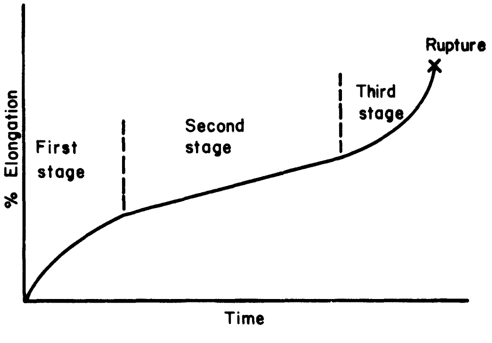


Fig. 5.40—Typical creep-rupture elongation curve.

transverse creep tests are seldom conducted since the variations in elongation in each welded joint region make the total elongation measurements meaningless.

The test is conducted in an appropriate furnace and load is generally applied in the form of constant dead weights. In the case of a creep test, extensometers of some form are attached to the specimen so that elongation can be monitored during the course of the test. In the rupture test, time to failure at a given applied load is the principal variable measured, although final elongation and reduction of area are usually determined.

METHOD OF REPORTING AND EXTRAPOLATING

Rupture and creep data are most generally reported as log-log plots of stress versus time to rupture or time to attain a specified percentage creep elongation at a constant temperature. Such plots are generally straight lines as shown schematically in Fig. 5.41.

Rupture strength data generally are needed for equipment that must operate for long periods of time, such as refinery or power generation equipment. Typical design lives for these applications are 100 000 to 300 000 hours (11.4 to 34.2 years). Few tests are conducted this long. In fact even 10 000 hour tests require over a year and are conducted only on a limited basis. Therefore, to determine the strength at the design life, some form of extrapolation must be used. The most straightforward method of extrapolation involves extending the constant temperature log stress-log time plot as a straight line. Extrapolations of one to two log cycles in time are, of course, hazardous, but with reasonably good data, they can be done fairly accurately.

Perhaps the most widely used method of extrapolating creep-rupture data is by means of time-temperature parameters. Creep-rupture is predominantly a diffusion controlled phenomenon as the straight line log-log plot supports. As such it can be expressed by an Arrhenius-type rate equation and, from this, various time-temperature parameters can be developed. The most common equations are:

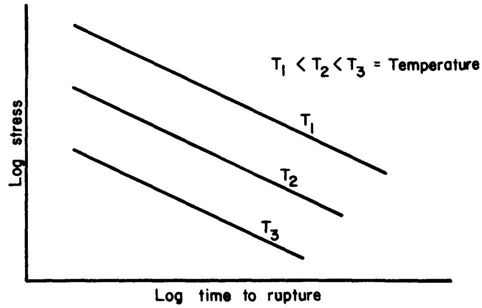


Fig. 5.41—Typical set of rupture data at three temperatures.

$$\text{Larson-Miller: } P = T\,(C + \log t_r) \quad (5.8)$$

where

P = the parameter against which stress is plotted
C = constant (generally 20)
T = absolute temperature in degrees Rankine
t_r = time to rupture in hours

$$\text{Manson-Haferd: } P = \frac{T - T_A}{\log t_r} - \log t_a \quad (5.9)$$

where

T_A and $\log t_a$ = constants
T = temperature in °F
t_r = time to rupture in hours

$$\text{Dorn: } P = t_r e^{\frac{-\Delta H}{RT}} \quad (5.10)$$

where

ΔH = constant
R = gas constant
T = temperature in degrees Rankine
t_r = time to rupture in hours

These parameter methods all substitute temperature for time and permit determination of long time strength from shorter time-higher temperature tests. This of course results in great time and cost savings, and these methods have been developed to the point that extrapolation can be very accurately achieved. Caution, of course, must be exercised in selecting the higher temperatures to insure that metallurgical phenomena encountered at the service temperature also occur at the test temperature and vice versa.

SIGNIFICANCE OF WELD DISCONTINUITIES

Increasing design demands are resulting in more critical inspection methods and acceptance standards. Ideally, these acceptance standards should represent the minimum weld quality that can be tolerated to assure satisfactory performance of the welded part or component and should be based on tests of welded specimens containing the particular discontinuity under consideration. Correlation of these test results with allowable results gives a basis for acceptance of these particular discontinuities. Usually, a safety factor will be added to yield the final acceptance standard. However, too frequently acceptance standards are arbitrary, bearing little or no relationship to actual performance, or are merely an attempt to define the limits for practical welding and good workmanship. Such standards can be either inadequate or overly conservative, thus increasing production costs unnecessarily. Much research is being conducted to correlate discontinuities with performance.

TYPES OF WELD DISCONTINUITIES

This section cannot cover all the imperfections that might be encountered in welded joints. There are many literature sources which describe the various weld imperfections and discuss their causes and prevention (see the Supplementary Reading List, p. 219). The purpose of this section is to briefly describe and discuss those imperfections which affect weld performance. (Most of these imperfections are also described in Appendix A, beginning on p. 279.)

Many imperfections give rise to structural discontinuities which affect the stress field. The term discontinuity does not necessarily mean that there is a change of metallurgical structure at these points; it means that there is an interruption or a discontinuity in the soundness of the weld, which can reduce certain performance characteristics of the weld. Much depends upon the orientation of the discontinuity within the stress field and the location in the weld. Orientation perpendicular to the principal stress is usually the most damaging.

Porosity

Porosity is the term for the gas pockets or voids free of any solid material that are frequently found in welds. Porosity can come from gases released by the cooling weld metal because of reduced solubility as the temperature drops, and from gases formed by chemical reactions in the weld. Porosity may be scattered uniformly throughout the entire weld, isolated in small areas or concentrated at the root. Pores are usually spherical in shape, although they may also occur as nonspherical pockets along grain boundaries or as elongated tubular voids called piping porosity or "wormholes." Most welds contain some amount of porosity which may be macro or micro in size.

Slag Inclusions

This term is used to describe the oxides and other nonmetallic, solid materials that are entrapped in weld metal or between weld metal and base metal. Slag inclusions may be caused by contamination of the weld metal by the atmosphere; however, they are generally derived from electrode-covering materials or fluxes employed in arc welding operations. In multilayer welding operations, failure to remove the slag between passes will result in slag inclusions in these zones. Slag inclusions are generally linear and may occur either as short particles or as long bands.

The majority of slag inclusions may be prevented by proper preparation of the groove before each bead is deposited, using care to correct contours that will be difficult to penetrate fully with successive passes.

Tungsten Inclusions

In the gas tungsten arc welding process, the occasional touching of the electrode to the work or to the molten weld metal, particularly in manual operation, may transfer particles of the tungsten into the weld deposit.

Incomplete Fusion

Incomplete fusion, or lack of fusion as it is frequently termed, describes the failure of adjacent weld metal and base metal to fuse together completely (see Figs. 5.42-5.44). This failure to obtain fusion may occur at any point in the weld.

Incomplete fusion may be caused by failure to raise the temperature of the base metal (or previously deposited weld metal) to the melting point or failure to remove slag, mill scale, oxides, or other material alien to the metal alloy which may be present on the surfaces with which the deposited metal must fuse. Incomplete fusion is usually elongated in the direction of welding and may have either rounded or sharp edges depending on how it is formed.

Cracks

Cracks are linear ruptures of metal under stress. Although sometimes wide, they are often very narrow separations in the weld or adjacent base metal. Usually little deformation is apparent. Three major classes of cracks are generally recognized: hot cracks, cold cracks, and microfissures. All types can occur in the weld or base metal.

Figure 5.45 illustrates a variety of cracks including underbead cracks, toe cracks, crater cracks, longitudinal cracks, and transverse cracks. The underbead crack, limited mainly to steel, is a base metal crack usually associated with hydrogen. Toe cracks in steel can be of similar origin. In other metals (including stainless steel), cracks at the toe are often termed edge of weld cracks, attributable to hot cracking in or near the fusion line. Crater cracks are shrinkage cracks which result from stopping the arc suddenly.

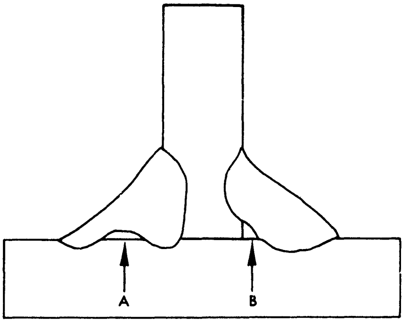


Fig. 5.42—Incomplete fusion in fillet welds. B is often termed "bridging."

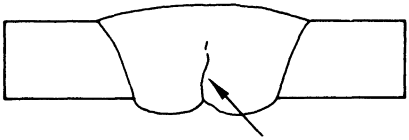


Fig. 5.43—Incomplete fusion from oxide or dross at the center of a joint, especially in aluminum.

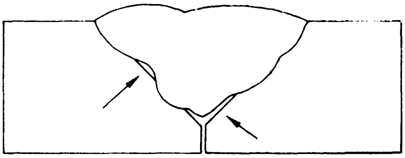


Fig. 5.44—Incomplete fusion in a groove weld.

Inadequate Joint Penetration

This term is used to describe the condition in which joint penetration is less than that

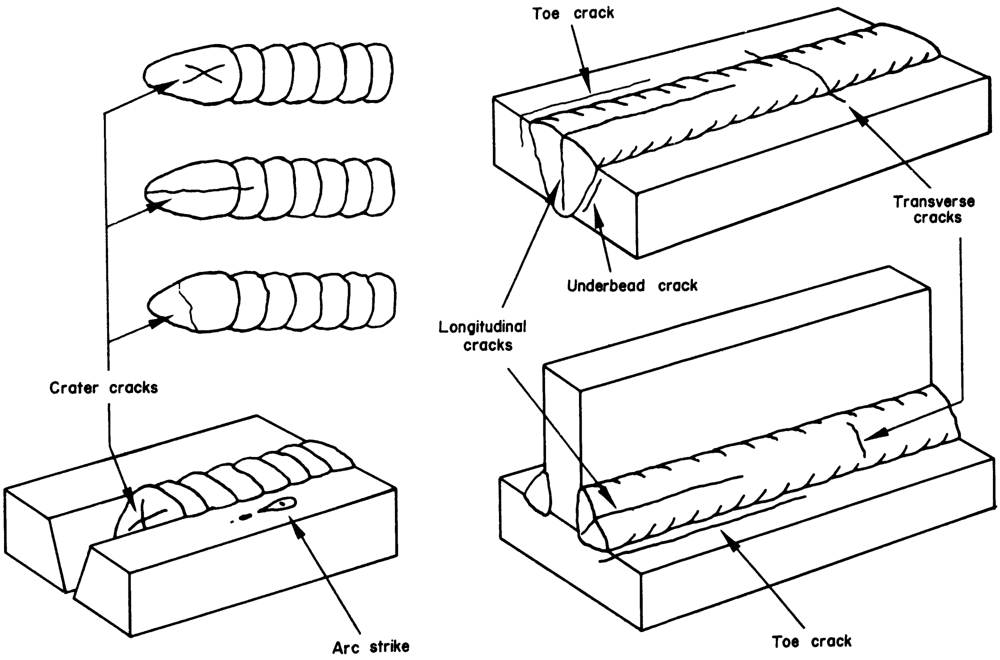


Fig. 5.45—Types of cracks in welded joints.

specified. The most frequent cause of this type of defect is an unsuitable groove design for the selected welding process or for the conditions of fabrication.

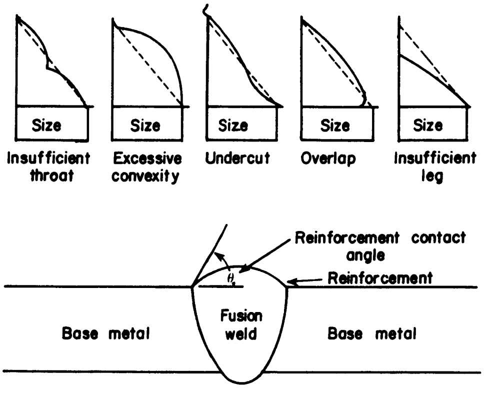
Undercut

This term is used to describe a groove melted into the base metal adjacent to the toe of a weld and left unfilled by the weld metal. It also describes the melting away of the sidewall of a welding groove at the edge of a layer or bead. This melting away of the groove forms a sharp recess in the sidewall in the area in which the next layer or bead must fuse. (Slag may be "keyed" into this undercut which, if not removed prior to subsequent passes, may become trapped in the weld.) An undercut, therefore, is a groove that may vary in depth, width, and sharpness at its root.

Weld Profile

The profile of a finished weld may have considerable effect on weld performance under load; moreover, the profile of a single pass or layer of a multipass weld may have a considerable effect on the tendency to produce such defects as incomplete fusion or slag inclusions when subsequent layers are deposited. Figure 5.46 illustrates various types of defective fillet weld profiles.

Overlap (see Fig. 5.47) is usually associated with fillet welding, but also can occur at the edge of groove welds. The term describes a protrusion of weld metal beyond the bond at the toe of a weld. This condition tends to produce notches that are obviously harmful due to the resultant concentration of stress under load and also reduces the effective size of the fillet. Overlap is usually caused by incorrect welding techniques or welding currents.



Schematic showing excessive weld reinforcement

Fig. 5.46—Defective fillet weld profiles.

Arc Strikes

Arc strikes represent unintentional melting or heating outside the intended weld deposit area. They usually are caused by the welding arc, but can be produced beneath an improperly secured ground connection or magnetic particle inspection electrical connections (prods). The result is a small remelted area that can produce undercut, hardening, or localized cracking depending upon the metal composition.

EFFECT OF DISCONTINUITIES ON THE PERFORMANCE OF WELDED JOINTS

The significance of a particular discontinuity in a weld depends on the function that the weld must perform. Certain weld discontinuities which have no effect on mechanical properties can, nevertheless, become significant by virtue of corrosion considerations; for example, inclusions of heavy metals at or near the weld surface cannot be tolerated in certain environments. It is important to note that a repair of a harmless discontinuity can result in a more damaging, less readily detectable discontinuity.

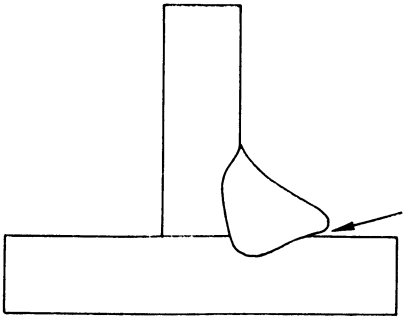
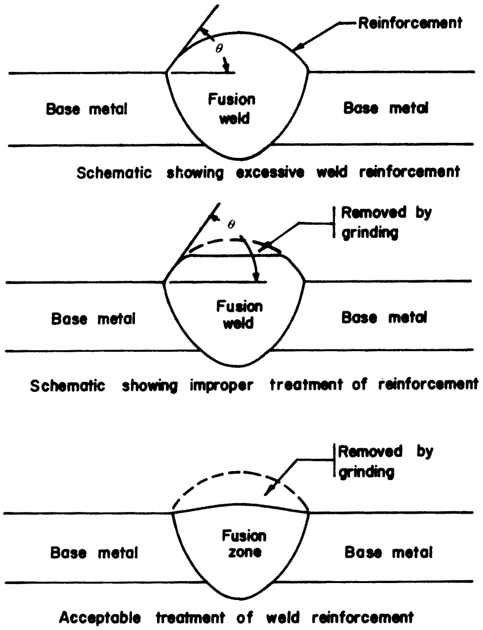


Fig. 5.47—Overlap. The protrusion of weld metal beyond the end of fusion.

The heat-affected zone plays a major role in the determination of mechanical properties of the joint and can render the presence of weld discontinuities less significant. The heat-affected zone itself can be considered a discontinuity because it almost invariably experiences modifications of mechanical properties. For example, strain-hardened materials with mechanical properties enhanced by prior cold work experience both recrystallization and grain growth in the heat-affected zone. In such alloys, both the strength and hardness of the heat-affected zone are invariably diminished. A drastic loss in tensile strength also occurs in the heat-affected zone of precipitation-hardened alloys since some region in the heat-affected zone usually experiences overaging during welding.

The effects of discontinuities on mechanical properties are governed by the shape, size, quantity, interspacing, distribution, and orientation of the discontinuities within the weld. Due to the number of variables, any qualitative correlation between a specific discontinuity class and mechanical parameters is extremely difficult. Therefore, trends rather than direct relationships are indicated.

As the strength of the base metal is increased, so is its sensitivity to discontinuities. Ultra-high strength steels, as well as hard heat-affected zones in relatively mild steels, may be extremely sensitive to very small discontinuities. When welding very strong steels, it is also difficult to match the strength of the weld to that of the base metal. Therefore, the pro-



Schematic showing excessive weld reinforcement

Schematic showing improper treatment of reinforcement

Acceptable treatment of weld reinforcement

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Fig. 5.48—Acceptable treatment of weld reinforcement.

tection afforded to discontinuities in mild steels by the overmatching strength of the weld metal is no longer available.

Tensile Strength

For the purpose of characterizing static tensile performance, welded joints fall into two categories: (1) those having weld metal strengths that closely match or undermatch the base metal strength and (2) those having weld metal strengths that overmatch the base metal strength.

In general, the welded joints in category (1) are weakened more by weld discontinuities than those in category (2) because there is no reserve of additional weld metal strength to counteract the decrease in cross-sectional area. Because of this additional strength of category (2) welds, a certain amount of discontinuity can be tolerated before transverse tensile properties are adversely affected. The loss in transverse tensile strength is roughly proportional to the loss in cross-sectional area. Additional cross-sectional area provided by any weld reinforcement compensates for some of this loss.

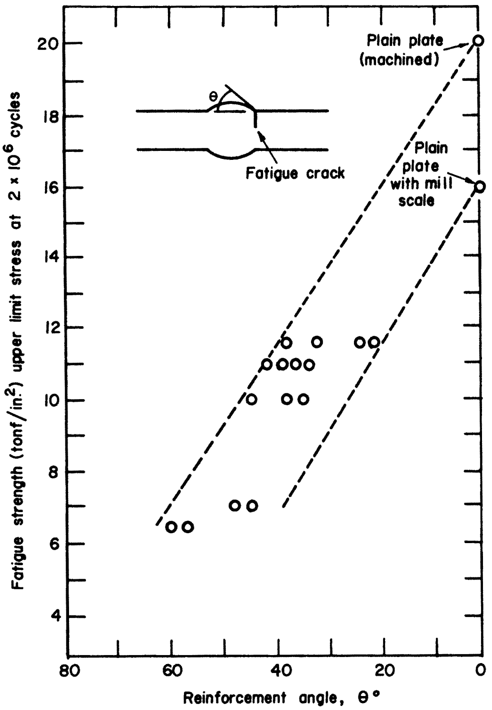

Fig. 5.49—Fatigue strength versus reinforcement angle. (For SI equivalents of U.S. customary values, see the table on p. 216.)

In welded joints of category (2), the transverse strength degradation is usually accompanied by a change in location of the fracture from base metal when a few or no weld discontinuities exist to weld metal when a significant amount of discontinuities are present. Usually, the elongation at failure will be reduced roughly proportional to the discontinuities present. The yield strength is not significantly affected.

Fatigue

Fatigue failure at normal working stresses is invariably associated with stress concentrations around weld or design discontinuities. Fatigue is probably the most common cause of failure in welded construction. The discontinuities most significant in promoting fatigue, except for the obvious effect of gross cracking or extensive incomplete fusion, are those which affect the weld surface. The combination of excessive weld reinforcement and slight undercutting is one of the most serious causing fatigue. Fabrication codes usually specify the maximum permissible height of the reinforcement. However, many welding fabricators merely grind off the excess without altering the reinforcement contact angle. This practice does not improve the fatigue life, and therefore probably would not in itself provide a finished weld meeting the required quality level. Most codes also specify that the reinforcement shall blend smoothly into the base metal at the edges of the weld (see Fig. 5.48).

Figure 5.49 illustrates the influence of the contact angle on fatigue strength under repeated tension loading for an endurance of 2 x 10^6 cycles. This figure makes it clear why design defects are often responsible for service failures. The use of a load-carrying lap joint with a fillet weld in place of a butt welded joint, for example, has the effect of reducing the strength by a factor of up to three.

Test specimens with both porosity and a reinforcement have shown that fatigue cracks initiate at the reinforcement contact angle and that porosity has little effect on the fatigue life. However, when the reinforcement was removed, the position and orientation of the porosity rather than magnitude is the important factor, with the fatigue strength being critically dependent on the presence of pores breaking the surface or just under the surface.

Test specimens with reinforcement intact and containing very large tungsten inclusions have also shown that fatigue cracks initiate at the reinforcement contact angle. When the specimens were blended (reinforcement removed), fatigue failure still did not occur from the tungsten, but from small oxide inclusions associated with it.

Testing has shown that increasing slag inclusion length initially leads to decreasing fatigue strength. However, when the discontinuity length becomes large relative to its depth through the thickness, no further reduction in fatigue strength occurs.

Discontinuities which are located in the middle of the weld can be blanketed by compressive residual stress so that other smaller discontinuities nearer to the surface control the fatigue strength. Such discontinuities may be below the size detectable by radiography.

In general, discontinuities in thick sections give higher fatigue strengths than similar discontinuities in thin sections.

Brittle Fracture

The fracture mechanics approach permits the determination of a relationship between stresses and the critical size of a discontinuity that will propagate. This critical discontinuity size decreases in proportion to the square of the increase in applied stress whereas, in general, the fracture toughness of all materials decreases as the yield strength increases.

For a given weld structure, an appropriate equation must be developed that relates the fracture toughness to the applied stress and discontinuity size. This equation should account for the location, dimension, and shape of the discontinuity. The location and shape (depth-to-length ratio) of the discontinuity must be known or accurately predicted, particularly in those instances when discontinuities can grow by fatigue or stress corrosion. With this information and a valid plane strain fracture toughness value, one can estimate the combination of stress and discontinuity size at which a structure can be operated safely.

Since the effectiveness of a discontinuity as an initiator of fracture in a given material depends on the degree of stress concentration and triaxiality at the discontinuity tip, it is clear that the edge radius of discontinuities will have an effect on performance. Thus, one would expect sharp natural cracks to be the severest kind of defect for brittle fracture considerations. In a similar manner, incomplete fusion can be the next most severe discontinuity. Inadequate joint penetration normally would not be as severe as incomplete fusion because the edges of the former do not have as sharp a radius. Slag inclusions and porosity would be relatively harmless as initiating defects unless there is cracking associated with them.

Discontinuities can be described as either three-dimensional (porosity and inclusions) or two-dimensional (incomplete fusion and cracks). In welded 20 mm (0.8 in.) thick, wide-plate tests on ASTM A302B steel, three-dimensional defects lowered the fracture stress only at very low temperatures—below about −120 °C (−185 °F). Some work performed in Japan has shown that about five percent porosity in ASTM A302B steel welds raised the transition temperature for unnotched impact bend specimens from about −150 °C (−240 °F) to −40 °C (−40 °F). However, the reasons for this behavior are not clearly understood.

Results of precracked Charpy tests have shown that the weld metal's resistance to crack propagation under impact loading is not significantly affected by porosity. Porosity should be considered a risk only when the material is too brittle to be used safely or when fatigue loading initiates cracks.

CODE STANDARDS

The AWS Structural Welding Code, the ASME Boiler and Pressure Vessel Code, and other standards all specify the nature and size of acceptable discontinuities which may remain in a particular type of welded structure for a specific service. They usually require the removal and repair of cracks, but permit limited amounts of some other discontinuities, particularly porosity.

Table of SI and U.S. customary values for Chapter 5 figures

Linear measurements

mm	in.	mm	in.
6	1/4	175	7
6.40	0.252	200	8
12.83	0.505	250	10
13	½, 0.5	300	12
15.88	0.625	400	16
16	5/8	450	18
25	1	600	24
32	1¼		
38	1.5		
41.28	1.625		
44.4	1.75		
50	2		
75	3		
100	4		
120.7	4.75		
125	5		
150	6		
165	6.5		

Temperature

°C	°F
−84	−120
−73	−100
−50	−60
15.6	60
21	70
49	120

Stress, yield strength

MPa	ksi	MPa	tonf/in.^{2}
140	20	55	4
275	40	83	6
415	60	110	8
550	80	138	10
690	100	165	12
830	120	193	14
1100	160	221	16
1240	180	248	18
1380	200	275	20
1655	240		

REFERENCE LIST

1. Jubb, J. E. M. 1971. Lamellar tearing. *Welding Research Council Bulletin* 168.
2. Stout, R. D. 1973. Hardness as an index of the weldability and service performance of steel weldments. *Welding Research Council Bulletin* 189.
3. Rice, J. R. *Fracture, An Advanced Treatise.* Vol. 2, edited by H. Libowitz. New York: Academic Press, 1968, pp. 192-311.
4. Griffith, A. A. 1920. The phenomena of rupture and flow in solids. Philosophical Transactions, London Royal Society, Series A, vol. 221, p. 163.
5. Irwin, G. R. 1957. Analyses of stresses and strains near the end of a crack transversing a plate. *Journal of Applied Mechanics.* 24: 361.
6. Williams, M. L. 1957. Stress distribution at the base of a stationary crack. *Journal of Applied Mechanics.* 24: 109.
7. Paris, P. C. and Sih, G. C. Stress analysis of cracks. *Fracture Toughness Testing and Its Applications,* ASTM STP 381. Philadelphia: American Society for Testing and Materials, 1965.
8. Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials, E399. *Annual Book of ASTM Standards,* part 10. Philadelphia: American Society for Testing and Materials. Published annually.
9. Shoemaker, A. K. and Rolfe, S. T. 1971. The static and dynamic low-temperature crack-toughness performance of seven structural steels. *Engineering Fracture Mechanics* 2 (4): 319-340.
10. Shabbitts, W. O. Dynamic fracture toughness properties of heavy section A533 B, Class 1 steel plate, WCAP-7623, 1970. Pittsburgh: Westinghouse Electric Corporation.
11. Nash, G. E. and Lange, E. A. 1969. An analysis of the forces and bending moments generated during the notched beam impact test. *International Journal of Fracture Mechanics* 5: 269.
12. Begley, J. A. and Landes, J. D. The J integral as a failure criterion. *Fracture Toughness,* ASTM STP 514. Philadelphia: American Society for Testing and Materials, 1972, pp. 1-20.
13. Landes, J. D. and Begley, J. A. Test results from J integral studies — an attempt to establish a J_{Ic} testing procedure. Scientific Paper 73-1E7-FMPWR-P3, Oct. 18, 1970. Pittsburgh: Westinghouse Electric Corporation.
14. Standard Methods for Notched Bar Impact Testing of Metallic Materials, E 23. *Annual Book of ASTM Standards,* part 10. Philadelphia: American Society for Testing and Materials. Published annually.
15. Method for 5/8-inch Dynamic Tear Testing of Metallic Materials, MIL-STD-1601 (Ships) (latest edition). Washington, D.C.: Navy Department.
16. Standard Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels, E 208. *Annual Book of ASTM Standards,* part 10. Philadelphia: American Society for Testing and Materials. Published annually.
17. Methods for crack opening displacement (COD) testing. 1972. Draft for development, vol. 19. British Standards Institution.
18. Pellini, W. S. Evolution of engineering principles for fracture-safe design of steel structures. NRL Report 6957, Sept. 23, 1969. Washington, D.C.: Naval Research Laboratory.
19. Williams, M. L. Analysis of brittle behavior in ship plates. Ship Structure Committee Report, Serial No. NBS-5, Feb. 7, 1955. Washington, D.C. (Also ASTM STP 158. Philadelphia: American Society for Testing and Materials, 1954.)
20. Pellini, W. S. and Puzak, P. P. Practical considerations in applying laboratory fracture test criteria to the fracture-safe design of pressure vessels. NRL Report 6030, Nov. 5, 1963. Washington, D.C.: Naval Research Laboratory.
21. PVRC recommendations on toughness requirements for ferritic materials. 1972. *Welding Research Council Bulletin* 175.
22. Puzak, P. P. and Lange, E. A. Significance of Charpy-V test parameters as criteria for quenched and tempered steels. NRL Report 7483, Oct. 10, 1972. Washington, D.C.: Naval Research Laboratory.
23. Pellini, W. S. and Puzak, P. P. Fracture analysis diagram procedures for the fracture-safe engineering design of steel structures. NRL Report 5920, Mar. 15, 1963. Washington, D.C.: Naval Research Laboratory. (Also *Welding Research Council Bulletin* 88, 1963.)
24. Dolby, R. E., Egan, G.R., Dawes, M., Saun-

ders, G.G., and Sicher, G.L. 1969. Brittle fracture initiation in welded low strength steels. *Practical Fracture Mechanics for Structural Materials.* London: Chapman and Hall Ltd.

25. Paris, P. C. The fracture mechanics approach to fatigue. *Fatigue—An Interdisciplinary Approach.* Proceedings Tenth Sagamore Army Material Research Conference. Syracuse, New York: Syracuse University Press, 1964.

26. Signes, E. G., Baker, R. G., Harrison, J. D. and Burdekin, F.M. 1967. Factors affecting the fatigue strength of welded high strength steels. *British Welding Journal* 14 (3): 108.

27. Fisher, J. W., Albrecht, P. A., Yen, B. T., Klingerman, D. J., and McNamee, B. M. 1974. Fatigue strength of steel beams with transverse stiffeners and attachments. NCHRP Report 147. Washington, D.C.: Highway Research Board.

28. Gurney, T. R. *Fatigue of Welded Structures.* Cambridge: Cambridge University Press, 1968.

29. Fisher, J. W., Frank, K. H., Hirt, M. A., and McNamee, B. M. 1970. Effect of weldments on the fatigue strength of steel beams. NCHRP Report 102. Washington, D.C.: Highway Research Board.

30. Harrison, J. D. 1970. The analysis of fatigue test results for butt welds with lack of penetration defects using a fracture mechanics approach. *Welding in the World* 8 (3): 168-181.

31. Maddox, S. J. 1970. Fatigue crack propagation in weld metal and heat affected zone material. *Metal Construction* 2 (7): 285.

32. Barsom, J. M. 1971. Corrosion—fatigue crack propagation below K_{ISCC}. *Engineering Fracture Mechanics* 3 (1): 15-25.

33. Hirt, M. A. and Fisher, J. W. 1973. Fatigue crack growth in welded beams. *Engineering Fracture Mechanics* 5 (2): 415-429.

34. Yao, J. T. P. and Munse, W. H. 1962. Low-cycle fatigue of metals—literature survey. *Welding Journal* 41 (4): 182s.

35. Morrow, J. D. *Cyclic Plastic Strain Energy and Fatigue of Metals,* ASTM STP-378. Philadelphia: American Society for Testing and Materials, 1965.

36. Kooistra, L. F. 1957. Effect of plastic fatigue on pressure-vessel materials and design. *Welding Journal* 36 (3): 120s.

37. Popov, E. P. 1973. Low-cycle fatigue of connections and details. Committee 18 SOA Report no. 3 of ASCE-IABSE Proceedings of the International Conference on the Planning and Design of Tall Buildings, vol. 2, Bethlehem, Pennsylvania: Lehigh University, p. 741.

38. Fisher, J. W. and Gurney, T. R. 1973. High cycle fatigue of connections and details. Committee 18 SOA Report no. 4 of ASCE-IABSE Proceedings of the International Conference on the Planning and Design of Tall Buildings, vol. 2, Bethlehem, Pennsylvania: Lehigh University, p. 757.

39. Sanders, W. W., Jr. 1972. Fatigue behavior of aluminum alloy weldments. *Welding Research Council Bulletin* 171.

40. Watkinson, F., Bodger, P. H., and Harrison, J. D. 1970. The fatigue strength of welded joints in high strength steels and methods for its improvement. Proceedings on the Fatigue of Welded Structures. London: The Welding Institute.

41. Fisher, J. W., Sullivan, M. D. and Pense, A. W. 1974. Improving fatigue strength and repairing fatigue damage. Fritz Engineering Laboratory Report no. 385.3. Bethlehem, Pennsylvania: Lehigh University.

42. Barsom, J. M., 1974. Subcritical crack growth in steel bridge members. NCHRP Project 12-14, Interim Report. Final report in preparation.

43. Wei, R. P. 1970. Some aspects of environment-enhanced fatigue-crack growth. *Engineering Fracture Mechanics* 1: 633-651.

SUPPLEMENTARY READING LIST

ASME Boiler and Pressure Vessel Code, Section 8, Pressure Vessels. Divisions 1 and 2 (latest edition). New York: American Society for Mechanical Engineers.

ASME Boiler and Pressure Vessel Code, Section 9, Welding and Brazing Qualifications for Welders, Brazers, and Welding and Brazing Operators (latest edition). New York: American Society of Mechanical Engineers.

Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels, E 208. *Annual Book of ASTM Standards.* Philadelphia: American Society for Testing and Materials. Published annually.

Egan, G. R. 1972. An assessment of defects in welded carbon manganese steels—Part I. *Welding Research Abroad* 18 (3): 2-32.

Free Bend Test for Ductility of Welds, E 16. *Annual Book of ASTM Standards.* Philadelphia: American Society for Testing and Materials. Published annually.

Guided Bend Test for Ductility of Welds, E 190. *Annual Book of ASTM Standards.* Philadelphia: American Society for Testing and Materials. Published annually.

Henthorne, M. 1974. Corrosion testing of weldments. *Corrosion* 30: 39-46.

Manson, S. S. *Thermal Stress and Low Cycle Fatigue.* New York: McGraw-Hill, 1966.

Mechanical Testing of Steel Products, A 370. *Annual Book of ASTM Standards.* Philadelphia: American Society for Testing and Materials. Published annually.

Metals—Mechanical, Fracture, and Corrosion Testing; Fatigue; Erosion; Effect of Temperature, parts 10 and 11. Philadelphia: American Society for Testing and Materials. Published annually.

Munse, W. H. and Grover, L M. *Fatigue of Welded Steel Structures.* New York: Welding Research Council, 1964.

Notched Bar Impact Testing of Metallic Materials, E 23. *Annual Book of ASTM Standards.* Philadelphia: American Society for Testing and Materials. Published annually.

Recommended Practice for Laboratory Immersion Corrosion Testing of Metals, G 31. *Annual Book of ASTM Standards.* Philadelphia: American Society for Testing and Materials. Published annually.

Recommended Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens, G 1. *Annual Book of ASTM Standards.* Philadelphia: American Society for Testing and Materials. Published annually.

Recommended Practices for Resistance Welding, Cl.1 (latest edition). Miami: American Welding Society.

Specification for Bare Mild Steel Electrodes and Fluxes for Submerged Arc Welding, A5.17 (latest edition). Miami: American Welding Society.

Standard Method for Evaluating the Strength of Brazed Joints, AWS C3.2 (latest edition). Miami: American Welding Society.

Standard Methods for Mechanical Testing of Welds, B4.0 (latest edition). Miami: American Welding Society.

Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials, E 399. *Annual Book of ASTM Standards.* Philadelphia: American Society for Testing and Materials. Published annually.

Structural Welding Code, D1.1 (latest edition). Miami: American Welding Society.

Tension Testing of Metallic Materials, E 8. *Annual Book of ASTM Standards.* Philadelphia: American Society for Testing and Materials. Published annually.

Thielsch, H. 1952. Thermal fatigue and thermal shock. *Welding Research Council Bulletin* 10.

Vagi, J. J., Meister, R. P., and Randall, M. D. Weldment evaluation methods. DMIC Report 244, Aug. 1968. Columbus, Ohio: Battelle Memorial Institute.

Yen, T. C. 1961. Thermal fatigue—a critical review. *Welding Research Council Bulletin* 72.

6

Residual Stresses and Distortion

Prepared by:

K. MASUBUCHI, *Chairman*
Massachusetts Institute of Technology

Chapter Reviewers:

W. H. KIELHORN
Le Tourneau College

R. L. ROTHMAN
Battelle Columbus Labs

6

Residual Stresses and Distortion

INTRODUCTION

Because a weldment is locally heated (by most welding processes), the temperature distribution in the weldment is not uniform and changes take place as welding progresses. Typically, the weld metal and the base metal heat-affected zone immediately adjacent to it are at a temperature substantially above that of the unaffected base metal. As the molten pool solidifies and shrinks, it begins to exert shrinkage stresses on the surrounding weld metal and heat-affected zone area. When it first solidifies, this weld metal is hot, relatively weak, and can exert little stress. As it cools to ambient temperature, however, the shrinkage of the weld metal exerts increasing stress on the weld area and eventually reaches the yield point of the base metal and the heat-affected zone.

A weld is usually made progressively, which causes the already solidified portions of the weld to resist the shrinkage of later portions of the weld bead. Thus, the portions welded first are strained in tension in a direction longitudinal to the weld (that is, down the length of the weld bead as shown in Fig. 6.1). In addition, in the case of a butt weld, there commonly is little motion of the weld permitted in the transverse direction because of the weld joint preparation or the stiffening effect of underlying passes. In these welds, then, as shown in Fig. 6.1, there will be transverse residual stresses as well. For fillet welds, as shown in Fig. 6.2, the shrinkage stresses will be tensile down the length of the weld and across its face. The types and distribution of these stresses are complex, and a detailed analysis of stresses in single pass and multipass welds along with a discussion of the various factors which interact to increase or decrease their magnitude is found in subsequent sections of this chapter (see pp. 244-247).

Residual stresses in weldments have two major effects. First, they produce distortion, and second, they may be the cause of premature failure in weldments. Distortion is caused when the heated weld region contracts nonuniformly, causing shrinkage in one part of the weld to exert eccentric forces on the weld cross section. The weldment strains elastically in response to these stresses, and this nonuniform strain is seen in macroscopic distortion. The distortion may appear in butt joints as both longitudinal and transverse shrinkage or contraction, and as angular change (rotation) when the face of the weld

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Note: The SI (metric) and U.S. customary values given in this chapter are not, in most cases, exact equivalents. The SI values are the primary measurements used in this and all Volume 1 chapters. The secondary U.S. measurements (given parenthetically in text) are rounded off conversions from the SI values. For a further explanation of the system of measurements used in Volume 1, refer to the Foreword on p. xi.

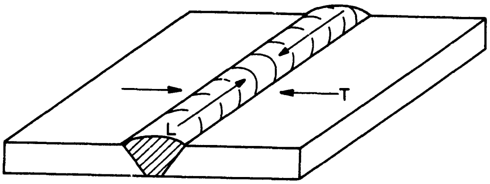


Fig. 6.1—Longitudinal (L) and transverse (T) shrinkage stresses in a butt weld.

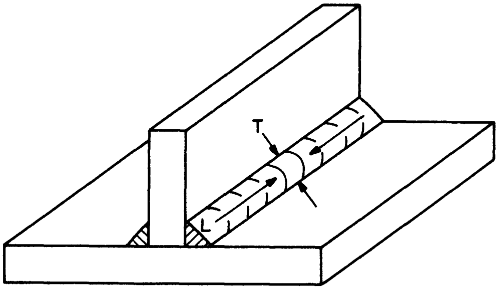


Fig. 6.2—Longitudinal and transverse shrinkage stresses in a fillet weld.

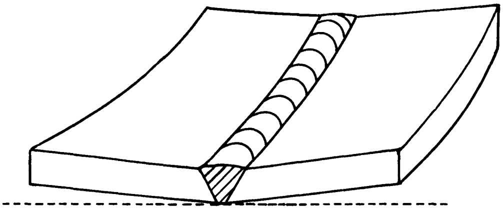


Fig. 6.3—Distortion in a butt weld.

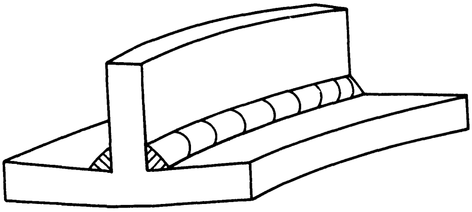


Fig. 6.4—Distortion in a fillet weld.

shrinks more than the root. The latter change produces transverse bending in the plates along the weld length. These effects are shown in Fig. 6.3.

Distortion in fillet welds is similar to that in butt welds: transverse and longitudinal shrinkage as well as angular distortion result from the unbalanced nature of the stresses in these welds (see Fig. 6.4). Since fillet welds are often used in combination with other welds in a weldment, the specific resulting distortion may be complex. Distortion in weldments is an important factor in their use, and subsequent sections of this chapter describe ways in which the distortion in weldments may be predicted (see pp. 248-264).

Control of distortion can be achieved by a number of techniques. The most commonly used are those which control the geometry of the weld joint, either before or during welding. Examples of these techniques include prepositioning the workpieces prior to welding so that weld distortion leaves them in the desired final geometry, or restraining the workpieces so they cannot move (and distort) during welding. Designing the joint so that weld deposits are balanced on each side of the weld center line is another useful technique. Welding process selection and weld sequence also influence distortion and residual stress. Eventually, some distorted weldments can be straightened mechanically after welding, if necessary, and thermal or flame straightening can also be applied. These procedures are also discussed later (see pp. 265-268).

Residual stresses and distortion affect the fracture behavior of materials by contributing to buckling and brittle fracture when these failures occur at low-applied-stress levels. When residual stresses and their accompanying distortion are present, buckling may occur at lower compressive loads than would otherwise be predicted. In tension, residual stresses may lead to high local stresses in weld regions of low toughness, and as a result may trigger running brittle cracks that can be propagated by the low overall stresses that may be present. In addition, residual stresses may contribute to fatigue or corrosion failures.

Residual stress may be eliminated by both thermal and mechanical means. During thermal stress relief, the weldment is heated to a temperature at which the yield point of the metal is low enough for plastic flow to occur and thus allow relaxation of stress. In the process, the mechanical properties of the weldment may also change, usually but not always toward a more uniform distribution across the joint. For example, the brittle fracture resistance of many steel weldments is improved by thermal stress relief not only because the residual stresses in the weld are reduced, but also because hard weld heat-affected zones are tempered (and therefore rendered tougher) by this procedure. Mechanical stress relief treatments will also reduce residual stresses, but will not change the microstructure or hardness of the weld or heat-affected zone. Peening, proofstressing, and other techniques are applied to weldments to accomplish these ends. Both the effects of residual stress and the means for their elimination are discussed in later sections of this chapter (see pp. 231-237; 268-274).

It is important to recognize the broad problem of improving the reliability of welded metal structures. Engineers must consider not only reducing the effects of residual stresses and distortion, but also many other aspects including the reduction of cracks, porosity, and other discontinuities; material degradation due to thermal effects during welding; the extent of nondestructive testing; and fabrication cost, to mention only a few. Practicing engineers must weigh the advantages and disadvantages of processes and procedures from various perspectives. For example, a process or procedure which produces less distortion may also produce more porosity.

Increasing knowledge of the effects of residual stresses and distortion will not in itself achieve the goal of reducing their effects. This must be achieved through a number of different ways, including:

(1) Reducing residual stresses and distortion in the first place by selecting proper processes and procedures.

(2) Developing better means for stress relieving and removing distortion.

(3) Changing the structural design and the material so that the effects of residual stresses and distortion can be minimized.

CAUSES OF RESIDUAL STRESSES

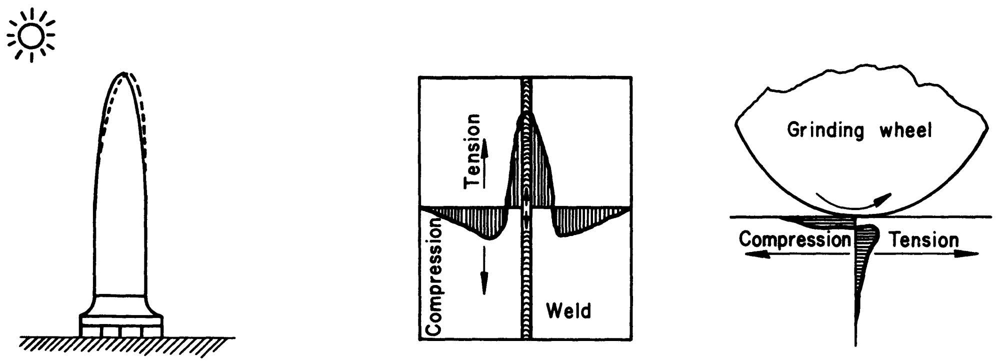
Residual stresses are those stresses that would exist in a body if all external loads were removed. Various technical terms have been applied to residual stresses such as internal stresses, initial stresses, inherent stresses, reaction stresses, and locked-in stresses. Residual stresses that occur when a body is subjected to nonuniform temperature change are usually called thermal stresses.

Residual stresses in metal structures occur for many reasons during various manufacturing stages. Residual stresses may be produced in many materials including plates, bars, and sections during rolling, casting, forging, etc. They may occur during forming and shaping of metal parts by such processes as shearing, bending, machining, and grinding and during fabrication, such as during welding.

Heat treatments at various stages can also influence residual stresses. For example, quenching produces residual stresses while stress relieving heat treatments reduce residual stresses.

MACROSCOPIC AND MICROSCOPIC RESIDUAL STRESSES

Areas in which residual stresses exist vary greatly from a large portion of a metal structure down to areas on the atomic scale. Figure 6.5 shows macroscopic residual stresses on various scales. For example, when a structure is heated by solar radiation from one side, thermal distortions and thermal stresses are produced in the structure, as shown in Fig. 6.5a. Figure 6.5b shows residual stresses produced by welding; residual stresses are distributed in areas near the weld. Figure 6.5c shows residual stresses produced by grinding;



a. Thermal distortion in a structure due to heating by solar radiation

b. Residual stresses due to welding

c. Residual stresses due to grinding

Fig. 6.5—Macroscopic residual stresses on various scales.

residual stresses are highly localized in a thin layer near the surface.

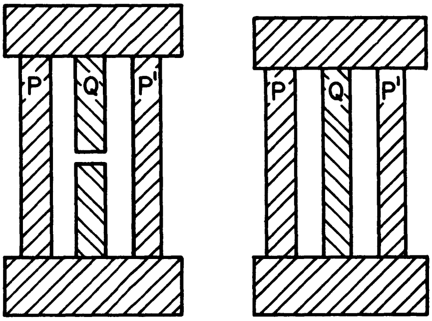
Residual stresses also occur on a microscopic scale. For example, residual stresses are produced in areas near martensitic structures* in steel since the martensite transformation that takes place at relatively low temperatures results in the expansion of the metal. Residual stresses on the atomic scale exist in areas near dislocations. This chapter is primarily concerned with macroscopic residual stresses.

FORMATION OF RESIDUAL STRESSES

Residual stresses are classified according to the mechanisms that produce them. These mechanisms are structural mismatching and the uneven distribution of nonelastic strains, including plastic and thermal strains.

Residual Stresses Produced by Mismatch

Figure 6.6 shows a simple case in which residual stresses are produced when bars of different lengths are forcibly connected. Tensile stresses are produced in the shorter bar, Q, and compressive stresses are produced in the longer bars, P and P′.



a. Free state

b. Stressed state

Fig. 6.6—Residual stresses produced when bars of different lengths are forcibly connected.

Figure 6.7 shows how a heating and cooling cycle causes mismatch resulting in residual stresses. Illustrated is the case in which three carbon steel bars of equal lengths and cross sectional areas are connected by two rigid blocks. The blocks and the middle bar are heated to 595 °C (1100 °F) and then cooled to room temperature while the side bars are kept at the room temperature. The diagram of Fig 6.7, plotted with the stress in the middle bar against temperature, shows how residual stresses are produced. Since the two side bars are resisting the deformation of the one middle bar, the stress in each side bar is always

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*Martensitic structures are described in Chapter 4, pp. 110 and 113.

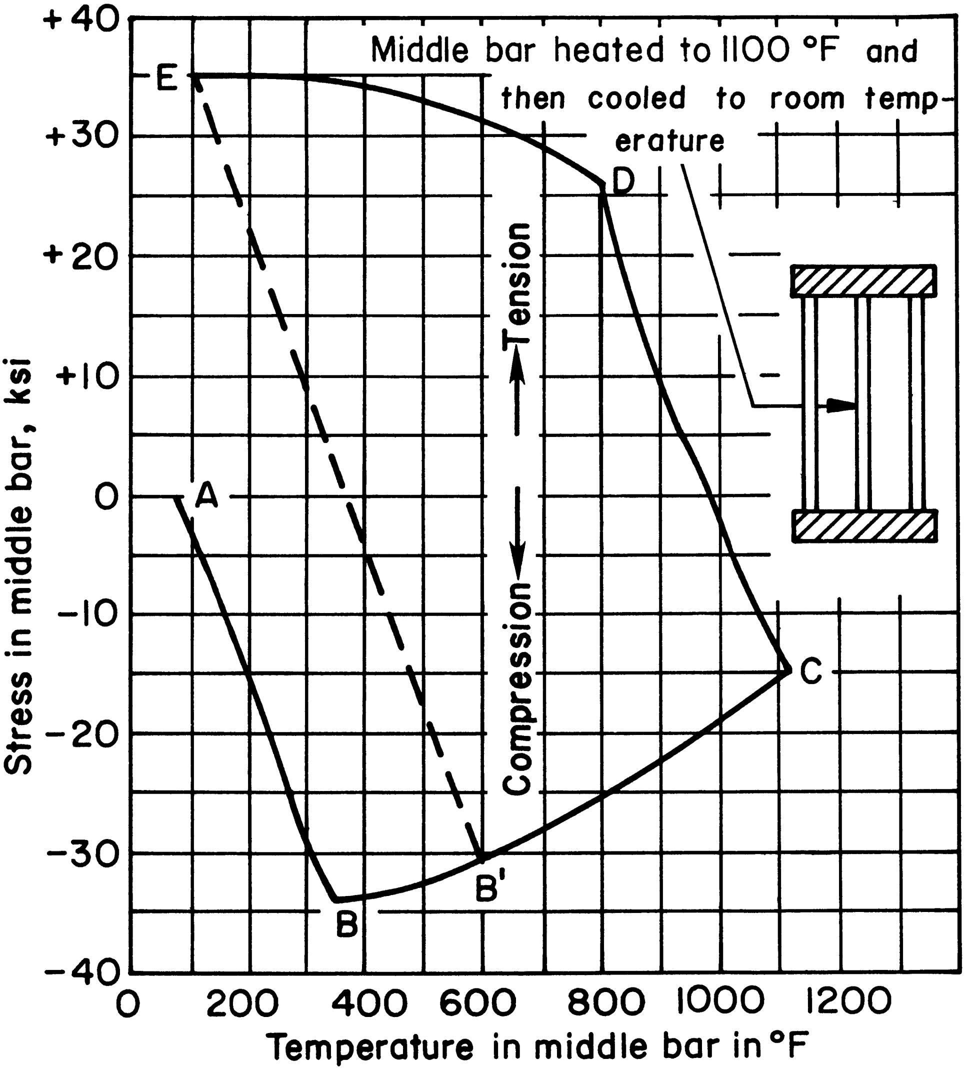


Fig. 6.7—Stress-temperature curve for middle bar of a three-bar frame. (For SI equivalents of U.S. customary values, see the table on p. 275.)

equal to half the stress in the middle bar and opposite in sign from the equilibrium condition.

When the middle bar is heated, compressive stresses are produced in the bar because its expansion is restrained by the side bars. As the temperature of the middle bar increases, the stress in it changes as shown by Line AB. The yield stress in compression is reached when the temperature is approximately 170 °C (340 °F) as indicated by Point B. Beyond Point B, as the temperature rises, the stress in the middle bar is limited to the yield stress at each corresponding temperature, as shown by Curve BC.

When the temperature decreases below 595 °C (1100 °F) on cooling, the action in the middle bar is elastic again. The compressive stress in the middle bar drops rapidly, changes to tension, and soon reaches the yield stress in tension, as indicated by Point D. Then, as the temperature decreases further, the stress in the middle bar is once more limited to the yield stress at each corresponding temperature, as shown by Curve DE. Thus, a residual tensile stress equal to the yield stress at room temperature is set up in the middle bar. The residual stresses in the side bars are compressive stresses and equal to one-half of the tensile stress in the middle bar. Line B′E indicates that residual stress of the same magnitude, which is equal to the yield stress at room temperature, will be produced by heating the middle bar at any temperature exceeding 315 °C (600 °F).

Residual Stresses Produced by Unevenly Distributed Nonelastic Strains

As noted previously, when a material is heated uniformly, it expands uniformly and no thermal stress is produced. On the other hand, when a material is heated unevenly, thermal stresses are produced. Residual stresses are also produced when unevenly distributed nonelastic strains such as plastic strains exist. The following are fundamental relationships for a two-dimensional plane stress ($\sigma_z = 0$) residual stress field:*

(1) Strains are composed of elastic strain and nonelastic strain:

$$\begin{aligned} \epsilon_x &= \epsilon'_x + \epsilon''_x \\ \epsilon_y &= \epsilon'_y + \epsilon''_y \\ \gamma_{xy} &= \gamma'_{xy} + \gamma''_{xy} \end{aligned} \qquad (6.1)$$

where

ϵ_x, ϵ_y, γ_{xy} are components of the total strain

ϵ'_x, ϵ'_y, γ'_{xy} are components of the elastic strain

ϵ''_x, ϵ''_y, γ''_{xy} are components of the nonelastic strain

The nonelastic strain can be plastic strain, thermal strain, etc.**

(2) A Hooke's Law relationship exists between stress and elastic strain, thus:

$$\begin{aligned} \epsilon'_x &= \frac{1}{E}(\sigma_x - \nu\sigma_y) \\ \epsilon'_y &= \frac{1}{E}(\sigma_y - \nu\sigma_x) \\ \gamma'_{xy} &= \frac{1}{G}\tau_{xy} \end{aligned} \qquad (6.2)$$

(3) The stress must satisfy the equilibrium conditions:

$$\begin{aligned} \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} &= 0 \\ \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} &= 0 \end{aligned} \qquad (6.3)$$

(4) The total strain must satisfy the condition of compatibility:

$$\left[\frac{\partial^2 \epsilon'_x}{\partial y^2} + \frac{\partial^2 \epsilon'_y}{\partial x^2} - \frac{\partial^2 \gamma'_{xy}}{\partial x \cdot \partial y}\right] + \left[\frac{\partial^2 \epsilon''_x}{\partial y^2} + \frac{\partial^2 \epsilon''_y}{\partial x^2} - \frac{\partial^2 \gamma''_{xy}}{\partial x \cdot \partial y}\right] = 0 \qquad (6.4)$$

Equations (6.3) and (6.4) indicate that residual stresses exist when the value of *R*, which is determined by the nonelastic strain as follows, is not zero:†

$$R = -\left[\frac{\partial^2 \epsilon''_x}{\partial y^2} + \frac{\partial^2 \epsilon''_y}{\partial x^2} - \frac{\partial^2 \gamma''_{xy}}{\partial x \cdot \partial y}\right] \qquad (6.5)$$

R, which has been called "incompatibility," can be considered the cause of residual stresses.[1]

Many investigators have made mathemat-

---

*In a general three-dimensional stress field, six stress components exist: σ_x, σ_y, σ_z, τ_{xy}, τ_{zy}, τ_{zx}.

**In the case of thermal stress:

$\epsilon''_x = \epsilon''_y = \alpha \cdot \Delta T$, $\gamma''_{xy} = 0$

where α is the coefficient of linear thermal expansion and ΔT is the change of temperature from the initial temperature.

†If the nonelastic strain components are linear functions of the position,

$\epsilon''_x = a + bx + dy$, $\epsilon''_y = e + fx + gy$, $\gamma''_{xy} = k + lx + my$,

then $R = 0$. Consequently, residual stresses will not occur.

ical analyses of residual stresses. Several equations have been proposed to calculate stress components, σ_x, σ_y, and γ_{xy} for given values of nonelastic strain, σ''_x, σ''_y, and γ''_{xy}. Important findings obtained from these mathematical analyses include the following:

(1) Residual stresses in a body cannot be determined by measuring the stress change that takes place when external load is applied to the body. (Because of this, the body must be cut to determine residual stresses.)

(2) Residual stresses σ_x, σ_y, and γ_{xy} can be calculated from equation (6.2) when elastic strain components ϵ'_x, ϵ'_y, and γ'_{xy} are determined. However, components of nonelastic strain ϵ''_x, ϵ''_y, and γ''_{xy}, which have caused residual stresses, cannot be determined without knowing the history of residual stress formation.

Equilibrium Condition of Residual Stresses

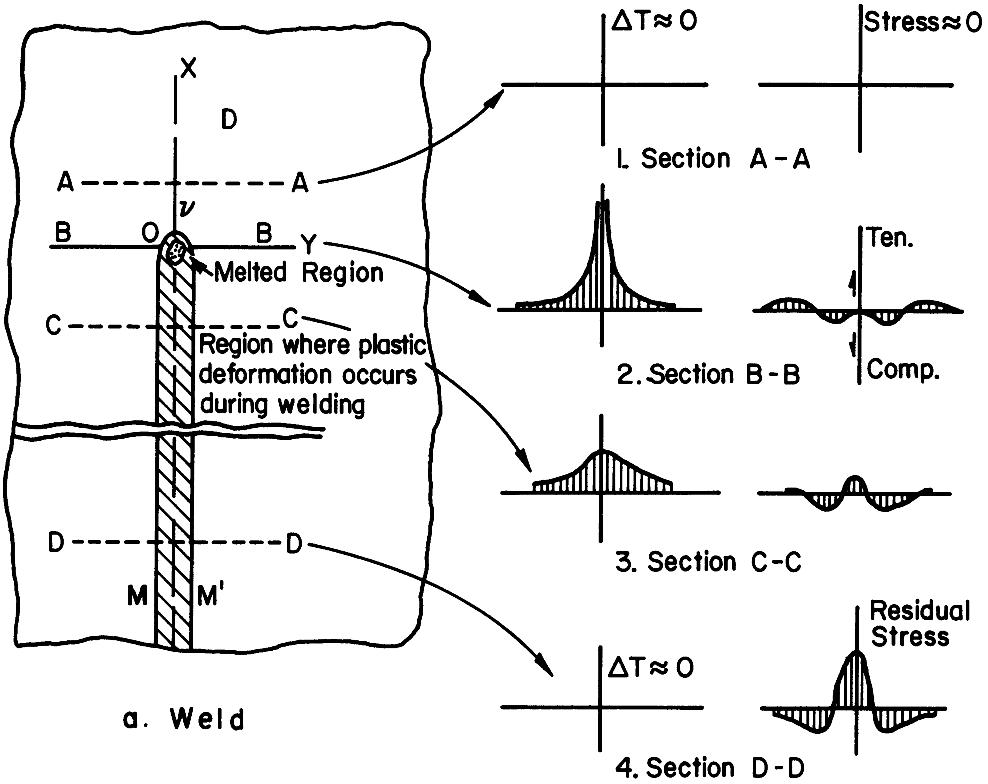
Since residual stresses exist without external forces, the resultant force and the resultant moment produced by the residual stresses must vanish:

$$\int \sigma \cdot dA = 0 \text{ on any plane section} \quad (6.6)$$

and

$$\int dM = 0 \quad (6.7)$$

It is very important to check whether residual stress data determined in any experiment satisfy the above conditions.



a. Weld

b. Temperature change

c. Stress σ_x

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Fig. 6.8—Schematic representation of changes of temperature and stresses during welding.[1]

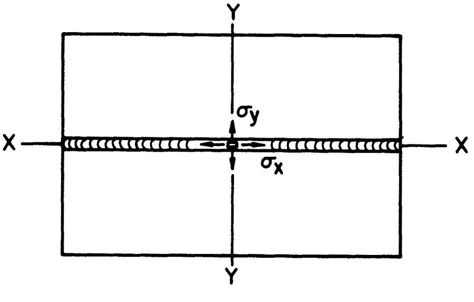
THERMAL STRESSES DURING WELDING AND RESULTING RESIDUAL STRESSES

Figure 6.8 shows schematically changes of temperature and stresses during welding. A bead-on-plate weld is being made along the x axis. The welding arc, which is moving at a speed, ν, is presently located at the origin, O, as shown in Fig. 6.8a.

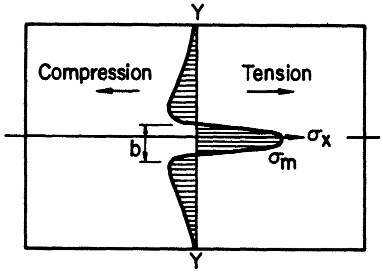
The crosshatched area, M-M′, in Fig. 6.8a shows the region where plastic deformation occurs during the welding thermal cycle. The ellipse near the origin O indicates the region where the metal is melted. The region outside the crosshatched area remains elastic during the entire welding thermal cycle.

Figure 6.8b shows temperature distribution along several cross sections. Along Section A-A, which is ahead of the welding arc, the temperature change due to welding, ΔT, is almost zero. Along B-B, which crosses the welding arc, the temperature distribution is very steep. Along Section C-C, which is some distance behind the welding arc, the distribution of temperature change is much less steep. Along Section D-D, which is very far from the welding arc, the temperature change due to welding again diminishes to nearly zero.

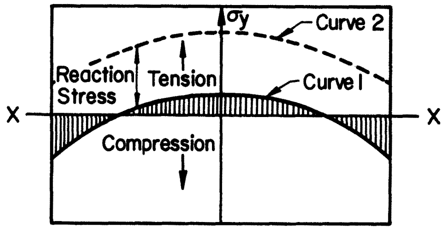
Figure 6.8c shows the distribution of stresses along these sections in the x direction, σ_x. Stress in the y direction, σ_y, and shearing stress, τ_{xy}, also exist in a two-dimensional stress field.



a. Butt weld



b. Distribution of σ_x along YY



c. Distribution of σ_y along XX

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Fig. 6.9—Typical distributions of residual stresses in a butt weld.[1]

Along Section A-A, thermal stresses due to welding are almost zero. The stress distribution along Section B-B is shown in Fig. 6.8c. Stresses in regions underneath the welding arc are close to zero because molten metal does not support loads. Stresses in regions somewhat away from the arc are compressive because the expansion of these areas is restrained by surrounding metal that is at lower temperatures. Since the temperatures of these areas are quite high and the yield strength of the material is low, stresses in these areas are as high as the yield strength of the base metal at corresponding temperatures. The magnitude of compressive stress passes through a maximum with increasing distance from the weld or with decreasing temperature. However, stresses in areas away from the weld are tensile and balance with compressive stresses in areas near the weld. Thus, the stress distribution along Section B-B is as shown in Fig. 6.8c.

Along Section C-C, as shown in Fig. 6.8c, the weld metal and base metal regions near the weld have cooled and they try to shrink causing tensile stresses in regions close to the weld.

As the distance from the weld increases, the stresses first change to compressive and then become tensile.

Along Section D-D, high tensile stresses are produced in regions near the weld, while compressive stresses are produced in regions away from the weld.

As may be concluded from the preceding paragraphs, thermal stresses during welding are produced by a complex mechanism which involves plastic deformation at a wide range of temperatures from room temperature to melting temperature. Because of the difficulty in analyzing plastic deformation, especially at elevated temperatures, mathematical analyses are presently limited to very simple cases such as in spot welding.

RESIDUAL STRESSES AND REACTION STRESSES IN WELDMENTS

Residual stresses that occur during the fabrication of welded structures are classified into (1) residual welding stresses that are produced in the welding of unrestrained members and (2) reaction stresses that are caused by external restraint.

A typical distribution of both longitudinal and transverse residual stresses in a butt weld is shown in Fig. 6.9. The stresses of concern are those parallel to the weld direction, designated σ_x, and those transverse to it, designated σ_y.

Figure 6.9b shows the distribution of the longitudinal residual stress, σ_x. Tensile stresses of high magnitude are produced in the region near the weld; these taper off rapidly and become compressive after a distance several times the width of the weld metal. The stress distribution is characterized by two parameters: (1) the maximum stress at weld region, σ_m, and (2) the width of the tension zone of residual stress, b. In weldments made in low carbon steel, the maximum residual stress, σ_m, is usually as high as the yield stress of the weld metal.

The distribution of the transverse residual stress, σ_y, along the length of the weld is shown on Curve 1 in Fig. 6.9c. Tensile stresses of relatively low magnitude are produced in the middle part of the joint and compressive stresses at the ends of the joint.

If the lateral contraction of the joint is restrained by an external constraint, tensile stresses approximately uniform along the weld are added as the reaction stress. An external constraint, however, has little influence on the distribution of σ_x, residual stresses.

When a weldment is made with a heavy plate, such as over 25 mm (1 in.) thick, residual stresses in the thickness direction, σ_z, can become significant.

EFFECTS OF RESIDUAL STRESSES

Residual stresses decrease the fracture strength of welded structures only when certain conditions exist; however, the loss of strength can be drastic under these conditions. In general, the effects of residual stresses are significant when fractures take place under low applied stress.

FRACTURE UNDER TENSILE STRESSES

Changes of Residual Stresses in Weldments Subjected to Tensile Loading

Figure 6.10 shows how residual stresses change when a butt weld is subjected to tensile loading. Curve O shows the lateral distribution of longitudinal residual stress in the as-welded condition. When uniform tensile stress $\sigma = \sigma_1$ is applied, the stress distribution will be shown by Curve 1. The stresses in areas near the weld reach yield stress, and most of the stress increase occurs in areas away from the weld. When the tensile applied stress increases to σ_2, the stress distribution will be as shown by Curve 2. As the level of applied stress increases, the stress distribution across the weld becomes more even; that is, the effect of welding residual stress on the stress distribution decreases.

When the level of applied stress is further increased, general yielding takes place; that is, yielding occurs across the entire cross section. The stress distribution at general yielding is shown by Curve 3. Beyond general yielding, the effect of residual stresses on the stress distribution virtually disappears.

The next consideration is the distribution of residual stresses after the tensile loads are released. Curve 1′ shows the residual stress which remains after unloading when the tensile stress $\sigma = \sigma_1$ is applied to the weld and then released. Curve 2′ shows the residual stress distribution when the tensile stress $\sigma = \sigma_2$ is applied and then released.

Compared to the original residual stress distribution (Curve O), residual stress distributions after loading and unloading are more even. As the level of loading increases, the residual stress distribution after unloading becomes more even; that is, the effect of welding residual stress on the stress distribution decreases.

The preceding discussions lead to the following basic facts about the effects of residual stresses:

(1) The effect of residual welding stresses on the performance of welded structures is significant only on phenomena which occur under low applied stress, such as brittle fracture and stress corrosion cracking.

(2) As the level of applied stress increases, the effect of residual stress decreases.

(3) The effect of residual stress is negligible on the performance of welded structures under applied stresses beyond yielding.

(4) The effect of residual stress tends to decrease after repeated loading.

Brittle Fracture or Unstable Fracture under Low Applied Stress*

Extensive studies have been conducted on the effects of residual stresses on brittle fracture of welded steel structures.

Experimental Studies. Investigators have observed differences between the data obtained from brittle fractures in ships and other structures and the experimental results obtained with notched specimens. Actual fractures occurred at stresses far below the yield stress of the material; however, the nominal

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*See the section on fracture toughness in Chapter 5, p. 170.

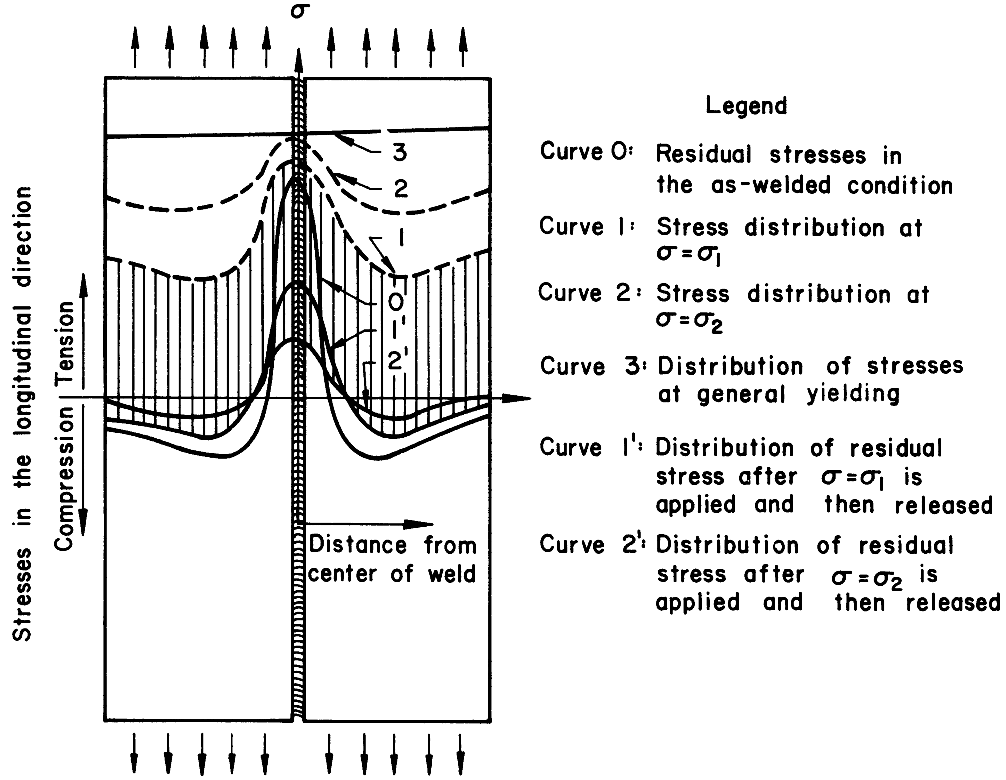

Fig. 6.10—Schematic distributions of stresses in a butt weld when uniform tensile loads are applied and the residual stresses that result after the loads are released.

fracture stress of a notched specimen is as high as the yield stress, even when the specimens contain very sharp cracks. A number of research programs have been carried out on low-applied-stress fracture of weldments.[2] Under certain test conditions, complete fracture of a specimen occurred while the magnitude of applied stress was considerably below the yield stress of the material.

Figure 6.11 shows the general fracture strength tendencies of welded carbon steel specimens at various temperatures, and the effects of a sharp notch and residual stress on fracture strength.[3]

When a specimen does not contain a sharp notch, fracture will occur at the ultimate strength of the material at the test temperatures, as shown by Curve PQR. When a specimen contains a sharp notch (but no residual stress), fracture will occur at the stresses shown by Curve PQST. When the temperature is higher than the fracture transition temperature, T_f, a high energy (shear-type) fracture occurs at high stress. When the temperature is below T_f, the fracture appearance changes to a low energy (cleavage) type, and the stress at fracture decreases to near the yield stress. When a notch is located in areas where high residual tensile stresses exist, these various types of fracture can occur:

(1) At temperatures higher than T_f, fracture stress is the ultimate strength (Curve PQR). Residual stress has no effect on fracture stress.

(2) At room temperatures lower than T_f but higher than the crack-arresting temperature, T_a, a crack may initiate at a low stress, but it will be arrested.

(3) At temperatures lower than T_a, one of

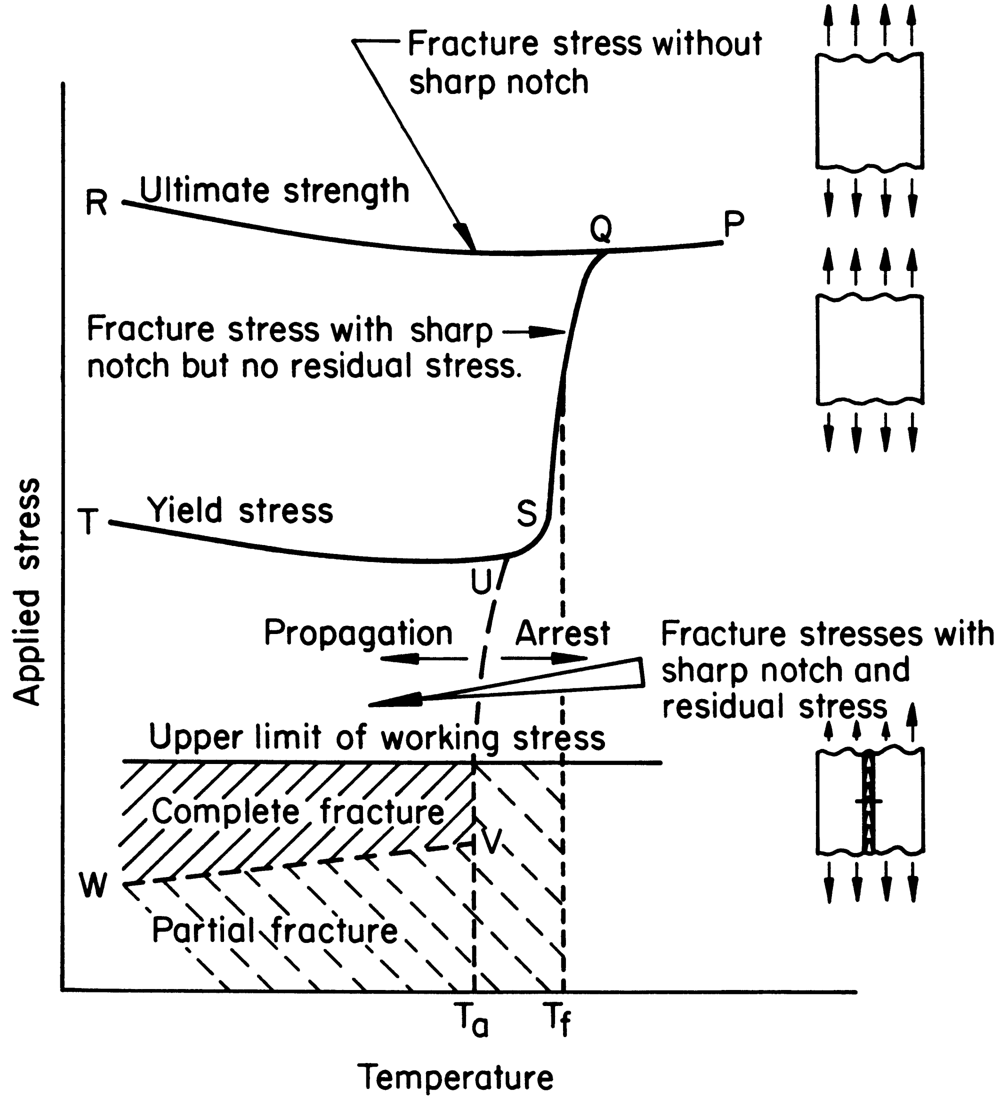

Fig. 6.11—Effects of sharp notch and residual stress on fracture strength.[3]

two phenomena can occur, depending upon the stress level at fracture initiation:

(a) If the stress is below the critical stress, VW, the crack will be arrested after running a short distance. Complete fracture will occur at the yield stress, ST.

(b) If the stress is higher than VW, complete fracture will occur.

Fracture mechanics concepts have been used to analyze the effect of residual stress on unstable fracture.[4] These concepts are described in more detail in Chapter 5, p. 185. This kind of analysis shows that an unstable fracture can develop even from small cracks that would normally be stable if residual stresses were not present. The sequence of events is as follows. When a small, subcritical flaw lies in a region free of residual stress, the stress intensity, K, at the flaw tip is less than the critical value, K_c, for fracture of the material. K is a function of both the stress at the tip of the flaw and its length. If the flaw should occur in a region of high residual stress, such as near or in a weld joint, the stress intensity is elevated to a much higher value, perhaps above K_c, and the crack grows unstably until it runs beyond the residual stress region. At this point the crack may arrest or continue to grow, depending on the stress state. If the overall stress level is low, the stress intensity may decay to a low value and, in spite of the increased crack size, the crack may arrest. Alternatively, if the crack size is now large enough to provide a substantial increase in K in spite of the decreasing stress field, the K value associated with the flaw may still exceed K_c. In the latter case the crack will continue to grow unstably and fracture of the structure may result.

This analysis is quite similar to that discussed previously, but uses a critical crack size and K value rather than the fracture temperature as the fracture control parameter. The two approaches are not inconsistent with each other because the critical K value, K_c, for a material is a function of temperature, and thus raising the temperature in a material to T_a is equivalent to raising K_c to a value high enough to cause crack arrest.

Effect of Stress Relieving Treatments on Brittle Fracture of Weldments. Residual stresses in weldments can be reduced by producing plastic deformation in proper amounts and distribution. The plastic deformation may be applied thermally, mechanically, or by a combination of the two. In the most commonly used technique, which is called the stress relieving treatment, a weldment is placed for a certain period in a furnace at a specific temperature, depending upon the type of material and thickness, and then cooled slowly.

When a load is applied to a weldment, residual stresses are redistributed due to local plastic deformation. When the load is removed, these stresses are reduced. This effect, called mechanical stress relieving, was demonstrated in a series of experiments on welded and notched wide-plate specimens in carbon steel.[5]

In a series of tests, external loads were applied to different stress levels, 50, 100, 150, 200, and 230 MPa (7250, 14 500, 21 760, 29 010, and 33 360 psi) at 20 °C (68 °F), which was above the critical temperature for crack initiation, T_c, then the load was reduced. After these mechanical stress relieving treatments, the specimens and applied tensile loads were cooled again at temperatures below −30 °C (−22 °F). For these specimens fractures occurred only after the preloaded stresses were exceeded, even at this low temperature.

In another series of tests, specimens were thermally stress relieved by placing them in a furnace for one hour at 320, 420, 520, and 620 °C (608, 788, 968, and 1148 °F). Fracture stresses for these specimens were higher when welds were heat treated at higher temperatures, indicating that more stresses were relieved by heating at higher temperatures.

BUCKLING UNDER COMPRESSIVE LOADING

Failures due to instability or buckling sometimes occur in metal structures composed of slender bars or thin plates when they are subjected to compressive axial loading, bending, or torsional loading. Residual compressive stresses decrease the buckling strength of a metal structure and in addition, initial distortions caused by residual stresses also decrease the buckling strength. Problems related to the effects of residual stresses on the buckling strength of welded structures can be classified into the following:

(1) Buckling strength of straight columns which contain residual stresses.

(2) Buckling strength of flat plates which contain residual stresses.

(3) Buckling strength of columns and plates which have initial distortions as well as residual stresses.

Columns under Compressive Loading

Instability of built-up columns has been studied both analytically and experimentally by a number of investigators. They have found that residual stresses can significantly reduce the buckling strength of welded columns, particularly when made from universal mill plate.[6,7]

Figure 6.12 shows buckling strengths of steel I-beams built up by welding universal mill plate under compressive axial loading.[6,7] It shows the relationship between the slenderness ratio of specimen, *L/r (L* is the specimen length and *r* is the radius of gyration), and the ratio of the critical stress and yield strength of the material. Curves PQR and ST show distributions of residual stresses in the longitudinal direction of an as-welded column in the flange and web plate, respectively. Welded joints between the web and flange plates cause residual tensile stresses in areas near the weld and compressive stresses in outer areas of the flanges and in the web plate. Curve AB shows the buckling strengths of as-welded columns, while Curve CDE shows the buckling strengths of stress relieved specimens and specimens with tensile residual stresses in the outer areas of the flange. Curves AB and CDE are obtained by theoretical analysis; DE is the so-called Euler curve and AB is obtained by considering the effect of residual stress on buckling strength. Buckling occurred in the weak axis of the columns. As-welded universal mill specimens had considerably lower critical buckling strength than did the other type of specimens indicating that an unfavorable residual stress distribution can cause a substantial decrease in the buckling strength. Close agreement was obtained between the experimental data and the theoretical values. If the column also has initial distortion, its buckling strength will be reduced further.

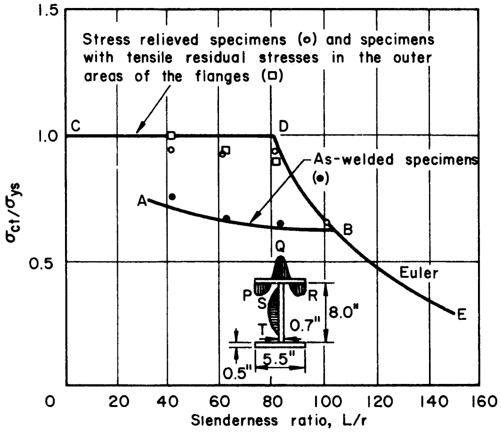

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Fig. 6.12—Effects of residual stresses on buckling strength of columns.[6] *(For SI equivalents of U.S. customary values, see the table on p. 275.)*

On the other hand, the columns made from oxygen cut plates normally have residual tensile stresses in the outer areas of the flange. From Fig. 6.12, it may be seen that in these columns, the residual stresses assume a more favorable pattern and are similar to the stress relieved columns. In this case, the residual stresses that result from preparing plate by oxygen cutting and from subsequent welding into the column section will combine to counterbalance each other from the buckling strength viewpoint. The performance of these columns should be about equivalent to hot rolled ones.

Plates and Plate Structures under Compression

Figure 6.13 shows the effects of residual stresses on the buckling strength of panel structures.[8,9] In preparing Fig. 6.13, residual stress distributions were estimated as shown in the insert in Fig. 6.13. It is assumed that:

(1) Tensile residual stresses in areas near the weld are as high as the yield stress, σ_{ys}, and they extend in the area with the width of ηt, where t is plate thickness and η is on both sides of the weld.

(2) Compressive residual stresses in areas away from the weld are constant (all equal to σ_r).

Then,

$$(b - 2\eta t)\sigma_r = 2\eta t \cdot \sigma_{ys} \qquad (6.8)$$

$$\sigma_r = \frac{2\eta}{b/t - 2\eta} \cdot \sigma_{ys} \qquad (6.9)$$

Curves in Fig. 6.13 show values of σ_u/σ_{ys}, where σ_u is the buckling strength for $\eta = 0$ (no residual stress), $\eta = 3$, and $\eta = 4.5$. Also shown here are values of $\Delta\sigma_u/\sigma_{ys}$, where $\Delta\sigma_u$ is reduction in buckling strength due to residual stresses; E_t is tangent modulus. While this figure appears complex, it provides an approach that can be used by designers in estimating the buckling strength of welded panels.

FATIGUE FRACTURE*

Although the effects of residual stresses on fatigue strength of weldments have been studied extensively, the subject is still a matter of debate.[10,11]

Fatigue strength increases when a specimen has compressive residual stresses, especially on the specimen surface. Many investigators have reported that the fatigue strength (the number of cycles at fracture under a given load or the endurance limit) increased when specimens had compressive residual stresses. For example, they have found experimentally that local spot heating of certain types of welded specimens increases their fatigue strength.[10] On the other hand, a number of investigators believe that residual stresses are relieved during cyclic loading; therefore, the effects of residual stress on fatigue strength of weldments are negligible.

An important characteristic of fatigue fracture is that most fatigue cracks originate at the surface.[12] Smoothness of surface is very important for obtaining high fatigue strength. For example, removing weld reinforcement, grinding surface irregularities, and other treatments are effective in reducing stress concentrations and increasing fatigue strength.

In conducting experiments to determine the effects of residual stresses on fatigue strength of weldments, the surface conditions of specimens must be carefully considered. A specimen which has compressive residual stresses on the surface is thus expected to have high fatigue strength. Yet the specimen may yield a poor result if it contains a sharp notch causing a fatigue crack to initiate from the notch.

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*See the section on fatigue in Chapter 5, p. 186.

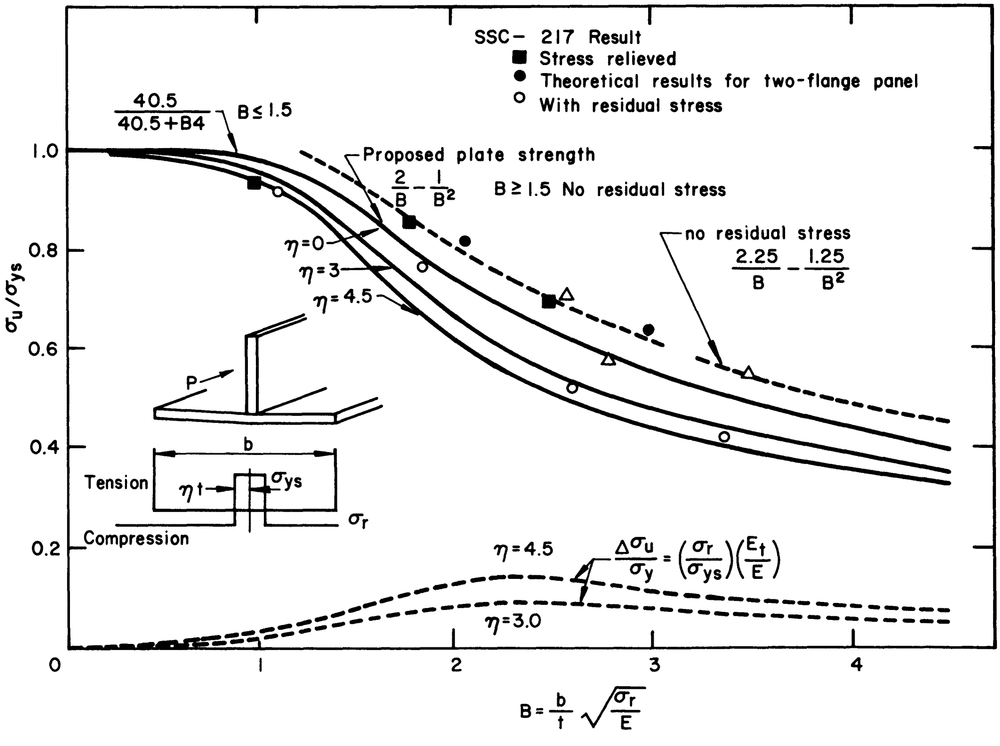

Fig. 6.13—Buckling strength of stiffened panels.

EFFECTS OF ENVIRONMENT

Cracking can occur in weldments, even without external loading, when the material is embrittled by exposure to certain environments and residual stresses are present. As described in Chapter 5, p. 203, stress corrosion cracking is a brittle-type fracture in a material exposed to a certain environment, and it should not be confused with other types of localized attack such as pitting, galvanic attack, intergranular corrosion, or cavitation.[13-15] Stress corrosion cracking has been observed on a number of ferrous and nonferrous alloys exposed to certain environments. Some of the sensitive combinations are given in Table 6.1.

High strength steels are sensitive to hydrogen. Many cracks in weldments are caused by hydrogen introduced during welding, as discussed in Chapter 4, pp. 127; 129-130; 136; 146. In addition to steels having a body centered cubic (BCC) crystal structure,* titanium and zirconium and their alloys can be embrittled by hydrogen.[13]

Hydrogen-induced cracking of weldments in various steels has been studied and an attempt made to develop a technique for determining the distribution of residual stresses in a weldment by observing the pattern of hydrogen-induced cracks.[16] Figure 6.14 shows a crack pattern in a simple butt weld made from SAE 4340 steel oil quenched and tempered at 260 °C (500 °F), after a hydrogen charging test for 50 minutes. A system of transverse cracks was obtained with longer cracks in the central region of the specimen. The crack pattern indicates that high tensile residual stresses in the direction parallel to the weld exist in areas near the weld. When welds were made in steels with lower strength, a longer time was required to produce cracks, and cracks were less extensive. Figure 6.14 also demonstrates the extent of cracking that can result from hydrogen or stress corrosion mechanisms when residual stresses are present.

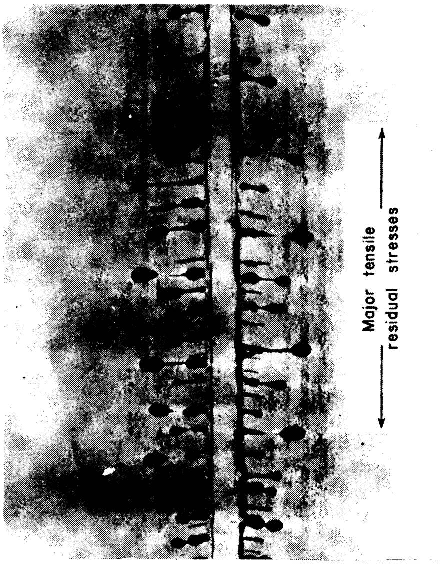

Fig. 6.14—Crack pattern in a simple butt joint made from SAE 4340 steel oil-quenched and tempered at 260 °C (500 °F) after hydrogen-induced cracking test for 50 minutes.[16]

Table 6.1—Environments producing stress corrosion cracking

Alloy	Sensitive Environment
Low alloy steels	Nitrates, hydroxides, hydrogen sulfide
Chromium stainless steels (greater than 12% Cr)	Halides, hydrogen sulfides, steam
Austenitic stainless steels (18 Cr-8 Ni)	Chlorides, hydroxides
Aluminum alloys	Sodium chloride, tropical environments
Titanium alloys	Red fuming nitric acid, chlorinated hydrocarbons

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*Austenitic steels having a face centered cubic (FCC) crystal structure (such as 300 series stainless steel) are usually not susceptible to hydrogen embrittlement.

MEASUREMENT OF RESIDUAL STRESSES IN WELDMENTS

CLASSIFICATION OF TECHNIQUES FOR MEASURING RESIDUAL STRESSES

Many techniques have been proposed and used for measuring residual stresses in metals. Table 6.2 classifies presently available techniques for measuring residual stresses into the following groups: (1) stress-relaxation techniques, (2) x-ray diffraction techniques, (3) techniques using stress-sensitive properties, and (4) cracking techniques.

In the stress-relaxation techniques, residual stresses are determined by measuring elastic strain release. This takes place when residual stresses are relaxed by cutting the specimen into pieces or by removing a piece from the specimen. In most cases, electric or mechanical strain gages are used for measuring the strain release (Group A-1). A variety of techniques exists depending upon ways of sectioning specimens to determine residual stresses. Some techniques are applicable primarily to plates, while others are applicable to cylinders, tubes, or three-dimensional solids. Strain release during stress relaxation can be determined using a grid system, brittle coatings, or photoelastic coatings rather than using electric or mechanical strain gages (Group A-2). An inherent disadvantage of the stress-relaxation techniques is that they are destructive; the specimen must be sectioned either entirely or partly. Nevertheless, the stress-relaxation techniques are most widely used for measuring residual stresses in weldments primarily because these techniques provide reliable, quantitative data.

Elastic strains in metals that have crystalline structures can be determined by measuring the lattice parameter using x-ray diffraction techniques. Since the lattice parameter of a metal in the unstressed state is known or can be determined separately, elastic strains in the metal can be determined nondestructively without machining or drilling. Two techniques are available at present: the x-ray film technique and the x-ray diffractometer technique. With the x-ray diffraction techniques, surface strains can be determined in a small area, say to a depth and diameter of 0.003 mm (0.0001 in.). The x-ray diffraction techniques are the only techniques applicable for measuring such residual stresses as those in ball bearings and gear teeth and surface residual stresses after machining or grinding.

However, the x-ray diffraction techniques have several disadvantages. First, they are rather slow processes. At each measuring point, measurements must be made in two directions, each requiring 15 to 30 minutes' exposure time for the film technique. Secondly, measurement is not very accurate, especially when applied to heat treated materials in which atomic structures are distorted.

Attempts have been made to determine residual stresses in metals by measuring stress-sensitive properties. Proposed stress measuring techniques include ultrasonic and hardness methods.

The ultrasonic technique may utilize polarized ultrasonic waves and make use of stress-induced change in the angle of polarization of polarized ultrasonic waves (similar to the photoelastic technique) or make use of stress-induced changes in the absorption of ultrasonic waves, that is, ultrasonic attenua-

Table 6.2—Classification of techniques for measuring residual stresses

A-1 Stress-relaxation techniques using electric and mechanical strain gages	Techniques applicable primarily to plates	1. Sectioning technique using electric resistance strain gages 2. Gunnert technique 3. Mathar-Soete drilling technique 4. Stablein successive milling technique
	Techniques applicable primarily to solid cylinders and tubes	5. Heyn-Bauer successive machining technique 6. Mesnager-Sachs boring-out technique
	Techniques applicable primarily to three-dimensional solids	7. Gunnert drilling technique 8. Rosenthal-Norton sectioning technique
A-2 Stress-relaxation techniques using apparatus other than electric and mechanical strain gages		9. Grid system-dividing technique 10. Brittle coating-drilling technique 11. Photoelastic coating-drilling technique
B X-ray diffraction techniques		12. X-ray film technique 13. X-ray diffractometer technique
C Techniques using stress-sensitive properties	Ultrasonic techniques	14. Polarized ultrasonic wave technique 15. Ultrasonic attenuation technique
		16. Hardness techniques
D Cracking techniques		17. Hydrogen-induced cracking technique 18. Stress corrosion cracking technique

tion. The hardness technique makes use of stress-induced changes in hardness.

None of these techniques has been developed beyond the laboratory stage and none has been used successfully for measuring residual stresses in weldments.

Techniques have been developed for studying residual stresses by observing cracks in the specimen produced by residual stresses. The cracks may be induced by hydrogen or stress corrosion. The cracking techniques are useful for studying residual stresses in complex structural models which have complicated residual stress distributions. However, these techniques provide qualitative rather than quantitative data.

The emphasis in this chapter is on those techniques which are applicable to weldments.

MEASUREMENT OF RESIDUAL STRESSES BY STRESS-RELAXATION TECHNIQUES

The stress-relaxation techniques are based on the fact that strains taking place during unloading are elastic even when the material has undergone plastic deformation. Therefore, it is possible to determine residual stresses without knowing the history of the material.

The following paragraphs describe five techniques for measuring residual stresses based on stress-relaxation techniques that can be used for weldments. The first and second techniques apply primarily to plates; the third and fourth techniques apply primarily to three-dimensional solids. The first four techniques employ electric or mechanical strain

Table 6.3—Summary of stress-relaxation techniques for measuring residual stresses

Technique	Application	Advantages	Disadvantages
1. Sectioning Technique for a Plate Using Electric-Resistance Strain Gages	Relatively all-around use, with the measuring surface placed in any position.	Reliable method. Simple principle. High measuring accuracy.	Destructive. Gives average stresses over the area of the piece removed from the specimen; not suitable for measuring locally concentrated stresses. Machining is sometimes expensive and time consuming.
2. Mathar-Soete Drilling Technique	The method can be used for laboratory and field work and on horizontal, vertical, and overhead surfaces.	A simple principle. Causes little damage to the test piece; convenient to use on welds and adjoining material.	Drilling causes plastic strains at the periphery of the hole which may displace the measured results. The method must be used with great care.
3. Gunnert Drilling Technique	Can be used for laboratory and field work. The surface of the plate must be substantially horizontal.	Robust and simple apparatus. Semi-nondestructive; damage to the object tested can be easily repaired.	Relatively large margin of error for the stresses measured in a perpendicular direction. The underside of the plate must be accessible for the attachment of a fixture. The method entails manual training.
4. Rosenthal-Norton Sectioning Technique	For laboratory measurements.	Fairly accurate data can be obtained when measurements are carried out carefully.	A troublesome, time-consuming, and completely destructive method.
5. Photoelastic Coating-Drilling Technique	Primarily a laboratory method, but it can also be used for field measurements under certain circumstances.	Permits the measurement of local stress peaks. Causes little damage to the material.	Sensitive to plastic strains which sometimes occur at the edge of the drilled hole.

gages, while the last technique employs a photoelastic coating.*

The techniques are named on the basis of the principle involved, the strain-measuring techniques used, or the persons who developed or described them. The range of application and the advantages and disadvantages of each of the five techniques are summarized in Table 6.3.

Sectioning Technique for a Plate Using Electric-Resistance Strain Gages

Using this technique, electric-resistance strain gages are mounted on the surface of the test structure or specimen. A small piece of metal containing the gages is then removed from the structure, as shown in Fig. 6.15.** Measurement is made of strain changes, ϵ_x, ϵ_y, γ_{xy}, that take place during the removal of the piece. If the piece is small enough, it can be assumed that residual stresses no longer exist in the piece after removal and the following therefore holds true:

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*RSIC-410 discusses 15 different methods.[17]

**In the resistance-type bonded strain gage technique, gages made from either metallic wire or foil materials are bonded on the specimen. As the specimen is strained, the resistance of the gages changes, and the magnitude of strain is determined by measuring the resistance change. Information on electric strain gages is available from various sources including the *Handbook of Experimental Stress Analysis.*[18]

$$\bar{\epsilon}_x = -\epsilon'_x,$$
$$\bar{\epsilon}_y = -\epsilon'_y,$$
$$\bar{\gamma}_{xy} = -\gamma'_{xy} \qquad (6.10)$$

where, ϵ'_x, ϵ'_y, and γ'_{xy} are elastic strain components of the residual stress. The minus signs in equation (6.10) indicate that, when tensile residual stress exists, shrinkage (not elongation) takes place during stress relaxation. Then residual stresses are

$$\sigma_x = -\frac{E}{1-\nu^2}(\bar{\epsilon}_x + \nu\bar{\epsilon}_y)$$
$$\sigma_y = -\frac{E}{1-\nu^2}(\bar{\epsilon}_y + \nu\bar{\epsilon}_x)$$
$$\tau_{xy} = -G\,\bar{\gamma}_{xy} \qquad (6.11)$$

It is advisable to make strain measurements on both surfaces of the plate because residual stresses may be caused by bending. The mean value of strains measured on both surfaces represents the plate stress component, while the difference between the strains on both surfaces represents the stress component caused by bending.

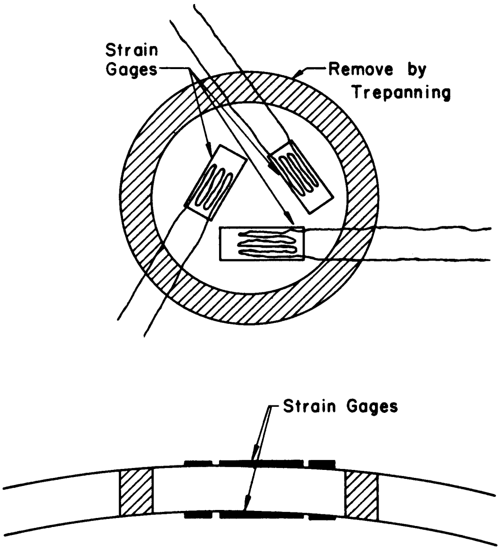


Fig. 6.15—Complete stress-relaxation technique applied to a plate.

The Mathar-Soete Drilling Technique

When a small circular hole is drilled in a plate containing residual stresses, residual stresses in areas outside the hole are partially relaxed. It is possible to determine residual stresses that existed in the drilled area by measuring stress relaxation in areas outside the drilled hole. The hole method of measuring stress was first proposed and used by Mathar and was further developed by Soete.[19]

A common way to determine residual stresses is to place strain gages in a star form, at 120 degrees from each other, and drill a hole in the center, as shown in Fig. 6.16. The magnitudes and directions of the principle stresses are calculated by measuring strain changes at the three gages.

The Gunnert Drilling Technique

Four 3 mm (0.12 in.) parallel holes located on a circle with a 9 mm (0.36 in.) diameter are drilled through the plate at the measuring point as shown in Fig. 6.17. The diametrical distance between these holes at different levels below the surface of the plate is measured by means of a specially designed mechanical gage. The perpendicular distance

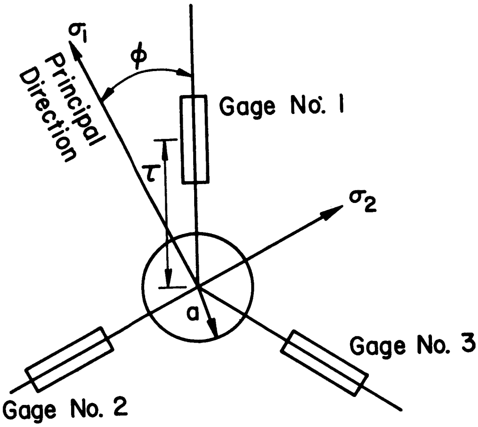
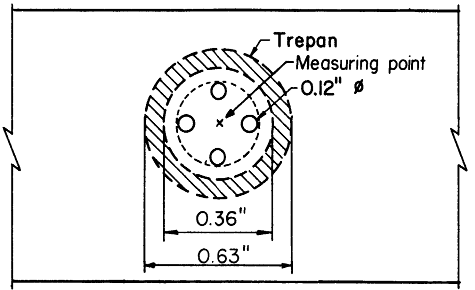
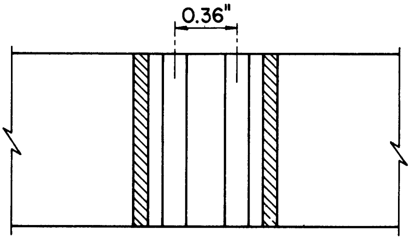


Fig. 6.16—120 degree star arrangement of strain gages for the Mathar-Soete drilling technique.



a. Plan



b. Side view

Fig. 6.17—The Gunnert drilling method. (For SI equivalents of U.S. customary values, see the table on p. 275.)

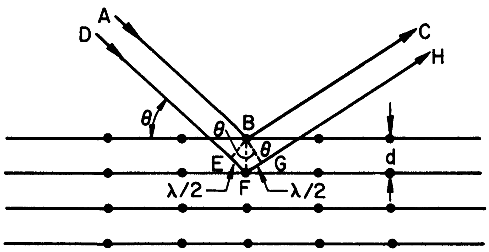
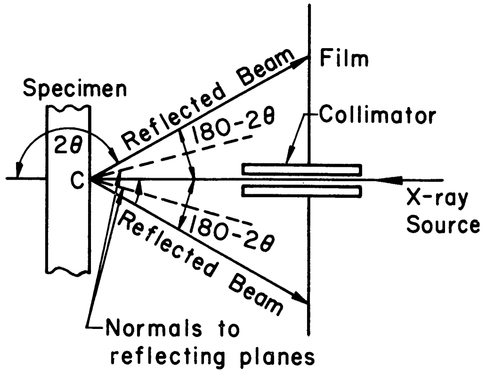
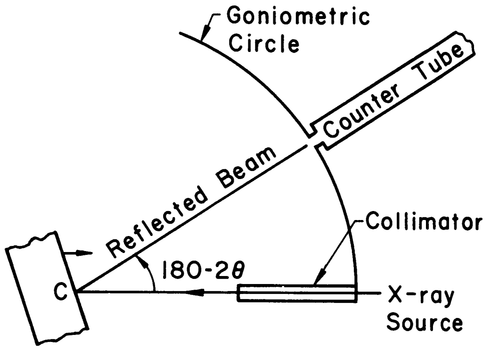


Fig. 6.18 — Diffraction produced by reflections from adjacent atomic planes of a monochromatic plane wave.

between the plate surface and the gage location at different levels below the surface is also measured. A groove 16 mm (0.63 in.) from the measuring point is then trepanned around the holes in steps, and the same measurements are made. Formulas are proposed to calculate residual stresses in the interior of the specimen from the measurement data.



a. Portable x-ray film technique



b. X-ray diffractometer technique

Fig. 6.19—Schematic diagrams of setups for x-ray diffraction techniques.

The Rosenthal-Norton Sectioning Technique

Rosenthal and Norton proposed a technique for determining residual stresses in a heavy weldment. Two narrow blocks with full thickness of the plate, one parallel to the weld and the other transverse to the weld, are cut from the weld. Then residual stresses still left in the narrow blocks are measured. Formulas have been proposed to estimate residual stresses in the interior of the weldments from (1) strain changes which take place while cutting the narrow blocks and (2) residual stresses which are left in the blocks.

Photoelastic Coating-Drilling Technique

A photoelastic coating is placed on the specimen.* A hole is drilled to a certain depth (for instance, equal to the diameter) at the measuring point through the photoelastic coating and a portion of the specimen. If residual stresses exist, birefringence occurs in areas near the drilled hole. By analysis, the birefringence strain release that took place due to drilling is determined and then the residual stresses that existed in the drilled area are calculated.

MEASUREMENT OF RESIDUAL STRESSES BY X-RAY DIFFRACTION TECHNIQUES

When external or internal forces are applied to a structure made of metallic crystals, the crystalline lattice is distorted, thus changing the interatomic distances. When the deformation exceeds the elastic limit, plastic deformation takes place as a result of slip along the lattice planes. In any event, the change in the interatomic spacing is directly proportional to the stress.

Suppose that a monochromatic plane wave is introduced to the atomic planes in the direction AB, as shown in Fig. 6.18. The reflected beams from successive parallel planes of atoms are reinforced in one direction, BC, the diffraction direction. Bragg's law defines the condition for diffraction as follows:

$$n\lambda = 2d \sin \theta \tag{6.12}$$

where

λ = the wave length of incident beam

θ = the angle between incident or reflected beams and surface of reflecting planes

d = the interplanar spacing

n = the order of reflection ($n = 1, 2, 3. . .$)

Equation (6.12) shows that if the wave length of the x-ray is known, the interplanar spacing, *d*, can be determined by measuring the angle θ.

Figure 6.19 shows schematic diagrams of setups for x-ray diffraction techniques. Two general techniques are employed in the recording of diffraction patterns: (1) the photographic or x-ray film technique, as shown in Fig. 6.19a and (2) the x-ray diffractometer or counter tube technique, as shown in Fig. 6.19b.

Figure 6.19a shows a portable setup which employs the film technique. The apparatus consists essentially of a film in a light-tight cassette mounted perpendicularly to the incoming x-ray beam. The beam is collimated by the pinhole system inserted through a hole in the film. The film records the rays diffracted by the specimen, and shows, on development, near-circular rings. The diameter of a diffraction ring divided by the distance from the film to the specimen gives 2 tan (180 - 2θ) from which θ is obtained for insertion in equation (6.12).

Figure 6.19b shows an x-ray diffractometer setup. In most cases, the x-ray diffraction method and the film method differ only in the detector and the angle made by the specimen with the x-ray beam. The angle between the x-ray beam and the specimen surface is 90 degrees in the film method, but it is an angle of θ degrees for the diffraction method. A counter and a receiving slit are moved along a goniometric circle to record the intensity of the reflected beam. The diffraction angle is determined as the angle of maximum intensity.

The x-ray diffractometer technique usually provides more accurate results than does the film technique. However, only laboratory-type diffractometer setups are available at present, and the size specimen that could be tested is limited by the geometry of the instrument.

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*The photoelastic coating technique is a method of stress analysis in which the specimen to be stress analyzed is coated with a photoelastic plastic. When strains occur in the specimen, the plastic becomes birefringent. The strains are determined by measuring the birefringence (birefringence is the refraction of light in two slightly different directions to form two rays) using a reflection polaroscope.

TYPICAL RESIDUAL STRESSES IN WELDMENTS

DISTRIBUTION OF RESIDUAL STRESSES IN TYPICAL WELDS

Plug Weld

Figure 6.20 shows the distribution of residual stresses in a circular plug weld. In the weld and adjacent areas, tensile stresses as high as the yield stress of the material were produced in both radial and tangential directions. In areas away from the weld, radial stresses, σ_r, were tensile, and tangential stresses, σ_θ, were compressive: both stresses decreased with increasing distance from the weld, *r*.

Welded Shapes and Columns

Figure 6.21 shows typical distributions of residual stresses in welded shapes.

Figure 6.21a shows residual stresses and distortion produced in a welded T shape. In a section somewhat away from the end of the column, such as Section XX, high tensile residual stresses in the direction parallel to the axis are produced in areas near the weld. The figure at the right shows the distribution of residual stresses parallel to the axis in Section XX. In the flange, stresses are tensile in areas near the weld and compressive in areas away from the weld. Tensile stresses in areas near the upper edge of the web are due to the longitudinal bending distortion of the shape caused by the longitudinal shrinkage of the weld. Angular distortion is also produced.

Figures 6.21b and c show typical distributions of residual stresses in H shapes and in a welded box shape, respectively. Residual stresses are shown parallel to the axis; they are tensile in areas near the welds, and compressive in areas away from the welds.

Butt Welds in Plates

Typical residual stress patterns in butt-welded plates have been discussed previously and are shown in Fig. 6.9. The magnitude of these stresses is discussed in detail in the next section of this chapter.

VARIOUS FACTORS AFFECTING RESIDUAL STRESSES IN WELDS

Base Metal and Weld Metal

Residual stresses as high as the yield stresses of the weld metal and base metal are produced in carbon steel weldments. In addition, residual stresses near the weld zone in aluminum joints are as high as the yield stress of the metal.[17] However, residual stresses in welds of high strength steels are often considerably lower than yield-stress values.

Specimen Length

To study the effect of weld length on the residual stresses in unrestrained low carbon steel butt welds, two series of welds were prepared by the submerged arc process and the shielded metal arc process (manual arc welding) as shown in Fig. 6.22.[20] In each series, the only variable was the length of the weld as given in Fig. 6.23. The width of each specimen was sufficient to assure that full restraint was applied. Figure 6.23 shows the distributions of longitudinal and transverse residual stresses along the welds made by the two processes.

Longitudinal residual stresses must be zero at both ends of the welds, and high tensile stresses exist in the central regions of the welds. The peak stress in the central region increases with increasing weld length. This effect is clearly shown in Fig. 6.24 in which the peak stress for each panel is plotted versus the weld length. The figure indicates that welds longer than 457 mm (18 in.) are needed to produce

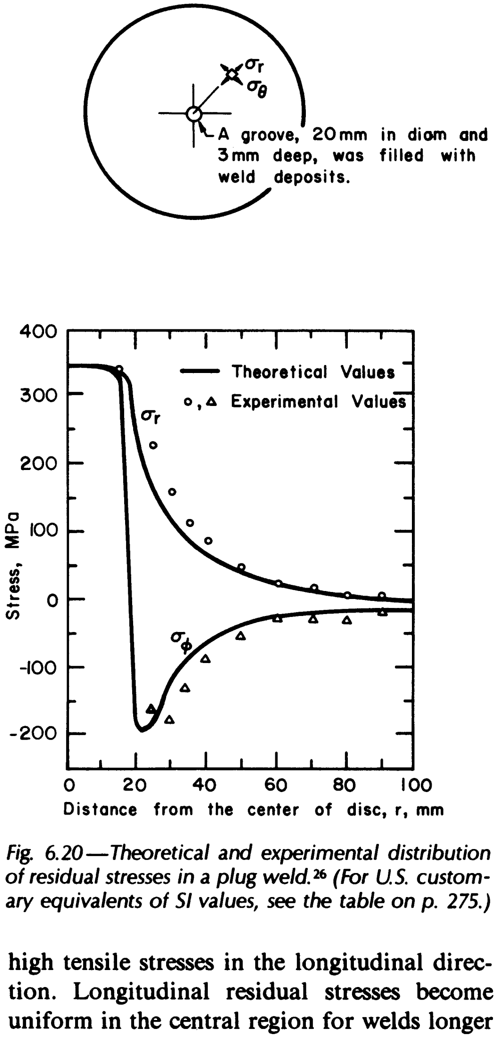


Fig. 6.20—Theoretical and experimental distribution of residual stresses in a plug weld.[26] *(For U.S. customary equivalents of SI values, see the table on p. 275.)*

high tensile stresses in the longitudinal direction. Longitudinal residual stresses become uniform in the central region for welds longer than 457 mm.

Concerning the transverse residual stresses shown in Fig. 6.23, stresses were tensile in central areas and compressive in areas near the plate ends. The weld length had little effect on the maximum tensile stresses in the central area and the maximum stress in areas near the plate ends.

Residual stress distributions were similar in welds made by the submerged arc process and the shielded metal arc process. Smooth stress distributions were obtained in welds made by the submerged arc process, while stress distributions in welds made by the shielded metal arc process were somewhat uneven.

Plate Thickness

Figure 6.25 shows distributions of residual stresses in the thickness direction in the weld metal of a butt joint, 25 mm (1 in.) thick, 500 mm (20 in.) long by 500 mm (20 in.) wide in low carbon steel. Shown in the figure are the longitudinal stresses, σ_x, the transverse stresses, σ_y, and the stresses normal to the plate surface, σ_z. Welds were made with covered electrodes, 2.5 to 5.0 mm (0.1 to 0.2 in.) in diameter; welding operations were conducted alternately from both sides so that angular distortion could be minimized.

The results were obtained by using the Gunnert drilling technique[21] (the technique described earlier). As shown in Figs. 6.25a and b, longitudinal and transverse stresses were tensile in areas near both surfaces of the plate. Compressive stresses in the interior of the weld were apparently produced during the welding of top and bottom passes.

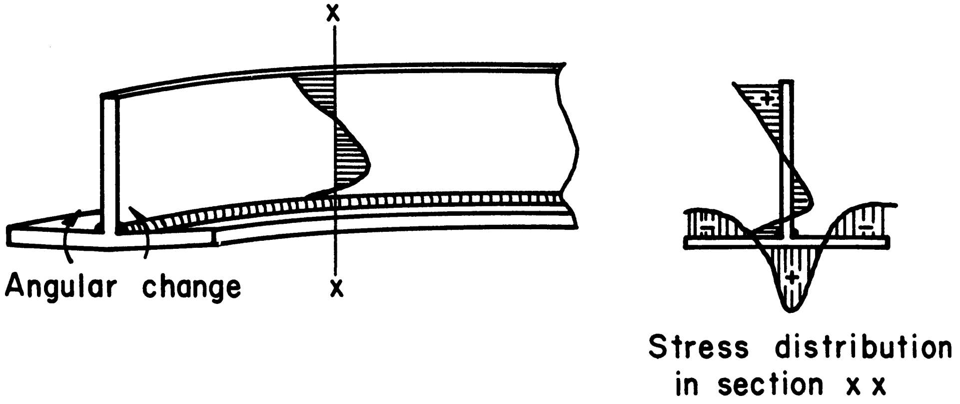
Figure 6.25c shows the distribution of stresses normal to the plate surface, σ_z. At both surfaces, σ_z. must be zero. Residual stresses were compressive in the case shown here. However, many investigators believe that σ_z in the interior of a thick weld can be tensile.

Welding Processes

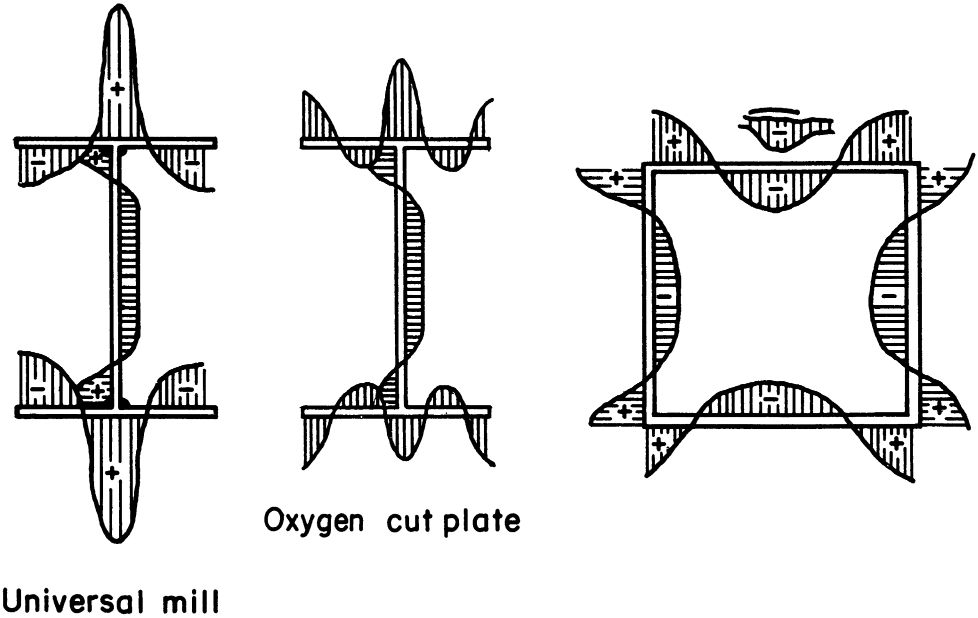
It is generally believed that similar residual stresses are produced in welds made by various processes including the shielded metal arc, submerged arc, gas metal arc, and gas tungsten arc processes. For example, Figs. 6.23a and b show that the residual stresses produced by the shielded metal arc process and the submerged arc process are similar.

Welding Sequence

In welding a long butt joint, various types of welding sequences, such as backstep, block, built-up, cascade, etc., are used in an attempt to reduce residual stresses and distortion. The selection of a proper welding sequence is an important practical problem, especially in



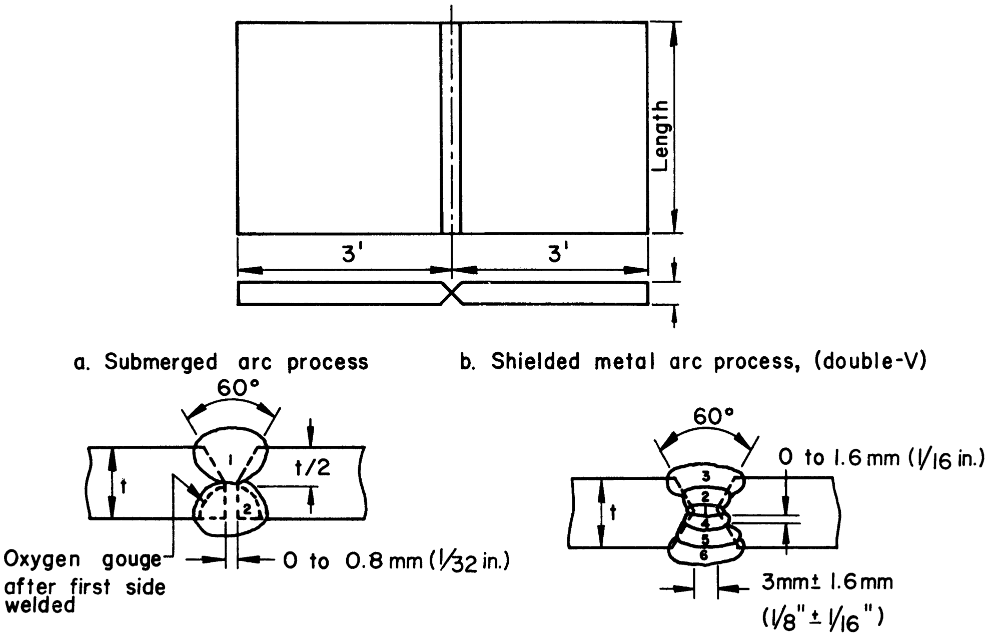
a. Residual stresses and distortion of a welded T-shape



b. Residual stresses in H-shapes

c. Residual stresses in a box shape

Fig. 6.21—Typical residual stresses in welded shapes.


a. Submerged arc process

b. Shielded metal arc process, (double-V)

Electrode:	EH14 6mm (1/4in.) F62-EH14-200	Electrode:	Passes 1 & 4; 4mm (5/32in.) E6010 Passes 2,3,5,6; 6mm (1/4in.) E6012
Voltage:	32		
Current:	1050 A		
Speed of arc travel:	~5.2 mm/s (~12.5 in./min)	Current:	Root passes: 150-165 A Other passes: 300-320 A
Details:	Pass 1: Oxygen gouge back side Pass 2.	Details:	Passes 1,2,3: back chip Passes 4,5,6.

Fig. 6.22—Specimens for studying the effect of weld length on residual stresses.[20] *(For SI equivalents of U.S. customary values, see the table on p. 275.)*

welding joints with high restraint, such as joints involved in making patches.

The effects of welding sequence on residual stresses have been widely studied.[22-25] In a comprehensive investigation of the effects of welding sequence on residual stresses and shrinkage in restrained butt welds and circular patch welds, welding sequences were classified into the following:[24]

(1) Multilayer sequences in which the first layer is completed along the entire weld length (there may be various ways to complete the first layer such as straight forward, backstep, skip, etc.); then, welding of the second layer is made, and so on.

(2) Block welding sequence in which some length of the joint, or a block, is completely welded, the next block is welded, and so on.

Results obtained in these investigations can be summarized as follows:

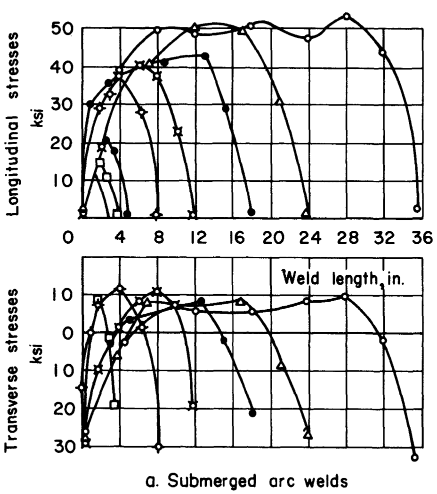
(1) As far as residual stresses along the weld are concerned, the effect of welding sequence was minor; high tensile longitudinal stresses were found in all welds tested.

(2) Differences in welding sequence caused considerable differences in transverse shrinkage, in the amount of total strain energy produced in restrained joints, and in the amount of reaction stresses in the inner plates of circular patch welds. Block welding sequences generally produced less shrinkage, less strain energy, and less reaction stress than multilayer sequences.

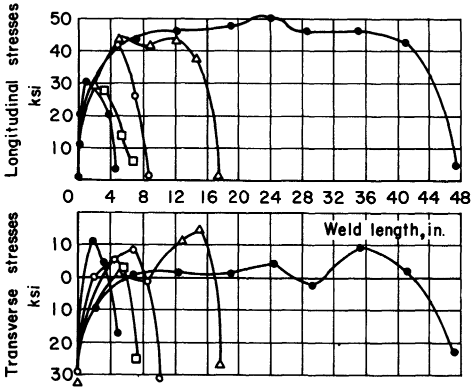
WELD DISTORTION

FUNDAMENTAL TYPES OF DISTORTION

The distortion found in fabricated structures is caused by three fundamental dimensional changes that occur during welding: (1) transverse shrinkage that occurs perpendicular to the weld line, (2) longitudinal shrinkage that occurs parallel to the weld line, and (3) an angular change that consists of rotation around the weld line. All three of these dimensional changes are shown in the sketches in Fig. 6.26.



a. Submerged arc welds



b. Shielded metal arc welds

Fig. 6.23—Distributions of residual stresses in butt welds of different lengths.[20] *(For SI equivalents of U.S. customary values, see the table on p. 275.)*

Figure 6.26 shows transverse shrinkage in a simple butt weld. The distribution of the longitudinal residual stress, σ_x, discussed earlier, is shown again in Fig. 6.26b. This stress causes the longitudinal shrinkage shown in the figure. The longitudinal shrinkage of the weld metal and base metal regions adjacent to the weld is restrained by the surrounding base metal regions.

Figure 6.26c shows the angular change that occurs in a butt weld. Nonuniformity of transverse shrinkage in the thickness direction causes this rotation. Figure 6.26d shows the angular change that occurs in a fillet weld. Here, the angular change is caused by the unbalance of shrinkage on opposite sides of the flange member.

Shrinkage and distortion that occur during the fabrication of actual structures are far more complex than those in Fig. 6.26. When longitudinal shrinkage occurs in a fillet

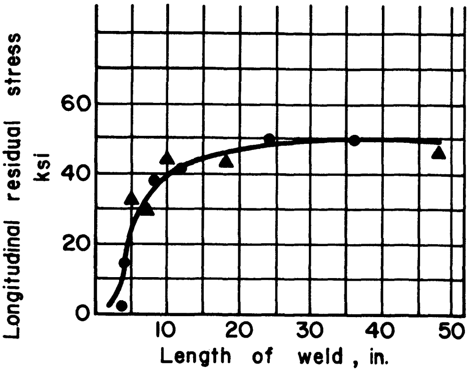
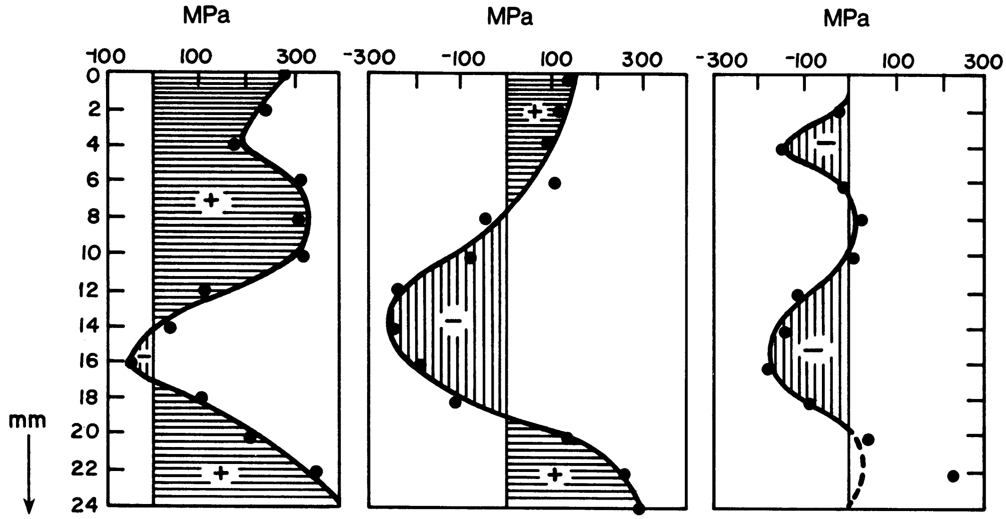


Fig. 6.24—Effect of length of weld on longitudinal residual stress.[20] *(For SI equivalents of U.S. customary values, see the table on p. 275.)*

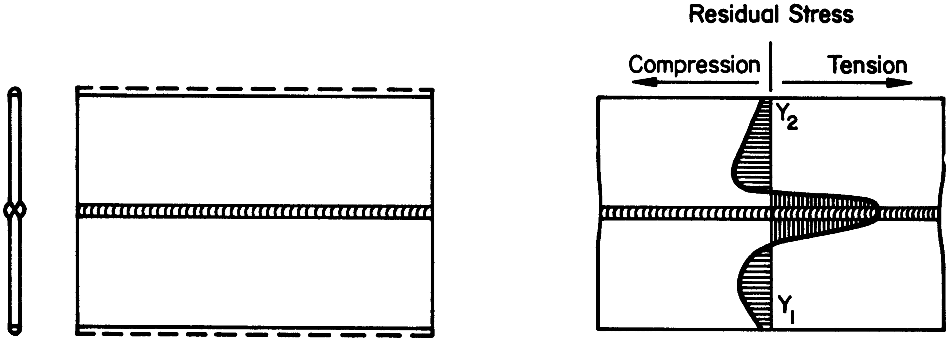


a. Longitudinal stresses, σ_x

b. Transverse stresses, σ_y

c. Normal-to-surface stresses, σ_z

Fig. 6.25—Distributions of residual stresses in the thickness direction in the weld metal of a butt joint.[21] *(For U.S. customary equivalents of SI values, see the table on p. 275.)*



a. Transverse shrinkage in a butt weld.

b. Longitudinal shrinkage in a butt weld. (Distribution of longitudinal residual stress, σ_x, is also shown)

c. Angular change in a butt weld.

d. Angular change in a fillet weld.

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Fig. 6.26.—The fundamental dimensional changes that occur in weldments.[1]

welded joint, the joint will bend longitudinally unless the weld line is located along the neutral axis of the joint (this problem will be discussed later). Whether or not a joint is constrained externally also affects the magnitude and form of distortion.

TRANSVERSE SHRINKAGE OF BUTT WELDS

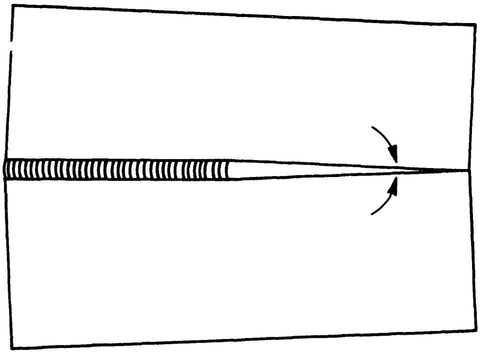
In Fig. 6.26a, the shrinkage is uniform along the weld. However, transverse shrinkage that occurs in butt welds, especially long welds, in actual structures is usually much more complex. The major factors causing nonuniform transverse shrinkage in butt welds are:

(1) *Rotational distortion.* When welding is conducted progressively from one end of a joint to the other, the unwelded portion of the joint moves, causing a rotational distortion, as shown in Fig. 6.27.

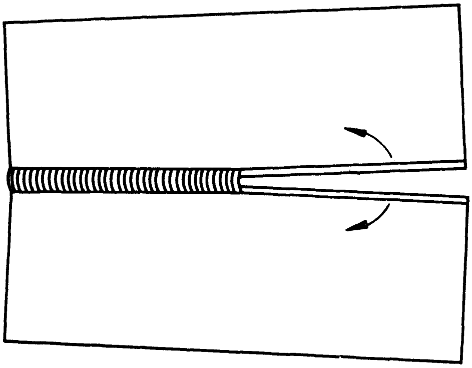
(2) *Constraint.* The amount of transverse shrinkage that occurs in welds is affected by the degree of constraint applied to the weld joint. The external restraint may be considered to act like a system of transverse springs; the degree of constraint is expressed by the rigidity of the system of springs. The amount of shrinkage decreases as the degree of constraint increases. In many joints, the degree of constraint is not uniform along the weld. For example, in a slit weld, as shown in Fig. 6.28, the degree of constraint varies along the length of the slit, and is highest at the ends.* Consequently, the amount of transverse shrinkage is greater near the center of the joint and very slight near the ends of the joint. Again, when a long butt joint is welded by a back-step sequence, the transverse shrinkage is not uniform along the weld.

The rotational distortion is affected by welding heat input and the location of tack welds. The welding sequence produces complex effects on the rotational distortion and the distribution of constraint along the weld.

The following discussion first presents



a. Unwelded portion of the joint closes (Covered electrode)



b. Unwelded portion of the joint opens (Submerged arc process)

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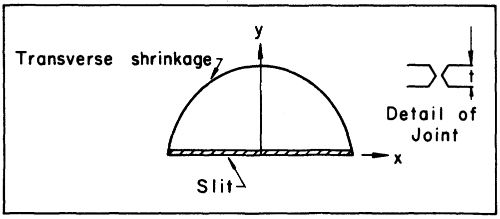
Fig. 6.27—Rotational distortion.[1]



Slit-weld specimen and typical distribution of shrinkage

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Fig. 6.28—Transverse shrinkage in a butt weld under restraint.[1]

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*Welds similar to the slit weld are frequently made in repairs. Transverse shrinkage in the slit weld is constrained by the base metal surrounding the weld.

formulas for transverse shrinkage of butt welds, and then examines rotational distortion and the effects of constraint on transverse shrinkage.

Formulas for Transverse Shrinkage of Butt Welds

Formulas for transverse shrinkage of butt welds have been proposed by many investigators.[1,26] The following simple formula was obtained through the analysis of data gathered from various sources:[27]

$$S = 0.2\frac{A_w}{t} + 0.05\ d$$

$$S' = 5.16\frac{A'_w}{t'} + 1.27\,d' \qquad (6.13)$$

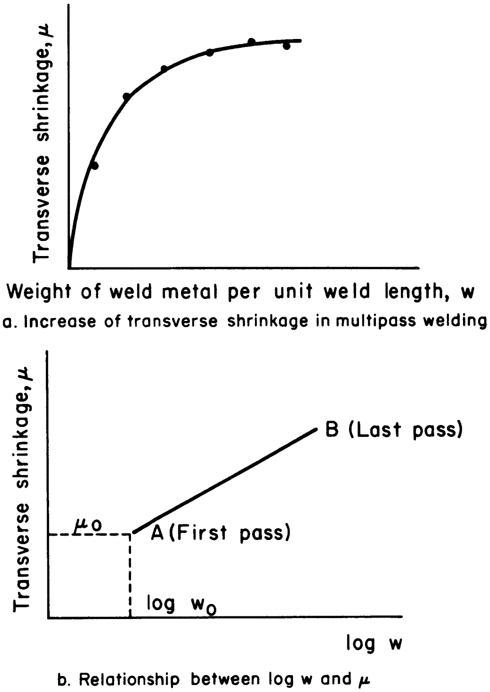
where

S = transverse shrinkage, in.
S' = transverse shrinkage, mm
A_w = cross-sectional area of weld, in.^{2}
A'_w = cross-sectional area of weld, mm^2
t = thickness of plates, in.
t' = thickness of plates, mm
d = free distance or root opening, in
d' = free distance or root opening, mm

An extensive study of transverse shrinkage during multipass welding of constrained butt joints in carbon steel shows how transverse shrinkage increases during multipass welding (see Fig. 6.29).[28] Shrinkage was relatively pronounced during the early weld passes but diminished during later passes, as shown in Fig. 6.29b. This was due to the resistance against shrinkage which increases as the weld gets larger. It was found that a linear relationship exists between tranverse shrinkage, u, and the logarithm of the weight of the weld metal deposited, w,

$$u = u_o + b\,(\log w - \log w_o) \qquad (6.14)$$

where, u_o and w_o are transverse shrinkage and the weight of the weld metal deposited, respectively, after the first pass is welded; b is a coefficient.



a. Increase of transverse shrinkage in multipass welding

b. Relationship between log w and μ

Fig. 6.29—Increase of transverse shrinkage during multipass welding of a butt joint.

Figure 6.30 shows that there are three methods for reducing transverse shrinkage:

(1) Decrease the total weight of weld metal, as shown by Arrow 1. The amount of shrinkage changes from B to C.

(2) Decrease the tangent b (equation 6.14), as shown by Arrow 2. The amount of shrinkage changes from B to D.

(3) Move the shrinkage after the first pass from A to A′, as shown by Arrow 3. The amount of shrinkage after the completion of the weld changes from B to E.

The effects of various factors on transverse shrinkage, including joint design, root opening, type and size of electrodes, degree of constraint, peening, and oxygen gouging were studied using ring-type specimens.[28] The results are summarized in Table 6.4. Among the various factors investigated, root gap and joint design produced the greatest effects.

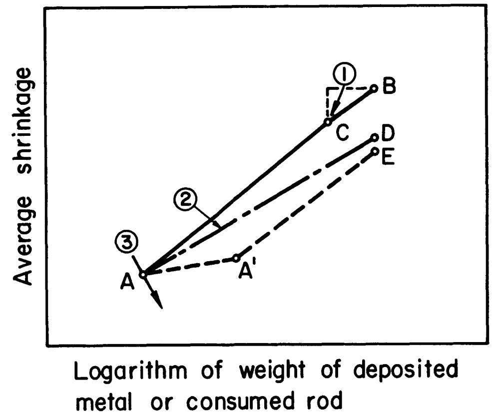


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Fig. 6.30—Schematic diagram showing the methods to reduce tranverse shrinkage of butt welds.[28]

Figure 6.31a shows the effect of root opening on transverse shrinkage. As the root opening increases, the shrinkage increases and the total amount of weld metal increases (Method 1, Fig. 6.30). The results show that Method 2 (Fig. 6.30) was also significant. A single-V-joint produced more shrinkage than a double-V-joint. This was partly due to Method 1, the larger joint sectional area, but Method 2 was also significant.

Figure 6.31b shows the effect of electrode size on transverse shrinkage. Shrinkage decreases as the electrode size increases, and Method 3 (Fig. 6.30) is most significant. This means that reduction of shrinkage cannot be obtained with large size electrodes unless the electrodes are used in the first pass. This was also confirmed experimentally.

Regarding the effect of welding heat input on transverse shrinkage, shrinkage decreases as the total heat input required to weld a certain joint decreases. (See Arrow 1 in Fig. 6.30.) However, when a weld is completed in several passes, shrinkage decreases when the first pass is welded with greater heat input. In this case, an increase in shrinkage is produced after welding the first pass by using a greater heat input. (Compare points A' and A in Fig. 6.30.) However, the amount of shrinkage after the completion of the weld decreases from B to E.

As to the effect of chipping and gouging on transverse shrinkage, chipping a part of the weld metal produces little effect on shrinkage, and shrinkage increases due to rewelding. Since heat is applied to the specimen during oxygen gouging, shrinkage increases by gouging; shrinkage increases further during repair welding.[28]

Rotational Distortion of Butt Welds

Rotational distortion is affected by both heat input and welding speed.[29] When 13 mm (1/2 in.) thick mild steel plates are welded with covered electrodes at a low welding speed, the unwelded portion of the joint tends to close, as shown in Fig. 6.27a. When steel plates are welded with the submerged arc process, the unwelded portion of the joint tends to open, as shown in Fig. 6.27b. This means that tack welds of a submerged arc welded joint must be large enough to withstand stresses caused by the rotational distortion.

Effect of Constraint on Transverse Shrinkage of Butt Welds

To study quantitatively the effect of constraint on the transverse shrinkage of a butt weld, it is first necessary to define analytically the degree of constraint in a joint. An attempt has been made to do this using a slit weld joint.[24,29] When welding is done in a part of the slit between $x = x_l$ and x_2 (slit length, L; weld length, $\ell = x_l$ to x_2), the degree of constraint in a slit-type joint is defined by the following equation (see Fig. 6.32):

$$K = \frac{\pi}{2}\,\frac{E}{L}\,\frac{\ell}{L}\,\frac{1}{F} \tag{6.15}$$

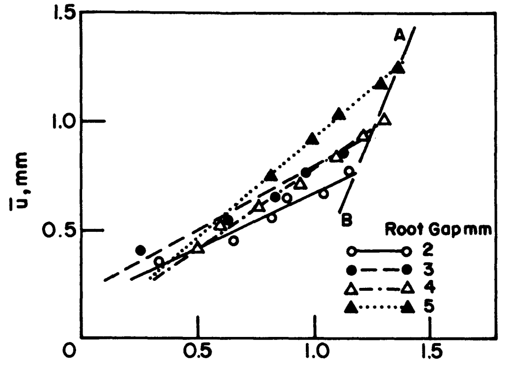
where

$$F = \sum_{n=1}^{\infty} \left[\int_{\theta_1}^{\theta_2} \sin\theta \, \sin n\theta \, d\theta\right]^2$$

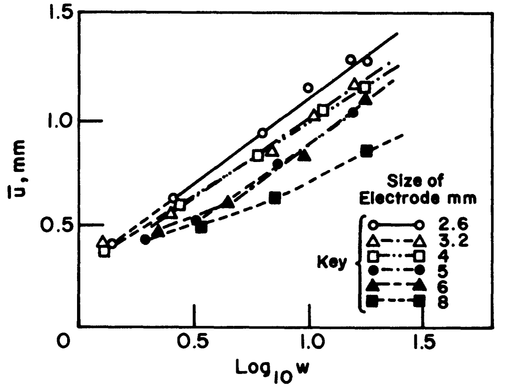
$$x_1 = \frac{L}{2}\cos\theta_1$$

$$x_2 = \frac{L}{2}\cos\theta_2$$

The physical meaning of K is as follows: When uniform stress, σ_0, is applied along the part of the slit between $x = x_l$ and x_2, the rela-



a. Effect of root opening



b. Effect of electrode size

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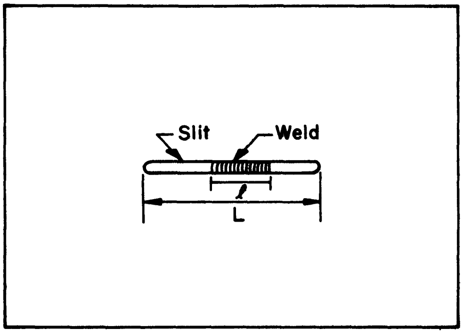
Fig. 6.31—Effect of root opening and electrode size on transverse shrinkage of butt welds. Note: Specimens were ring-shaped as shown in Fig. 6.34a. Outer diameter = 600 mm (24 in.); inner diameter = 300 mm (12 in.); plate thickness = 19 mm (0.7 in.); double V-groove; w = weight of electrode deposited per unit weld length, g/cm; $\bar{u}$ = transverse shrinkage (mean value along the weld line), mm (in.).[1] (For U.S. customary equivalents of SI values, see the table on p. 275.)

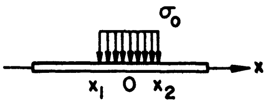
tionship between σ_0 and the mean value of dislocation over the portion of the slit where the load is applied, $[v]_\ell$, is given by:

$$\sigma_0 = K[\bar{v}]_\ell \tag{6.16}$$

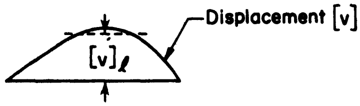
The parameter *K* has been used to study the effect of the degree of constraint on the transverse shrinkage of a slit-type weld.[24,29]



a. Slit - type specimen



b. Assumed stress distribution



c. Displacement transverse

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Fig. 6.32—Analysis of degree of constraint K of a slit-type weld.[1]

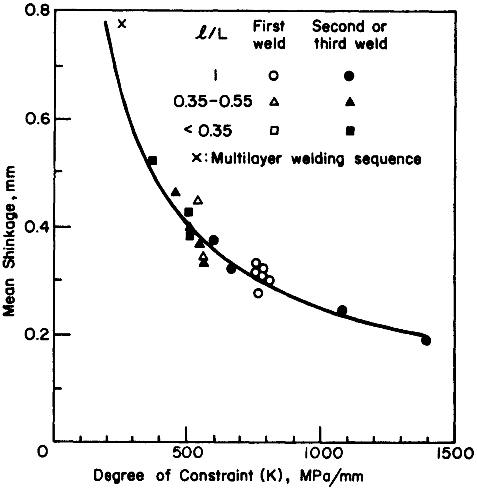

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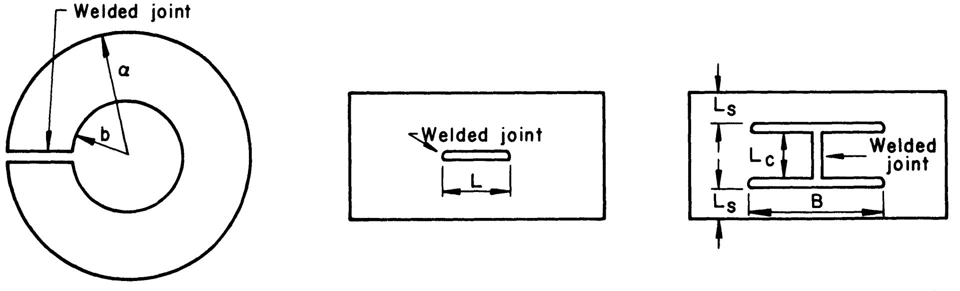
Fig. 6.33—Relationship between degree of constraint and transverse shrinkage in a slit-type specimen.[1] (For U.S. customary equivalents of SI values, see the table on p. 275.)

Table 6.4—Effects of various procedures on transverse shrinkage in butt welds

Procedures	Effects
Root opening	Shrinkage increases as root opening increases. See Fig. 6.31. Effect is great. (Methods 1 and 2.)*
Joint design	A single-V-joint produces more shrinkage than a double-V-joint. Effect is great. (Methods 1 and 2.)
Electrode diameter	Shrinkage decreases by using larger sized electrodes. See Fig. 6.31. Effect is medium. (Method 3.)*
Degree of constraint	Shrinkage decreases as the degree of constraint increases. Effect is medium. (Method 2.)
Electrode type	Effect is minor. (Method 2.)
Peening	Shrinkage decreases by peening. Effect is minor. (Method 2.)
Chipping and gouging	Read text.

*Methods 1, 2, and 3 are explained in Fig. 6.30.



a. Ring-type specimen

$$K = \frac{E}{4\pi} \cdot \frac{1}{b-a}\left(\log_e \frac{b}{a} - \frac{b^2-a^2}{b^2+a^2}\right)$$

b. Slit-type specimen

$$K = \frac{2E}{\pi \ell}$$

c. H-type restrained specimen

$$K = \frac{E}{B\left(1 + \frac{L_C}{2L_S}\right)}$$

Fig. 6.34—Specimen types used in analysis.[26]

Figure 6.33 shows a relationship between *K* values of joints and values of transverse shrinkage determined experimentally. Experiments were conducted on joints with various slit lengths, *L* (75 to 100 mm [3 to 4 in.]), and weld lengths (*L* = 8 to 25 mm [0.3 to 1.0 in.]). Results obtained with a block sequence and a multilayer sequence are also plotted. The figure shows that transverse shrinkage decreases as the degree of constraint increases.

The effect of the degree of constraint on the transverse shrinkage of a ring has been analyzed, as shown in Fig. 6.34a.[28] The results obtained by different investigators using different types of specimens can be compared by using the degree of constraint.[26] Figure 6.35 shows a relationship between the degree of constraint K and the ratio between the shrinkage of free welds, S_{tf}, and the shrinkage of constrained welds, S_t. Figure 6.35 indicates the formulas used to calculate the degree of constraint of the different specimens.

Effect of Welding Sequence on the Transverse Shrinkage of a Butt Weld

The effects of welding sequence on the magnitude and distribution of transverse shrinkage in slit weld specimens and patch weld specimens were the subject of another study.[24,30] Figure 6.36 shows examples of the experimental results obtained with slit weld specimens. Specimens 1-1, 1-2, and 1-3 were welded using a block welding sequence. The circled numbers under the specimen designation indicate the sequence in which blocks were welded. Specimen 1-4 was welded using a multilayer procedure. The figure shows that shrinkage was reduced when the center block was welded first, followed by the blades on each side.

TRANSVERSE SHRINKAGE OF FILLET WELDS

Much less transverse shrinkage occurs across a fillet weld than across a butt weld. Only limited studies have been made on the transverse shrinkage of fillet welds. Nevertheless, a simple formula has been proposed as follows:[27]

(1) For T-joints with two continuous fillets:

$$\text{Shrinkage} = \frac{\text{leg of fillet}}{\text{thickness of plate}} \times 0.04 \quad (6.17)$$

For shrinkage in millimetres, use fillet leg and plate thickness in millimetres. For shrinkage in inches, use fillet leg and plate thickness in inches.

(2) For intermittent welds, a correcting factor of proportional length of fillet to total length should be used.

(3) For fillets in a lap joint (two fillet welds):

$$\text{Shrinkage} = \frac{\text{leg of fillet}}{\text{thickness of plate}} \times 0.06 \quad (6.18)$$

For shrinkage in millimetres, use fillet leg and plate thickness in millimetres. For shrinkage in inches, use fillet leg and plate thickness in inches.

LONGITUDINAL SHRINKAGE OF BUTT WELDS

The amount of longitudinal shrinkage in a butt weld is on the order of 1/1000 of the weld length, much less than the transverse shrinkage. Longitudinal shrinkage in a butt weld has been the subject of only limited studies, but the following formula has been proposed:[31]

$$\Delta L = \frac{0.12 \times I \times L}{100\ 000 \times t} \quad (6.19)$$

where

I = welding current in amperes (A)

L = length of weld in inches

t = plate thickness in inches

If $t = {}^1\!/_4$ in. and $I = 200$ A, for example,

$$\Delta L = \frac{0.12 \times 200}{100\ 000 \times 0.25} L \doteqdot 0.001 \cdot L$$

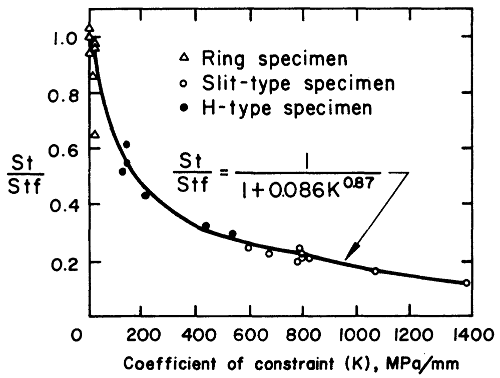


Fig. 6.35—Effect of external restraint on the transverse shrinkage of butt welded joints.[26]

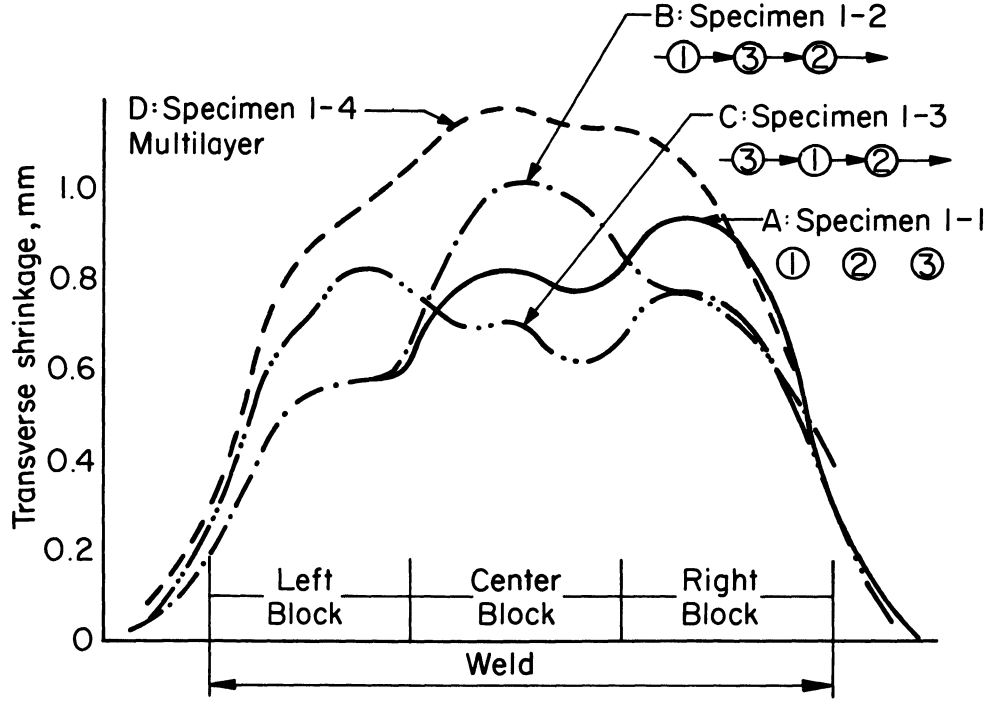


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Fig. 6.36—Distribution of transverse shrinkage obtained in a slit weld specimen (shown in Fig. 6.32) with different welding sequence. Plates were about 19 x 800 x 1200 mm (3/4 x 32 x 47 in.). Welds were about 500 mm (20 in.) long.[1] *(For U.S. customary equivalents of SI values, see the table on p. 275.)*

LONGITUDINAL SHRINKAGE OF FILLET WELDS

An extensive study of longitudinal shrinkage in carbon steel fillet welds showed that longitudinal shrinkage is primarily a function of the total cross section of the joints involved.[32] Restraint is more effective the thicker and wider the plates are. The total cross section of the welded plates in the transverse section is therefore called the "resisting cross section."

Figure 6.37 shows results obtained by Guyot.[32] In order to maintain symmetry in the transverse section and thereby keep longitudinal deflection to a minimum, he used cross-shaped assemblies as shown in the figure. Shrinkage values are expressed as a function of the resisting cross-sectional area, A_p, and the cross-sectional area of the weld metal, A_w. When the ratio A_p to A is less than 20, the following formula may be used:

$$\delta = \frac{A_w}{A_p} \times 25 \qquad (6.20)$$

where δ = longitudinal shrinkage in millimetres per metre or thousandths of inch per inch of weld.

ANGULAR CHANGE OF BUTT WELDS

Angular change often occurs in a butt weld when transverse shrinkage is not uniform in the thickness direction. Many investigations have been made on the angular change in butt welds and the effects of various welding procedure parameters, including the shape of the groove and degree of constraint.

Figure 6.38 shows experimental data gathered on ring-type specimens, discussed earlier.[28] A radial groove was cut and then welded using covered electrodes 6 mm (1/4 in.) in diameter. Five specimens with different

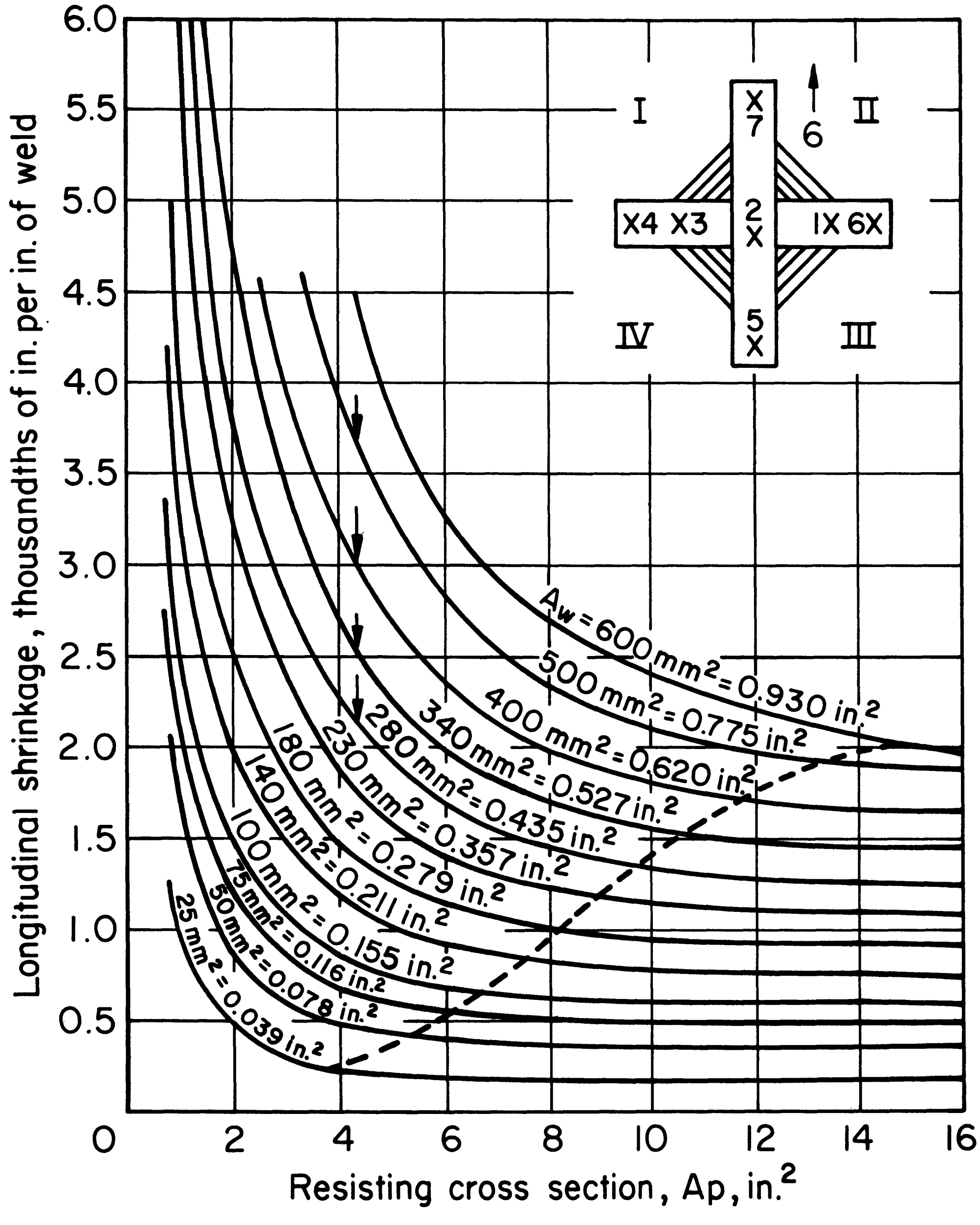


Fig. 6.37—Variation of longitudinal shrinkage as a function of the resisting cross-section area, A_p, and transverse cross-section area, A_w.[32] *(For SI equivalents of U.S. customary values, see the table on p. 275.)*

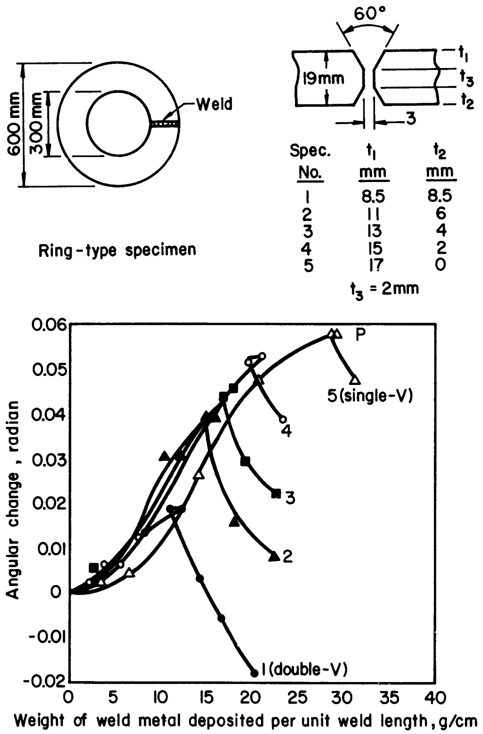


Fig. 6.38—Effect of shape of groove on angular change.[28] *(For U.S. customary equivalents of SI values, see the table in p. 275.)*

types of grooves ranging from symmetrical double-V to single-V were tested. Welding was first completed on one side; then the specimen was turned over and the other side was back chipped and welded. Angular change was measured after welding each pass. A rather mild increase of angular change was observed in the earliest stage of welding on the first side. The increase of angular change became greater in the intermediate stage, and then became mild again in the final stage. The back chipping did not affect the angular change.

Angular change in the reverse direction was produced during welding of the second side. The angular change remaining after completion of welding depended on the ratio of weld metal deposited on the two sides of the plates. Since the angular change increased more rapidly during welding of the second side, the minimum angular change was obtained in the specimen having a little larger groove in the first side welded. In the particular cases previously discussed,[28] the angular change could be minimized (near zero) for a butt joint having a $(t_l + 1/2\, t_3)$ to t ratio of 0.6.

An extensive research program was conducted by the Shipbuilding Research Association of Japan on angular change in butt welds. Figure 6.39 shows the groove shape most suitable to minimizing angular changes in butt welds of various thicknesses. Curves are shown for two conditions, with and without strongbacks.

DISTORTION CAUSED BY ANGULAR CHANGES OF FILLET WELDS

Angular changes occurring during fillet welding have been studied in many research programs. If a fillet joint is free from outer restraint, the joint simply bends to a polygonal form having a knuckle at the weld. (See Fig. 6.40a.) However, if the joint is restrained by some means, a different type of distortion is produced. For example, when the movement of stiffeners welded to a plate is prevented, wavy distortion of the plate, as shown in Fig. 6.40b, results. The problem of analyzing wavy distortion and the associated stresses can be handled as a problem of stress in a rigid frame.[33] In the simplest case of a uniform distortion, the relationship between angular change and distortion at the weld is given as follows:

$$\frac{\delta}{\ell} = 1/4\ \phi - [\frac{x}{\ell} - \frac{1}{2}]^2\ \phi \qquad (6.21)$$

where

δ = distortion

ℓ = length of span

ϕ = angular change

x = center

(See Fig. 6.40.)

The amount of angular change, ϕ, in a restrained structure is smaller than that in a free joint, ϕ_o The amount of ϕ also changes when the rigidity of the bottom plate, $D = Et^3 (12[1 - \nu^2])$, and the length of span, ℓ, change. The following equation has been obtained:

$$\phi = \frac{\phi_o}{1 + \frac{2D}{\ell} \cdot \frac{1}{C}} \qquad (6.22)$$

where C is a coefficient determined by welding conditions and plate thickness.

A study was conducted to determine values of ϕ_o as a function of plate thickness, t (mm), and weight of electrode consumed per weld length, w (g/cm).[34] In this particular experiment, using covered electrodes 5 mm (0.2 in.) in diameter, maximum angular changes were obtained when plate thickness was around 9 mm (0.35 in.). (See Fig. 6.41.) When the plate was thinner than 9 mm, the amount of angular change was reduced as the plate thickness was reduced. This was due to the more even heating of the plate in the thickness direction which reduced the bending moment. When the plate was thicker than 9mm, the amount of angular change was reduced as the plate thickness and thus the plate rigidity in-

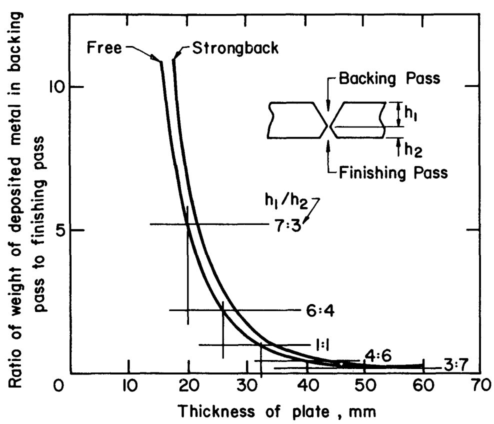
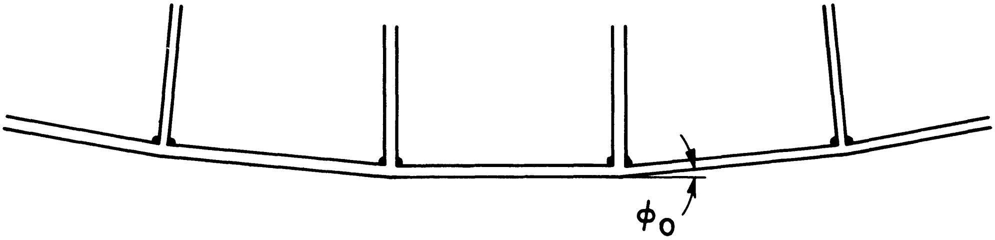
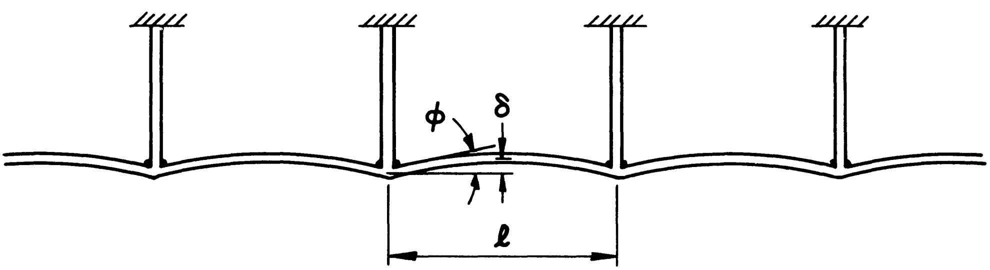


Fig. 6.39—The most suitable groove shape which gives zero angular change in butt welds. (For U.S. customary equivalents of SI values, see the table on p. 275.)



a. Free joint



b. Restrained joint

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Fig. 6.40—Distortion caused by angular change in two types of fillet welded structures.[1]

creased. The following formula has been proposed to calculate the C value:

$$C = \frac{t^4}{1 + \frac{w}{5}} \qquad (6.23)$$

where

t = plate thickness, mm

w = weight of weld metal deposited per unit weld length, g/cm

By using equations (6.21) through (6.23), it is possible to calculate the distortion that occurs when a given structure is fabricated with a given welding procedure.

BENDING DISTORTIONS INDUCED BY LONGITUDINAL SHRINKAGE

When the weld line does not coincide with the neutral axis of a weld structure, longitudinal shrinkage of the weld metal induces bending moments, and longitudinal distortion of the structure results. A theory similar to the bending beam theory has been developed for the analysis of longitudinal distortion caused by welding of a long, slender bar.[35] Longitudinal residual stress, σ_x, and curvature of longitudinal distortion, 1/R, are given in the following equations (see Fig. 6.42):

$$\sigma_x = -E\epsilon''_x + \frac{M_y{}^*}{I_y} + \frac{P_x{}^*}{A}$$

$$\frac{1}{R} = \frac{M_y{}^*}{EI_y} = \frac{P_x{}^* \ell^*}{EI_y} \qquad (6.24)$$

where

ϵ''_x = incompatible strain

A = sectional area of the joint

I_y = moment of inertia of the joint around the neutral axis

$P_x{}^*$ = apparent shrinkage force, $P_x{}^* = \int\int E\epsilon''_x \, dydz$

$M_y{}^*$ = apparent shrinkage moment, $M_y{}^* = \int\int E\epsilon''_x \, zdydz$ $= P_x{}^* \ell^*$

ℓ^* = distance between the neutral axis and the acting axis of apparent shrinkage force

Equation (6.24) shows that it is necessary to know the distribution of incompatible strain, ϵ''_x, in order to know the distribution of residual stress, σ_x; however, information about moment, $M_y{}^*$, is only sufficient for determining the amount of distortion, 1/R. Moment, $M_y{}^*$, is determined when the magnitude of apparent shrinkage force, $P_x{}^*$, and the location of its acting axis are known. Through experiments, it was found that the acting axis of $P_x{}^*$ is located somewhere in the weld metal. The apparent shrinkage force, $P_x{}^*$, is the origin of residual stress and distortion is produced as the result of the existence of $P_x{}^*$. More information can be obtained when the value of $P_x{}^*$ rather than the value of distortion itself is used in the analysis of experimental results. For example, in discussing the influence of various factors on the magnitude of distortion, it is possible to separate them into those attributable to the change in geometry (A, I_y, or ℓ^*) or those attributed to the change in the value of $P_x{}^*$ itself.

The increase of longitudinal distortion (apparent shrinkage force $P_x{}^*$) during multipass welding is as shown in Fig. 6.43. In all cases, the specimens were 1200 mm (47 in.) long. They were made with mild steel plates 12 to 13 mm (1/2 in.) thick. The values of $P_x{}^*$ increased proportionally with the weight of electrode consumed per weld length, except for the first layer. A rather large amount of distortion obtained in the first layer was due to a less resisting area at that stage of welding since the flange plate was not yet firmly fixed to the web plate.

Practically no distortion was produced by intermittent welding (Specimen I-4). This is probably due to the fact that longitudinal residual stress does not reach a high value in a short intermittent weld.†

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†According to one study, the reduction in angular change by the use of intermittent welding was not as great as that obtained in longitudinal distortion.

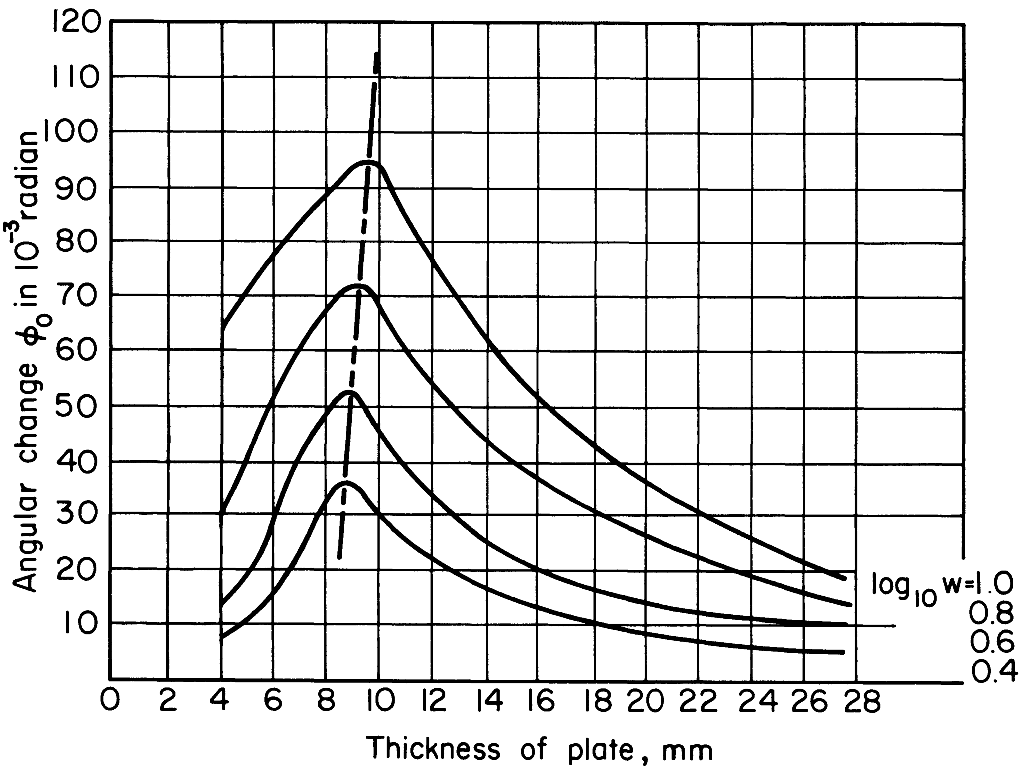

Fig. 6.41—Variation of angular change of free fillet welds, ϕ, as a function of plate thickness, t, and weight of electrode consumed per weld length.[34] *(For U.S. customary equivalents of SI values, see the table on p. 275.)*

BUCKLING DISTORTION

When thin plates are welded, residual compressive stresses occur in areas away from the weld and cause buckling.

Buckling distortion occurs when the specimen length exceeds the critical length for a given thickness of a given size specimen. In studying weld distortions in thin-plate structures, it is important to first determine whether the distortion is produced by buckling or by bending. Buckling distortion differs from bending distortion in that (1) there is more than one stable deformed shape, and (2) the amount of deformation in buckling distortion is much greater.

Buckling distortion of welded plates due to residual stresses has been the subject of several studies. One of these focused on buckling distortions of long steel strips, 2.3 mm (0.09 in.) by B* (100 to 400 mm [4 to 16 in.]) by 7 m (280 in.), after weld beads were laid along the center line of the strip by the submerged arc process. Figure 6.44 shows eight different stable deformation patterns found for one specimen along the weld center line.[36]

Figure 6.45 shows calculated values of the critical thickness for various sizes of butt welded plates.[37] For example, when two panels 1 m (40 in.) wide and 2 m (80 in.) long are butt welded (B = 2 m, B/L = 1), the plate is going to buckle after welding if the thickness is less than 4.6 mm (0.18 in.).

SOLUTION OF PRACTICAL PROBLEMS

In previous sections, the emphasis was

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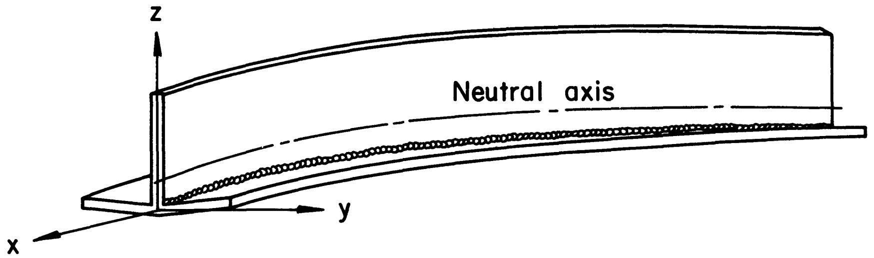
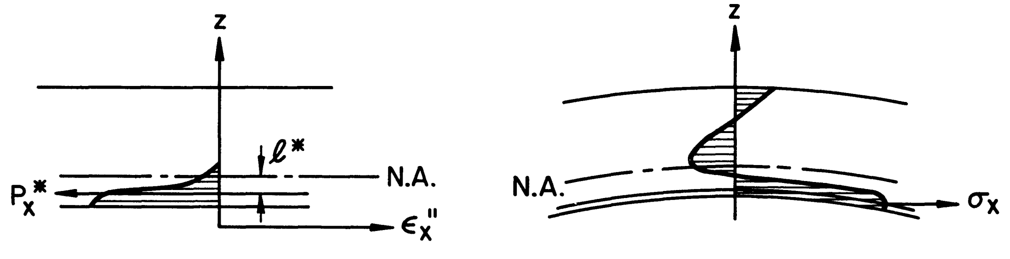
*Breadth of plate.[34]



a. General view



b. Incompatible strain, ϵ_x''

c. Residual stress, σ_x

Fig. 6.42—Analysis of longitudinal distortion in a fillet joint.[35]

placed on analyzing weld distortion in a systematic way rather than simply discussing various ways of controlling distortion. This section is designed to assist readers in making use of the information presented in previous sections for solving practical problems. The following pages present seven examples. Each example is given in a question-and-answer form. The first four examples are simple, while the last three involve some computations. These examples should provide the reader with an insight into how he can analyze various other problems which may confront him.

Question 1: What is the best joint design to minimize angular distortion of a butt weld?

Answer: As seen in Fig. 6.39 when the plate thickness is 25 mm (1 in.), for example, the ratio of h_1 and h_2 should be 6:4 if the joint is free. In such a case, the ratio of deposited metal (or the sectional area) of the backing pass to that of the finishing pass is about 2:2. If the joint is restrained by strongbacks, the ratio should be increased to about 2:5.

Question 2: In order to minimize transverse shrinkage of a butt joint, should small or large diameter electrodes be used?

Answer: See Table 6.4. Large diameter electrodes should be used from the first pass. The joint geometry will have to be taken into account, however.

Question 3: In welding a butt joint, does a block welding sequence usually provide less transverse shrinkage than a multilayer welding sequence?

Answer: Yes. Fig. 6.36 shows the best sequence in this case.

Question 4: How much reduction in distortion can be expected when intermittent fillet welds are used instead of continuous welds?

Answer: As shown in Fig. 6.42, longitudinal bending distortion decreases significantly by using intermittent fillet welds. However, reduction in angular change is not very significant. [34]

Question 5: Suppose that a steel structure,

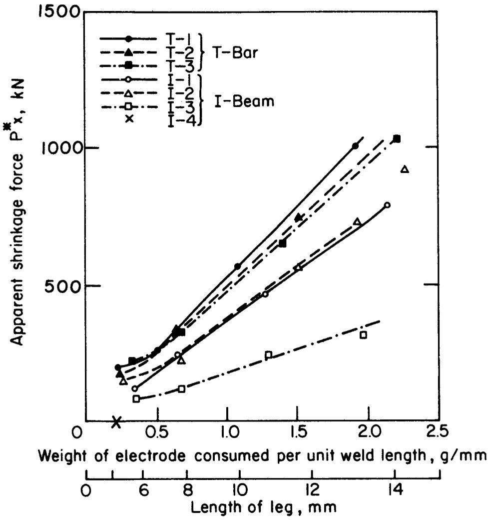


Fig. 6.43—Increase of longitudinal distortion during multipass welding.[35] *(For U.S. customary equivalents of SI values, see the table on p. 275.)*

such as shown in Fig. 6.40, is fabricated with covered electrodes. Calculate the maximum distortion of the bottom plate under the following conditions:

Plate thickness (t):19mm (3/4 in.)
Length of span (ℓ): 750 mm (30 in.)
Size of fillet: 7.1 mm (0.28 in.) leg length

Answer: By assuming that the fillet is triangular shaped, the total sectional area of the weld metal is:

$$7.1 \text{ mm} \times 7.1 \text{ mm} \times 0.5 \times 2$$
$$= 50 \text{ mm}^2 \ (0.08 \text{ in.}^2)$$

By further assuming that the deposition index of the electrode consumed, w(g/cm), is:

$$w = \frac{0.5 \times 7.85}{0.65} = 6.04 \text{g/cm}$$

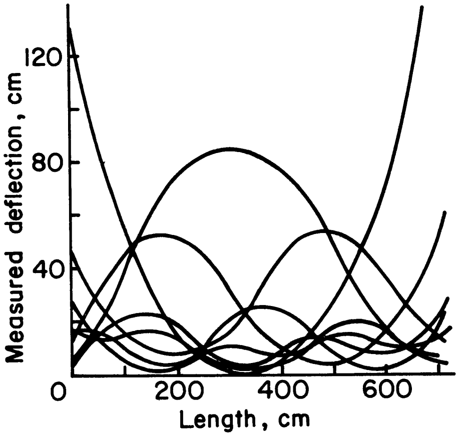
where density of the steel weld metal is considered to be 7.85 g/cm^3. Then, log $w = 0.78$.

From Fig. 6.41, the angular change of a free weld, ϕ_O, for $t = 19$ mm (0.7 in.) log $w = 0.78$ can be determined:

$$\phi_O = 0.027 \text{ radian}$$

However, the value of angular change of the actual weld, ϕ , is less than ϕ_O because of the

a. Buckling distortion



b. Eight stable distortions observed In one specimen

Fig. 6.44—Buckling distortion of a bead-welded plate. Distortions along the weld line are shown.[1]

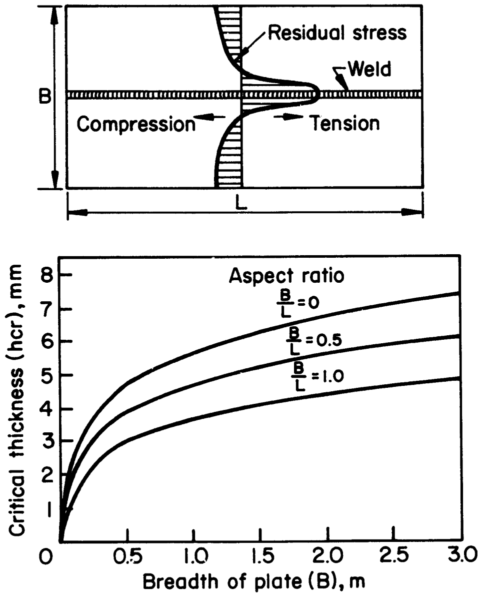


Fig. 6.45—Critical thickness for buckling distortion of a butt weld.[39] *(For U.S. customary equivalents of SI values, see the table on p. 275.)*

restraint from the structure. From equations (6.22) and (6.23):

$$\phi_o/\phi = 1 + \frac{2D}{\ell} \cdot \frac{1}{C}$$

$$= 1 + \frac{2E\,t^3}{12\,(1-\nu^2)\ell} \quad \frac{(1+\frac{w}{5})}{t^4}$$

$$= 1 + \frac{E}{6\,(1-\nu^2)\ell} \quad \frac{1+\frac{w}{5}}{t}$$

E = 206 GPa (30 × 10^6 psi),
$\nu = 0.3, t = 19$
$\ell = 760, w = 6.04$

$$\phi_o/\phi = 1 + \frac{21\,000}{5.46 \times 760} \times \frac{2.2}{19} = 1 + \frac{46\,400}{78\,800} = 1.586$$

$$\phi = \frac{27}{1.586} \times 10^{-3} = 0.017 \text{ radian}$$

Deflection of the bottom plate, δ , can be calculated from equation (6.21). The maximum deflection, δ_m, occurs at the center of the span $x = 1/2\ \ell$;

$$\delta_m = 1/4\ \phi \cdot \ell = 1/4 \times 17 \times 10^{-3} \times 760 = 3.23 \text{ mm}$$

The maximum deflection, δ_m is 3.23 mm or 0.127 in.

Question 6: In the above case, how will the distortion change if the length of span, ℓ, is reduced from 750 to 375 mm (30 to 15 in.) while other conditions remain the same?

Answer: ϕ_O is the same, but ϕ will change:

$$\phi_o/\phi = 1 + \frac{21\,000}{5.46 \times 380} \times \frac{2.2}{19} = 1 + \frac{46\,400}{39\,400} = 2.175$$

$$\phi = 12.45 \times 10^{-3} \text{ radian}$$
$$\delta_m = 1/4\phi\ell = 1/4 \times 12.45 \times 10^{-3} \times 380 = 1.18 \text{ mm (0.046 in.)}$$

Compared with the preceding case, the maximum distortion reduced by over 70 percent, because of the combined effect of:

(1) ϕ decreasing due to additional restraint

(2) δ_m further decreasing with decreasing length of span, ℓ.

Question 7: Someone is making a series of steel panels 1 × 2 m (40 × 80 in.) by butt welding longitudinally two 0.5 × 2 m (20 × 80 in.) plates, in three different thicknesses, 10 mm (0.4 in.), 8 mm (0.3 in.), and 4 mm (0.16 in.). He is having trouble with the 4 mm thick panels. To avoid distortion, he clamps the plates to a jig when he welds. However, the welded panel distorts badly as soon as he removes the clamps. Why does this happen?

Answer: See Fig. 6.45. For $B = 1$ m and $B/L = 0.5$, the critical thickness of the welded panel is 4.7 mm (0.18 in.). Panels 4 mm (0.16 in.) thick will buckle because the thickness is below the critical value. If he reduces the panel size to 1 × 1 m (40 × 40 in.), he will not have such a distortion problem because buckling occurs after welding if the thickness is less than 3.7 mm (0.15 in.).

DESIGN AND PROCEDURES FOR REDUCING RESIDUAL STRESSES AND DISTORTION

In order to develop effective means for reducing residual stresses and distortion, it is essential to understand how residual stresses and distortion are formed and how they are affected by design and welding procedures. Consequently, some of the discussions given in the preceding sections should be useful in determining appropriate designs and procedures. The preceding question and answer section is useful for selecting design procedures for reducing distortion. The following pages describe some additional practical approaches to the reduction of residual stress and control of distortion.

REDUCTION OF RESIDUAL STRESSES

Although the extent of the effects of residual stresses on the service behavior of welded structures varies significantly, depending upon a number of conditions, it is generally preferable to have few residual stresses. Therefore, it is advisable to take various precautions to reduce residual stresses. This is particularly important when welding heavy sections.

Effect of Amount of Weld and Welding Sequence

Since residual stresses and distortion are caused by thermal strains due to welding, a reduction in the amount of weld metal usually results in reduction of residual stresses and distortion. For example, the use of a U-groove instead of a V-groove should result in the reduction of the amount of weld metal. It is desirable to use bevel angles and root openings in the smallest size possible that will not restrict accessibility. In general, a reduction in the amount of free shrinkage of a butt joint results in a reduction of reaction stresses. The effect of welding sequences, particularly block welding, was discussed previously on page 245.

CONTROL OF DISTORTION

Design

The most economic design for a welded fabrication is the one which requires the fewest number of parts and a minimum of welding; such a design also assists in reducing distortion, and is to be recommended on that account.

The type of joint preparation is important, particularly for unrestrained butt welds, because the joint preparation can influence the amount of angular distortion which will result from welding.

With fillet welded joints, it is not possible to vary the joint preparation, and all that good design can achieve is to specify the minimum sizes of welds with regard to strength requirements. In this way, overwelding can be avoided and distortion minimized.

Distortion cannot be controlled solely by good design and well-chosen joint details, but they serve to reduce the magnitude of the problem and make it easier during manufacture to apply practical measures to achieve the desired results.

Assembly Procedure

Once it is accepted that distortion in some form or another is inevitable, it becomes necessary to consider how it can be controlled. Experience has shown that success may be achieved by adopting one or the other of two assembly methods:

(1) By estimating the amount of distortion likely to occur during welding and then assembling the job with the members preset to compensate for the distortion and,

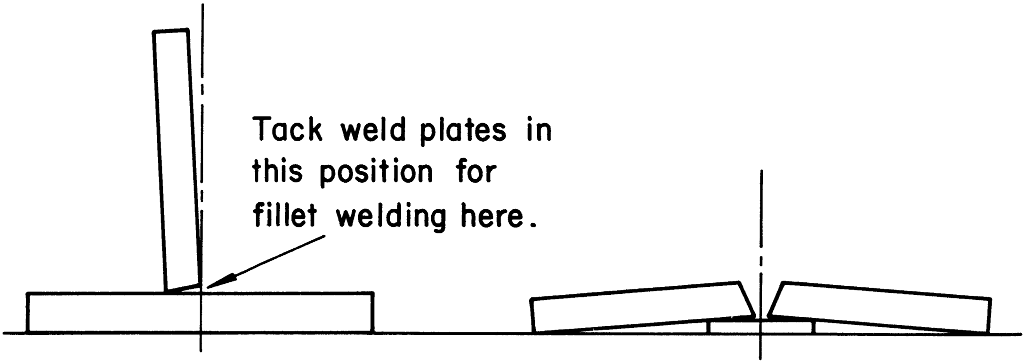


Fig. 6.46—Presetting for fillet and butt welds.

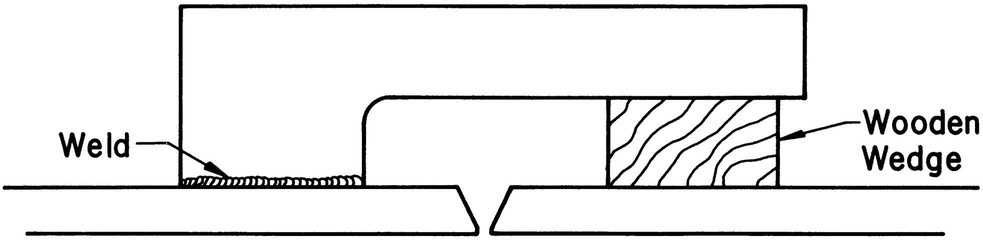


Fig. 6.47—Arrangement of clamp to prevent angular distortion while permitting transverse shrinkage.

(2) By assembling the job so that it is nominally correct before welding and by employing some form of restraint to minimize the welding distortion after welding.

The first method is attractive because the parts have almost complete freedom to move during welding and there will be less residual stress than with the second method. However, it is a difficult method to apply, except on relatively simple fabrications. For this reason, it is usual to break down the work into subassemblies that can be welded without restraint, when dealing with fabrications comprising a large number of parts. The subassemblies are then assembled together and welded to complete the job, but often this final welding has to be carried out under conditions of restraint.

Figure 6.46 shows simple examples of the presetting method as applied to fillet and butt welds. The amount of preset required varies somewhat according to plate thickness, plate width, and the welding procedure. For this reason, it is advisable to establish the amount by experiment; otherwise, it is only possible to make an "intelligent guess" at what it should be.

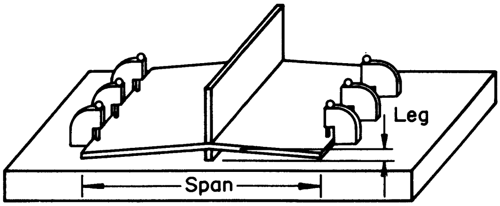


Fig. 6.48—Apparatus for welding T-joints submitted to plastic prestrain by bolting down both free ends. A round bar stock was used for the spacer.

The second or restrained assembly method is the one more generally preferred because of its comparative simplicity. The restraint may be applied by clamps, the use of fixtures, or simply by adequate tack welding.

While this method minimizes distortion, it can result in high residual stresses. These high residual stresses and the risk of cracking can often be reduced by the use of a suitable

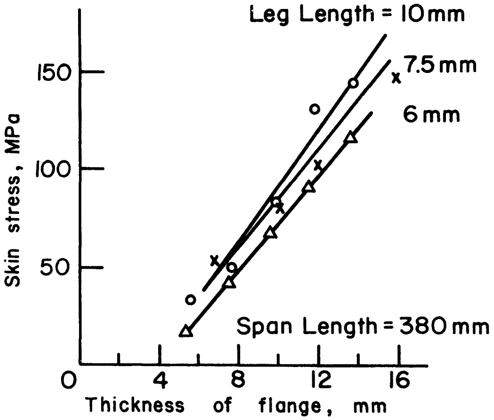


Fig. 6.49—Curves of skin stress versus flange plate thickness required for obtaining zero angular change due to elastic prespringing.[38] *(For U.S. customary equivalents of SI values, see the table on p. 275.)*

welding sequence and, with heavy sections, by preheating. Where service requirements demand the removal of residual stresses, a stress relieving heat treatment must be applied after welding. To attempt to impose complete restraint can be undesirable, but by restraining movement in one direction and allowing freedom in another, the overall effect can usually be controlled. An example is shown in Fig. 6.47 where the clamping arrangement is designed to prevent angular distortion in a V-butt joint while permitting transverse shrinkage.

Elastic Prespringing

Elastic prespringing is the method in which the bottom plate is elastically bent while girders are fillet welded to the plate, as shown in Fig. 6.48. Angular changes after the removal of the restraint can be reduced significantly by this method. A series of experiments was conducted using specimens as shown in Fig. 6.48.[38] and obtained results as shown in Fig. 6.49 which gives values of stresses on the plate surfaces required to obtain zero angular change.

Preheating

Preheating may be used as a method of reducing angular change in a fillet weld. (See

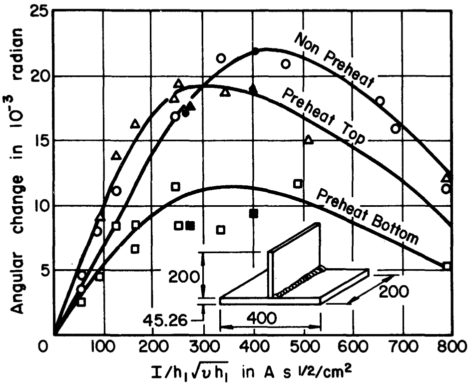


Fig. 6.50—Effect of preheating on angular change of T-fillet welded joint.[39] *(I = welding current; h = thickness of horizontal plate; v = welding speed.)*

Fig. 6.50.[39]) Figure 6.50 shows the effect of angular change in a steel fillet weld under different welding conditions and plate thickness.

CORRECTION OF DISTORTION

It is not always possible to control distortion within acceptable limits, especially when dealing for the first time with a new design or fabrication. There are bound to be instances where, despite the most careful planning, the distortion becomes excessive. In such circumstances, it is usually possible to rectify the trouble by one of the following methods.

Distortion can be removed by producing adequate plastic deformation in the distorted member or section. The required amount of plastic deformation can be obtained by the thermal or mechanical methods discussed in the following paragraphs:

(1) *Thermal Straightening.* Thermal or flame straightening has been used most successfully in the shipbuilding industry to remove distortion. The area to be straightened is heated to between 595 - 650 °C (1100 - 1200 °F) and then quenched with a water spray; repeated applications of heat in specific areas in a selected sequence or pattern are normally needed to straighten a distorted member or structure. The patterns are usually spot or linear heating techniques.

(2) *Pressing.* Distorted members can be

straightened in a press if the members can be moved and if the press is large enough to handle them; heat may or may not be required for straightening.

(3) *Other Methods.* Jacking is closely related to pressing in that distortion is removed by the application of pressure with or without added heat. Although its use is frowned upon, hammering of locally heated areas is sometimes used for straightening also.

Flame straightening, which is a relatively simple method and requires a minimum of equipment, has been widely used especially for structures in low carbon steel. However, there has been a concern over the possible material degradation when flame straightening is used for structures in high strength steels.

THERMAL AND MECHANICAL TREATMENTS OF WELDMENTS

Various thermal and mechanical treatments are often performed on weldments to reduce residual stresses and distortion. They include preheat, postweld thermal treatments, peening, proofstressing, and so forth. These treatments not only reduce residual stresses and distortion, but may also change the metallurgical properties of weldments. This section describes how these treatments are performed and how they affect residual stresses and distortion. Changes of metallurgical and mechanical properties by thermal treatments are discussed in detail in Chapter 4, pp. 107-117.

REASONS FOR THERMAL AND MECHANICAL TREATMENTS OF WELDMENTS

Thermal and mechanical treatments are necessary to maintain or restore the properties of base metal affected by the heat of welding. Thermal treatment may also improve or modify the properties of the weld deposit. These treatments may also be necessary to relieve stresses and to produce the desired microstructure in the base metal and filler metal. The extent of the changes in the base metal, which determines the subsequent thermal treatment, depends on the temperature to which the metal is subjected, the period of exposure, the composition of the metal, and the rate of cooling. Other factors include joint design, welding process, welding procedure, variables, and similar factors.

Among the many properties controlled or improved by suitable thermal or mechanical treatments are: distortion during welding; reduction of stresses that could seriously affect the service performance of a weldment; weldability (which may be improved considerably by preheat treatment, for example), and improvement of dimensional stability and machinability. When the preweld and postweld treatments are correctly integrated with approved procedure, skillful performance and good joint design, optimum properties are to be expected in the weldment.

In most metals, the reduction of the "metallurgical notch" effect, resulting from abrupt changes in hardness or other microstructural discontinuities around welds, can readily be accomplished by correct postweld heat treatment. Mechanical treatments sometimes are beneficial in superimposing counterstresses upon normal welding stresses. This can result in the reduction of stresses to a level compatible with the service conditions required of the components. When welding on carbon and alloy steels that are in a heat treated condition, complete residual stress control is not practical in some cases because preheating and postheating must be below the heat treating temperature used in producing the base metals.

On quenched and tempered steel where a

limited stress relieving temperature can be used, the machinability can be improved by using a tempering bead or weld. This weld bead is applied to the last weld bead at the base metal. The application of this arc energy provides for a tempering treatment of the last weld bead and the heat-affected zone of the base metal.

The resistance of the components to the propagation of cracks, especially in the heat-affected zone adjacent to the weld, is often directly related to correct welding procedures, which include preweld and postweld heat treatments. The improved mechanical properties in the weld and heat-affected zones adjacent to the weld, which are due to thermal and mechanical treatments, result in a greatly increased resistance to crack propagation. The corrosion resistance of the weldment is often greatly improved by postweld heat treatment.

Code Requirements

When a weldment has to be constructed in accordance with the recommendations of a code such as the ASME Boiler and Pressure Vessel Code, thermal treatments are specified for certain types of weldments. A code prepared by technical organizations or regulatory bodies is based on existing evidence that indicates when thermal treatment is necessary, or if the weldment can withstand service conditions in its as-welded state. The fabricator should understand that these are codes of minimum requirements. In addition to the thermal treatment specified, the fabricator should employ other treatments as his experience dictates in order to produce a quality weldment.

Some codes and standards pertinent to this chapter are listed in the Supplementary Reading List on p. 278. However, since these documents are constantly revised and updated, the organizations preparing them should be consulted as to the latest available versions of the documents.

Most of the states have adopted one or more of these codes or standards for control and regulation of new construction installed under their jurisdiction. It is the responsibility of the fabricator to make himself conversant in all laws and regulations in the state where he is operating. For pressure vessel installation, the Industrial Commission of the state having jurisdiction should be contacted for applicable rules concerning weld repairs on pressure vessels.

COMMON THERMAL TREATMENTS FOR WELDMENTS

Preheat

Preheating involves raising the temperature of the base metal or a section of the base metal above the ambient temperature before welding. Preheat temperatures may vary from as low as room temperature 26 °C (79 °F) when welding outdoors in winter to as high as 650 °C (1200 °F) when welding ductile cast iron and 315 °C (600 °F) when welding highly hardenable steels. Recommendations for preheating and postheating various grades of steel are included in publications such as *Weldability of Steels*, published by the Welding Research Council.

In many operations, the temperature to which the base metal is heated must be carefully controlled. The best means of control is to heat the part in a furnace held at the desired temperature, or to use electric induction coils or electric resistance heating blankets. On thin wall materials, radiant lamps or hot air blast can be used. In these methods, temperature indicators are attached to the part being preheated. If these methods are not practical, there are many other methods that may be used for measuring the temperature: surface thermocouples, magnetically attached bimetal surface thermometers, colored chalks that change color at known temperatures, and pellets that melt at a predetermined temperature. When using torches for preheating, it is important to prevent localized overheating and also to prevent deposits of incomplete combustion on the surfaces of the joints or areas to be welded.

Preheating is a very effective means of reducing weld metal and base metal cracking.

Preheating generally improves weldability with two major beneficial effects: It retards the cooling rates in the weld metal and heat-affected base metal, and reduces the magnitude of shrinkage stresses. However, when welding quenched or age-hardened materials, the effects of preheating can be detrimental unless controlled within allowable limits.

Cooling rates are usually faster for a weld made without preheat.* The higher the preheating temperature, the slower the cooling rates after the weld is completed. The temperature gradient is reduced and, in the case of iron, the thermal conductivity is decreased. At 595 °C (1100 °F), the thermal conductivity of iron is 50 percent less than at room temperature. At 800 °C (1470 °F) the thermal conductivity of many carbon steels is approximately 50 percent less than at room temperature. Low thermal conductivity ensures slow cooling rates because the heat is transferred from the welding zone at a lower rate.

Preheating, with a consequent reduction in cooling rate, may help to provide a favorable metallurgical structure in steel. The heat-affected zone at the joint remains in the transformation temperature range for a longer period of time, which promotes the transformation of austenite to ferrite and pearlite or bainite instead of to martensite. The preheated weld is less likely to have hard zones than a weld made without preheat. Preheating may reduce the cooling rate to such an extent that transformation is complete before the martensite initiation temperature is reached (205 °C [400 °F] for carbon steels).

Weld shrinkage is generally reduced by preheating. This often overlooked fact can mean the difference between an acceptable or unacceptable weldment. During the time the weld metal is near the transformation range, it has little strength. Consequently, it cannot exercise any appreciable force on the joint members. The plastic flow experienced by the weld metal adjusting to the changing dimensions is in the nature of hot working with no loss of ductility. The weld metal and heat-affected base metal become stronger as the temperature decreases, and the shrinkage forces naturally become greater. The plastic flow becomes cold work, and this results in the progressive loss of ductility. Actual measurement across welds during cooling have shown that 30 percent less total contraction occurred in joints preheated to 205 °C (400 °F) compared with similar joints welded at room temperature.

However, when an area being welded is under severe restraint, localized preheat may increase the amount of shrinkage and cause cracking. Preheating to the higher temperatures, above 315 °C (600 °F), reduces the yield strength of the material which relieves shrinkage stresses. If these stresses were forced to occur solely in the highly heated zone in the immediate vicinity of the weld, without preheat, they might lead to hot cracks in the weld metal or in the base metal close to the weld.

Preheat must be used with caution since detrimental effects may result under certain conditions. The welding of stainless steel containing 16 percent chromium is improved by preheating. It prevents shrinkage stresses acting on the coarse-grained weld metal and heat-affected zone at the low temperatures during which they are brittle. When preheat is too high, cooling rates become slower and the period of time lengthens during which the metal remains within the critical range. Similarly, in most alloy steels, prolonged heating above the martensitic temperature range may, on cooling, cause transformation to a lower strength pearlite structure. This would decrease the tensile and yield point values of the structure. Furthermore, if the material is in a quenched and tempered condition, preheating above the tempering temperature may cause additional tempering which could result in lower hardness and tensile strength.

In multipass welding, the interpass temperature is the preheat temperature for the next bead. The time interval between beads controls this temperature. Too high a preheat or interpass temperature is undesirable for some steels because the coarse-grained heat-affected zone may, on cooling, transform to ferrite or

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*See Chapter 3, p. 85.

upper bainite, both low in notch toughness; or it may cause an unfavorable alteration of properties produced by previous heat treatment.

Regular heat treating or stress relieving furnaces are often used to preheat entire structures, especially heavy forgings or castings for repair welds. When the piece to be welded is removed from the furnace, protection against rapid cooling should be provided with asbestos paper or blankets. Plate fabricating shops often use natural or manufactured gas as a fuel for the local preheating of weldments since the gas is relatively clean and convenient.

Electrical strip heaters of 100 to 200 V rating are being used for general and local preheating, for repairs in castings and pipe, and for pressure vessel joints, especially for field welding. These strip heaters must be carefully insulated at the terminals to avoid the danger of shock to workmen.

Induction heating, using 60 Hz transformers of suitable capacities especially built for this purpose, is probably the most common method of preheating pipe joints for welding. These transformers may be operated manually or with automatic controls that will maintain any temperature range or follow a predetermined time-temperature program.

Postweld Thermal Treatments

Stress relief heat treatment is defined as the uniform heating of a structure to a suitable temperature, holding at this temperature for a predetermined period of time, followed by uniform cooling. Heat treatments that involve changes in grain structure and dimensional changes may be injurious to a part; consequently, stress relief heat treatment is usually performed below the critical range.

In its Boiler and Pressure Vessel Code, the American Society of Mechanical Engineers indicates the minimum temperatures and times at which postweld heat treatment is to be performed for welded power boilers and unfired pressure vessels. These vary depending on the type or grade of steel involved.

Thermal Stress Relief. Residual stresses resulting from welding are reduced by a postweld thermal stress relief heat treatment. Stresses are reduced to a level just below the yield point of the material at the temperature of the stress relief treatment. The residual stress remaining in a material after thermal stress relief will depend on the rate of cooling. Uneven cooling from stress relief to ambient temperatures may undo much of the value of the heat treatment and result in additional stresses within the weldment.

The percentage relief of internal stresses is dependent on steel type, composition, or yield strength. The effects of varying time and temperature are shown in Fig. 6.51. The temperature reached during the stress relief treatment has a far greater effect in relieving stresses than the length of time the specimen is held at that temperature. The closer the temperature is to the critical or recrystallization temperature, the more effective it is in the removal of residual stresses, provided proper heating and cooling cycles are employed.

When a thermal stress relief treatment is employed to reduce residual stresses, other important properties must be taken into consideration. The microstructure and tensile and impact strength are among the properties affected by the stress relief treatment. It is necessary, therefore, to select a temperature that will develop the desirable properties in the steel while at the same time providing the maximum stress relief (Table 6.5).

Controlled Low Temperature Stress Relief. This process was originally developed to reduce residual stresses in weldments too large to be stress relieved in a furnace. The metal on either side of a welded joint is heated to a temperature of 175 to 205 °C (350 to 400 °F) while the weld itself is kept relatively cool. The progression of these heated bands of metal, parallel to the weld and adjacent to each side, results in a traveling zone of thermal expansion in the base metal and a reciprocal tensile stress in the weld. The theory of this procedure is that two zones of compression are expanded thermally, thereby increasing the tensile stress in the weld beyond the yield.

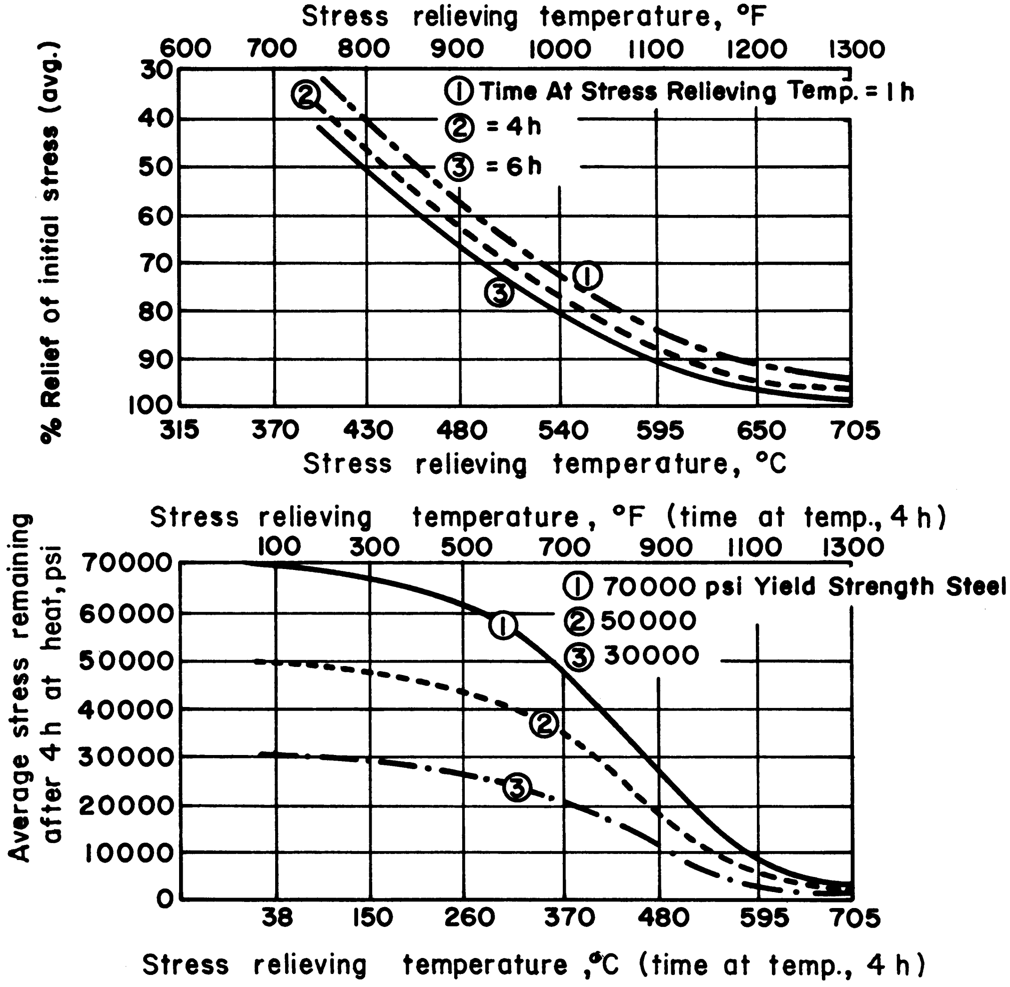


Fig. 6.51—Effect of temperature and time on stress relief. (For SI equivalents of U.S. customary values, see the table on p. 275.)

When the metal subsequently cools and contracts, the stress falls below the yield.

When the process is used correctly, a partial reduction in the longitudinal stress of butt welds is achieved.[40] Many consider that longitudinal weld stresses are of primary importance since they attain values up to the yield strength in tension. Others question the validity of low temperature stress relief, claiming that in restrained plates, both longitudinal and transverse residual stresses approach the yield point of the material. Reductions in transverse residual stresses ranging up to 60 percent, as well as a considerable reduction in the longitudinal stresses, are reported. This indicates that low temperature stress relief is an inexpensive means of obtaining a substantial reduction of shrinkage stress in ductile materials.

In most materials, the low temperature stress relief treatment will not improve the metallurgical properties of the weld metal and the heat-affected zones, and the treatment should not be regarded as a substitute for postweld thermal treatment when such treatment is required to provide ductility and notch tough-

Table 6.5—Typical thermal treatments for weldments

Material	Soaking Temperature	
	°C	°F
Carbon steel	595-680	1100-1250
Carbon–½% Mo steel	595-720	1100-1325
½% Cr–½% Mo steel	595-720	1100-1325
1% Cr–½% Mo steel	620-730	1150-1350
1¼% Cr–½% Mo steel	705-760	1300-1400
2% Cr–½% Mo steel	705-760	1300-1400
2¼% Cr–1% Mo steel	705-770	1300-1425
5% Cr–½% Mo (Type 502) steel	705-770	1300-1425
7% Cr–½% Mo steel	705-760	1300-1400
9% Cr–1% Mo steel	705-760	1300-1400
12% Cr (Type 410) steel	760-815	1400-1500
16% Cr (Type 430) steel	760-815	1400-1500
1¼% Mn–½% Mo	605-680	1125-1250
Low-alloy Cr-Ni-Mo steels	595-680	1100-1250
2 to 5% Ni steels	595-650	1100-1200
9% Ni steels	550-585	1025-1085
Quench & tempered steels	540-550	1000-1025

ness. The process operates in the temperature range associated with possible strain aging, but available data indicate that the medium strength ductile materials are not adversely affected.

PEENING

Peening has been used by the welding industry for over 35 years, but the code requirements and regulations governing this procedure have been based on opinion rather than on scientific data because there has been no practical method for measuring the effect of peening.

Various specifications and codes require that the first and last layers of a weld should not be peened. Vague statements such as "thoroughly peened" and "the work shall not be overpeened" do little to clarify a situation that is already confused. There is a firm foundation for the requirement that the first layer shall not be peened. Peening the first layer could actually pierce the weld or displace the member sideways. Peening the last layer is prohibited largely in the belief that cold working would injure the weld metal, and there is no subsequent application of heat to anneal it.

One method of checking the effectiveness of a peening procedure in an actual welding operation involves the use of punch marks made on opposite sides of the weld. The distance between these marks should be kept within + 0.8 mm (+1/32 in.). Peening is performed during the welding of the seam, with the first measurement being made after two layers of weld metal have been deposited. If the peening has been executed so that the deviation in distance between punch marks is held to a minimum until the depth of the weld is 32 to 38 mm (1¼ to 1½ in.), the same degree of peening may be applied safely to the remainder of the weld.

The results of laboratory tests conducted by the American Bureau of Shipping and explosion tests by the Naval Research Laboratory confirm the requirement prohibiting the peening of the first and last layers.

In conducting peening, the following special precautions may be necessary:

(1) Work hardening should be considered when certain AISI 300 series steels are involved.

(2) Hot shortness may preclude hot peening of certain bronze alloys.

(3) AISI 400 series steels have relatively poor notch ductility in the as-welded condition. The utmost care should be exercised if peening is attempted.

(4) The relative elongation values or ductility of welds and base metals should be considered before employing the peening process.

Peening equipment should be selected with care. The hammer, pneumatic tools, and so forth should be sufficiently heavy in striking force to be effective without producing excessive work hardening, but not so heavy as to involve bending moments or produce cracks in the weld.

Peening should be employed on each weld bead or layer (except the first and last) to be effective. The effectiveness decreases as the thickness of the bead or layer increases. Peening becomes of doubtful value for deposits of 6 mm (1/4 in.) or thicker, except in special instances where the rigidity or weight of the weldments permits the use of heavy blows.

Peening of resistance welds to reduce distortion of sheet metal parts is usually done with a mechanically operated trip hammer using flat wide dies for both the hammer and supporting anvil. Since the welds must be backed up by rigid anvils immediately under the hammer blow, the parts are usually moved through a stationary hammer. Metal adjacent to the welds is usually peened, as well as the weld itself.

PROOFSTRESSING

Investigations indicate that uniform heavy loading of weldments may tend to decrease longitudinal residual stresses by the amount of loading (see Fig. 6.10).

Cylindrical and spherical pressure vessels can be proofstressed readily by hydrostatic loading. In cylindrical vessels, hydrostatic loading produces circumferential stress approximately double the longitudinal stress so that relief of residual stress in circumferential welds will be only half the relief in longitudinal welds.

Proofstressing of weldments of more complex geometry usually presents considerable difficulty and is, therefore, seldom attempted. Proofstressing often serves as a final fabricating operation by smoothing out irregularities of form by plastic straining so that under subsequent service conditions, the strains will be wholly elastic and within safe limits.

This process is based on the plastic straining of the material. It is to be expected, therefore, that a potential cracking hazard may exist where the materials involved are notch sensitive or lack notch ductility at the proofstressing temperature.

VIBRATORY STRESS RELIEF

Mechanical energy in the form of low and high frequency vibrations has been used to relieve residual stresses in weldments. The procedures used vary, but generally consist of an oscillating or rotating wave generator which is mechanically coupled to the part to be stress relieved. The part may be vibrated at one of its natural (resonant) frequencies although this approach may be difficult to use in a part of complex shape. For such a system to be effective, it must produce plastic yielding in the region to be stress relieved; however, the yielded region may be quite local and may already be at a residual stress level at or near the yield point prior to treatment. The yielded region may also be moved progressively along the part to achieve full coverage. It may not be possible or even necessary to eliminate all residual stresses by this method, but it may be possible to reduce the magnitude of peak stresses. If such a reduction is accomplished, a vibratory stress relief system could provide a means of reducing distortion in parts machined after welding and could improve resistance to brittle fracture if it is triggered by high levels of residual stress. In some instances, plastic yielding is not achieved by vibratory stress relief due to the size or complexity of the part involved. Even in these cases, some improvement in distortion when machining after welding has been reported.

Unfortunately, vibratory stress relief treatments do not change the metallurgical structure of welds or heat-affected zones to which they are applied, and thus no improvement or change in mechanical properties of the treated zone may be expected. In those instances where thermal stress relief treatments are expected to alter the strength or toughness of the weldment by changes in microstructure, vibratory stress relief will not be a satisfactory substitute.

Vibratory stress relief is a somewhat controversial subject and there is little published research data on this topic. Moreover, opinions of this treatment vary greatly, some experts judging it to be very effective while others consider it to have no effect at all. However, it may be a possible alternative to thermal stress relief in some cases.

Table of SI and U.S. customary values for Chapter 6 figures

Linear measurements

mm	in.
0.2	0.008
0.4	0.016
0.5	0.196
0.6	0.024
0.8	0.03,1/32
1.0	0.04
1.5	0.06
1.6	1/16
2	0.08
2.6	0.10
3	0.12,1/8
3.2	0.13
4	0.16
5	0.196
6	0.24
7	0.28
7.5	0.30
8	0.31
8.5	0.33
9	0.36
10	0.39
11	0.43
12	0.47
13	0.51
14	0.55

mm	in.
15	0.59
16	0.63
17	0.67
18	0.7
19	0.75
20	0.79
22	0.87
24	0.94
26	1.02
28	1.10
30	1.1
40	1.6
50	2
60	2.4
70	2.8
80	3.1
100	4
140	5.5
200	8
250	10
300	12
380	15
400	16
500	20
600	24
700	28
750	30

mm	in.
800	32
900	36
1000	40
1100	44
1200	48
1250	50

m	ft.
0.2	0.7
0.4	1.3
0.5	1.6
0.6	2
0.8	2.6
0.9	3
1	3.3
1.2	3.9
1.5	5
2	6.6
2.5	8.2
3	9.8
4	13
5	16.4
6	19.6
7	23

Area dimensions

mm^2	$in.^2$
1300	2
2600	4
3900	6
5200	8
6450	10
7740	12
9000	14
10 300	16

Degree of Constraint

MPa/mm	ksi/in.
200	737
400	1474
500	1842
600	2210
800	2947
1000	3684
1200	4421
1400	5158
1500	5526

Temperature

°C	°F
95	200
205	400
316	600
430	800
540	1000
650	1200
593	1100

Pressure, stress

MPa	ksi	psi	MPa	ksi	psi
−300	−43.5	−43 500	140	20	20 000
−280	−40	−40 000	150	21.8	21 800
−210	−30	−30 000	200	29	29 000
−200	−29	−29 000	210	30	30 000
−140	−20	−20 000	280	40	40 000
−100	−14.5	−14 500	300	43.5	43 500
−70	−10	−10 000	340	50	50 000
50	7.3	7250	400	58	58 000
70	10	10 000	410	60	60 000
100	14.5	14 500	480	70	70 000

REFERENCE LIST

1. Masubuchi, K. 1970. Control of distortion and shrinkage in welding. *Welding Research Council Bulletin* 149.
2. Hall, W. S., Kihara, H., Soete, W., and Wells, A. A. *Brittle Fracture of Welded Plate.* Englewood Cliffs, New Jersey: Prentice-Hall, 1967.
3. Kihara, H. and Masubuchi, K. 1959. Effect of residual stress on brittle fracture. *Welding Journal* 38:159s-168s.
4. Kammer, P. A., Masubuchi, K., and Monroe, R. E. Cracking in high-strength steel weldments — a critical review. DMIC Report 197, Feb. 1964. Columbus, Ohio: Battelle Memorial Institute.
5. Kihara, H. Masubuchi, K., Iida, K., and Ohba, H. *Effect of Stress Relieving on Brittle Fracture Strength of Welded Steel Plate.* Document X-218-59, 1959. London: International Institute of Welding (distributed in the United States by the American Welding Society).
6. Kihara, H. and Fujita, Y. 1960. The influence of residual stresses on the instability problem. In colloquium on the *Influence of Residual Stresses on Stability of Welded Structures and Structural Members.* London: International Institute of Welding (distributed in the United States by the American Welding Society).
7. Tall, L., Huber, A. W. and Beedle, L. S. 1960. Residual stress and the instability of axially loaded columns. In colloquium on the *Influence of Residual Stresses on Stability of Welded Structures and Structural Members.* London: International Institute of Welding (distributed in the United States by the American Welding Society).
8. Faulkner, D. *Compression Strength of Welded Ship Panels.* Internal publication at Department of Ocean Engineering. Cambridge, Mass.: Massachusetts Institute of Technology, 1971.
9. Faulkner, D. Compression strength of welded grillages. In final technical report of SR-200, Ship Structure Committee. Washington, D.C., 1974.
10. Gurney, T. R. *Fatigue of Welded Structures.* Cambridge: Cambridge University Press, 1968.
11. Munse, W. H. *Fatigue of Welded Steel Structures.* New York: Welding Research Council, 1964.
12. Masubuchi, K. *Materials for Ocean Engineering.* Cambridge, Mass.: M.I.T. Press, 1970.
13. Tetelman, A. S. and McEvily, A. J., Jr. *Fatigue of Structural Materials.* New York: John Wiley and Sons, 1967.
14. Berry, W. E. Stress-corrosion cracking — a nontechnical introduction to the problem. DMIC Report 144, Jan. 1961. Columbus, Ohio: Battelle Memorial Institute.
15. Uhlig, H. H. *Corrosion and Corrosion Control, and Introduction to Corrosion Science and Engineering.* New York: John Wiley and Sons, 1963.
16. Masubuchi, K. and Martin, D. C. Investigation of residual stresses by use of hydrogen cracking. *Welding Journal* Part I, 1961 — 40 (12): 553s - 563s; Part II, 1966 — 45 (9): 401s - 418s.
17. Masubuchi, K. Nondestructive measurement of residual stresses in metals and metal structures. RSIC — 410, April 1965. Redstone Arsenal, Alabama: Redstone Scientific Information Center, U. S. Army Missile Command.
18. Horger, O. J., *Handbook of Experimental Stress Analysis.* New York: John Wiley and Sons, 1950, pp. 459-578.
19. Soete, W. 1949. Measurement and relaxation of residual stresses. *Welding Journal* 28(8): 354s-364s.
20. DeGarmo, E. P., Meriam, J. L., and Jonassen, F. 1946. The effect of weld length upon the residual stresses of unrestrained butt welds. *Welding Journal* 25 (8): 485s-486s.
21. Gunnert, R. 1958. Method for measuring tri-axial residual stresses. *Welding Research Abroad* 4 (10): 17-25.
22. Jonassen, F., Meriam, J. L., and DeGarmo, E. P. 1946. Effect of certain block and other special welding procedures on residual welding stresses. *Welding Journal* 25 (9): 492s-496s.
23. Weck, R. Transverse contractions and residual stresses in butt welded mild steel plates. Report R4, Jan. 1947. London: Admiralty Ship Welding Committee.
24. Kihara, H., Masubuchi, K., and Matsuyama, Y. Effect of welding sequence on transverse shrinkage and residual stresses. Report 24, Jan. 1957. Tokyo: Transportation Technical Research Institute.
25. Kihara, H., Watanabe, M., Masubuchi, K., and Satoh, K. 1959. *Researches on Welding Stress and Shrinkage Distortion in Japan.* 60th Anniver-

sary Series of the Society of Naval Architects of Japan, Vol. 4. Tokyo: Society of Naval Architects of Japan.

26. Watanabe, M. and Satoh, K. 1961. Effect of welding conditions on the shrinkage and distortion in welded structures. *Welding Journal* 40 (8): 377s-384s
27. Spraragen, W. and Ettinger, W. G. 1950. Shrinkage distortion in welding. *Welding Journal* 29 (6 and 7): 232s-294s and 323s-335s.
28. Kihara, H. and Masubuchi, K. Studies on the shrinkage and residual welding stress of constrained fundamental joint. *Journal of the Society of Naval Architects of Japan.* Part I, 1954 — 95: 181-195; Part II, 1955— 96: 99-108; Part III, 1955 — 97: 95-104 (in Japanese).
29. Masubuchi, K. 1960. Analytical investigation of residual stresses and distortions due to welding. *Welding Journal* 39 (12): 525s-537s.
30. Kihara, H., Masubuchi, K., and Ogura, Y. 1956. Radial contraction and residual stresses in circular patch weld. *Journal of the Society of Naval Architects of Japan.* Part I — 99: 111-122; Part II — 100: 163-170.
31. King, C. W. R. 1944. In *Transactions of the Institute of Engineers and Shipbuilders in Scotland.* 87: 238-255.
32. Guyot, F. 1947. A note on the shrinkage and distortion of welded joints. *Welding Journal* 26 (9): 519s-529s.
33. Masubuchi, K., Ogura, Y., Ishihara, Y., and Hoshino, J. 1956. Studies on the mechanism of the origin and the method of reducing the deformation of shell plating in welded ships. *International Shipbuilding Progress* 3 (19): 123-133.
34. Hirai, S. and Nakamura, I. Research on angular change in fillet welds. *Ishikawajima Review* April, 1956, pp. 59-68 (in Japanese).
35. Sasayama, T., Masubuchi, K., and Moriguchi, S. *Longitudinal Deformation of a Long Beam Due to Fillet Welding.* Document X-88-55, 1955. London: International Institute of Welding (distributed in the United States by the American Welding Society).
36. Masubuchi, K. 1954. Buckling-type deformation of thin plate due to welding. In *Proceedings of Third International Congress for Applied Mechanics of Japan,* pp. 107-111.
37. Watanabe, M. and Satoh, K. 1958. Fundamental studies of buckling of thin steel plate due to bead-welding. *Journal of the Japan Welding Society* 27 (6): 313-320.
38. Kumose, T., Yoshida, T., Abe, T., and Onoue, H. 1954. Prediction of angular distortion caused by one-pass fillet welding. *Welding Journal* 33 (10): 945-956.
39. Watanabe, M., Satoh, K., Morii, H., and Ichikawa, I. 1957. Distortion in web plate of welded built-up girder due to welding of stiffeners and the methods for decreasing it. *Journal of the Japan Welding Society* 26: 591-596.
40. McKinsey, C. R. 1954. Effect of low-temperature stress relieving on stress-corrosion cracking. *Welding Journal* 33 (4): 161s-166s.

SUPPLEMENTARY READING LIST

ASME Boiler and Pressure Vessel Code, Sections I, III, and VIII Divs. 1 and 2 (latest edition). New York: American Society of Mechanical Engineers.

Code for Pressure Piping, ANSI B31.1 to B31.8 (latest edition). New York: American National Standards Institute.

Fabrication Welding and Inspection; and Casting Inspection and Repair for Machinery, Piping and Pressure Vessels in Ships of the United States Navy, MIL-STD-278 (Ships) (latest edition). Washington, D.C.: Navy Department.

General Specification for Ships of the United States Navy, Spec. S9-1 (latest edition). Washington, D.C.: Navy Department.

Gurney, T. R. *Fatigue of Welded Steel Structures.* Cambridge: Cambridge University Press, 1968.

Hall, W. J., Kihara, H., Soete, W. and Wells, A. A. *Brittle Fracture of Welded Plates.* Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1967.

Masubuchi, K. 1970. Control of distortion and shrinkage in welding. *Welding Research Council Bulletin* 149.

Masubuchi, K. Nondestructive measurement of residual stresses in metals and metal structures. RSIC-410. April 1965. Redstone Arsenal, Alabama: Redstone Scientific Information Center, U. S. Army Missile Command.

Masubuchi, K. 1974. Residual stresses and distortion in welded aluminum structures and their effects on service performance. *Welding Research Council Bulletin* 174.

Munse, W. H. *Fatigue of Welded Steel Structures.* New York: Welding Research Council, 1964.

Osgood, W. R. *Residual Stresses in Metal and Metal Construction.* New York: Reinhold Publishing Corporation, 1954.

Rules for Building and Classing Steel Vessels (latest edition). New York: American Bureau of Shipping.

Structural Welding Code, AWS D1.1 (latest edition, as revised). Miami: American Welding Society.

Tall, L., ed. *Structural Steel Design.* 2d ed. New York: Ronald Press Co., 1974.

Treuting, R. G., Lynch, J. J., Wishart, H. B., and Richards, D. G. *Residual Stress Measurements.* Metals Park, Ohio: American Society for Metals, 1952.

United States Coast Guard Marine Engineering Regulations and Materials, Spec. CG-115 (latest edition). Washington, D.C.: United States Coast Guard.

Appendix

A

Terms and Definitions

Extracted from Welding Terms and Definitions, AWS A3.0, prepared by the AWS Committee on Definitions, Symbols and Metric Practice.

Appendix A
Terms and Definitions

INTRODUCTION

The terms and definitions included in this appendix were approved by the AWS Committee on Definitions, Symbols, and Metric Practice in 1975. The reader should keep this date in mind since the welding industry and its vocabulary are in a continual state of change. Research not only brings new techniques and procedures, but new terminology as well. Although most of the terms and definitions presented here are not likely to change significantly, the reader is nevertheless referred to the latest available edition of Welding Terms and Definitions, A3.0, for the most up-to-date and complete vocabulary listings, including illustrations.

The preferred terms and definitions included in this appendix are those that should be used in writing codes, specifications, procedures and all other documents concerning welding. The preparation of this appendix (as well as the A3.0 document), therefore, is an effort to standardize terminology. Although some may consider the terminology arbitrary, it is a result of deliberation and study with a dedicated effort towards technical accuracy. For simplicity of presentation, only two types of entries are used:

(1) Preferred terms and definitions

(2) Nonpreferred and erroneous terms

Some editorial comments or notes are offered where appropriate for certain processes which are believed to be obsolete.

TERMS FOR WELDING AND ALLIED PROCESSES

In the hierarchy of welding the "welding process" stands first. Each welding process definition is complete so that it will stand alone. Processes are defined for prescribed elements of operation instead of other characteristics such as metallurgical, source of energy, etc. This method of organization is the basis for the new Master Chart of Welding and Allied Processes which appears at the end of Appendix A on p. 335.

The chart is a visual display of a hierarchy of welding and allied processes, the highest generic levels (least specific) being in the center with the most specific in boxes around the perimeter. The chart is intended to be comprehensive and includes not only widely used production processes but some that are of limited use either because they have been largely replaced by other processes, have only recently been introduced, or have limited applications.

The basis for the separation of welding processes and allied processes depends upon the definition of a weld as follows:

> **weld.** A localized coalescence of metals or nonmetals produced either by heating the materials to suitable temperatures, with or without the application of

pressure, or by the application of pressure alone, and with or without the use of filler material.

All of the processes attached to the "Welding Processes" circle on the chart fall under the definition of "weld," but in each case the definition is more specific. Brazing and soldering are special forms of welding, the distinguishing characteristic being the distribution of filler metal in the joint by capillary flow which does not occur in the other welding processes or in braze welding. Also brazing and soldering do not involve melting of the base material as in other forms of welding.

Adhesive bonding is included as an allied process. An example of an application is "weldbonding" which involves both welding and adhesive bonding.

There are variations of welding processes such as pulsed and short circuiting arc in gas metal arc welding and these are listed on the chart with the processes with which they are used. Beyond this there are "methods and procedures." Included can be the "method of applying," such as manual, semiautomatic, machine, and automatic. The definition includes the degree to which the welding, brazing, soldering, thermal spraying, or cutting operation is performed under the observation and control of a person.

In order to maintain continuity in understanding old documents and for legal purposes, some welding process terms, which are believed to be no longer significant in the welding industry, have been retained. Beyond the legal aspect, however, is the fact that some old, but unique processes may be of vital importance in a specific industry or plant. Some of the newer welding processes are, no doubt, in the same category, that is, essential but very narrow in application. For these reasons, the appendix is a comprehensive, rather than an arbitrarily restricted, collection of terms and definitions. An example of an important older process is "roll welding;" as for newer processes, diffusion brazing and weldbonding are of great value in certain applications. If a formerly defined process is now considered a nonpreferred term or a method rather than a process, it is defined accordingly. For example, "hammer welding" is now considered a nonpreferred term for "forge welding" or "cold welding."

Because of the wider scope of the material prepared by the definitions committee, base metal is not always the proper term for the parts being joined. For example, brazing of ceramics to metal is now common. Metal matrix composite materials are sometimes welded and many plastics are routinely welded. Thus, "base material," rather than "base metal," is often the appropriate term.

THE WELD

The term weld, as used in this appendix, refers to a "coalescence" rather than a consolidation, since coalescence is defined as "a growing together, or growth into one body." In the welding of metals the metallic bond is formed as the weld is being made. The forces that hold materials together when welded, brazed, soldered, or adhesive bonded are complex and involve a number of not completely understood physical and chemical mechanisms. Several terms with definitions are included which on good authority describe the types of bonding forces that are involved in the joining of materials by welding, brazing, soldering, and adhesive bonding. See for example:

adhesive bond
bonding force
covalent bond
ionic bond
metallic bond
permanent dipole bond
van der Waals bond
weld

The difference between a weld, a braze, and a braze weld may at first seem confusing, but the definition of each will point out their distinguishing characteristics. Other terms often misunderstood and sometimes controversial include "fusion" and "penetration." The definitions distinguish between these as well as "joint geometry," "joint design," "throat of weld," and "size of weld." It is hoped that the definitions in this appendix will make these terms clear.

WELDER, WELDING OPERATOR, AND WELDING MACHINE

The terms "welder" and "welding operator" are applicable to the individual only, and the machine performing the welding operation should be referred to as the "welding machine." The equipment that supplies current for electric welding should be referred to as either a "welding generator" or a "welding transformer." Similar principles apply to the thermal cutting processes.

The use of the term "welder" to indicate a machine that performs the welding operation, or a machine that supplies power for electric welding, or an individual who is capable of performing manual welding operations, leads to considerable confusion in interpretation.

Also, the use of the term "welding operator" to indicate both the operator of a welding machine and the individual who is capable of doing manual welding is somewhat imprecise, since these two individuals do not necessarily have equal welding skill.

There are many proprietary brand and trademark names which are in common use to describe welding processes, equipment, filler metals, and materials. For the most part, however, only generic terms and definitions are used in this appendix as well as in the rest of the *Welding Handbook.*

GLOSSARY

A

abrasion soldering. A soldering method in which the surface of the base metal is mechanically abraded during soldering.

abrasive. Material such as sand, crushed chilled cast iron, crushed steel grit, aluminum oxide, silicon carbide, flint, garnet, or crushed slag used for cleaning or surface roughening.

abrasive blasting. See preferred term **blasting.**

absorptive lens (eye protection). A filter lens whose physical properties are designed to attenuate the effects of glare and reflected and stray light. See also **filter plate.**

accelerating potential. The potential in electron beam welding that imparts the velocity to the electrons, thus, giving them energy.

acceptable weld. A weld that meets all the requirements and the acceptance criteria prescribed by the welding specifications.

acid core solder. See **cored solder.**

activated rosin flux. A rosin or resin base flux containing an additive which increases wetting by the solder.

actual throat. See **throat of a fillet weld.**

adhesive bond. Attractive forces, generally physical in character between an adhesive and the base materials. Two principal interactions that contribute to the adhesion are van der Waals bonds and dipole bonds. See **van der Waals bond** and **permanent dipole bond.**

adhesive bonding (ABD). A materials joining process in which an adhesive, placed between the faying surfaces, solidifies to produce an adhesive bond. See **adhesive bond.**

air acetylene welding (AAW). A fuel gas welding process in which coalescence is produced by heating with a gas flame or flames obtained from the combustion of acetylene with air, without the application of pressure and with or without the use of filler metal. (This process is believed to be of minor industrial significance.)

air cap (thermal spraying). A device for forming, shaping and directing an air pattern for the atomization of wire or ceramic rod.

air carbon arc cutting (AAC). An arc cutting process in which metals to be cut are melted by the heat of a carbon arc and the molten metal is removed by a blast of air.

air feed (thermal spraying). Method by which an air stream carries the powdered material to be sprayed through the gun and into the heat source.

all-weld-metal test specimen. A test specimen with the reduced section composed wholly of weld metal.

alternate polarity operation (resistance welding). A method in which succeeding welds are made with pulses of alternating polarity.

angle of bevel. See preferred term **bevel angle.**

arc blow. The deflection of an electric arc from its normal path because of magnetic forces.

arc brazing (AB). A brazing process in which the heat required is obtained from an electric arc. See **twin carbon arc brazing.**

arc cutting (AC). A group of cutting processes which melts the metals to be cut with the heat of an arc between an electrode and the base metal. See **carbon arc cutting, metal arc cutting, gas metal arc cutting, gas tungsten arc cutting, plasma arc cutting,** and **air carbon arc cutting.** Compare with **oxygen arc cutting.**

arc force. The axial force developed by a plasma.

arc gouging. An arc cutting procedure used to form a bevel or groove.

arc oxygen cutting. See preferred term **oxygen arc cutting.**

arc plasma. See **plasma.**

arc seam weld. A seam weld made by an arc welding process.

arc spot weld. A spot weld made by an arc welding process.

arc time. The time during which an arc is maintained in making an arc weld.

arc voltage. The voltage across the welding arc.

arc welding (AW). A group of welding processes which produces coalescence of metals by heating them with an arc, with or without the application of pressure and with or without the use of filler metal.

arc welding electrode. See **electrode.**

arm (resistance welding). A projecting beam extending from the frame of a resistance welding machine, which transmits the electrode force and may conduct the welding current.

as-brazed. The condition of brazements after brazing, prior to any subsequent thermal, mechanical or chemical treatments.

as-welded. The condition of weld metal, welded joints, and weldments after welding but prior to any subsequent thermal, mechanical, or chemical treatments.

atomic hydrogen welding (AHW). An arc welding process which produces coalescence of metals by heating them with an electric arc maintained between two metal electrodes in an atmosphere of hydrogen. Shielding is obtained from the hydrogen. Pressure may or may not be used and filler metal may or may not be used. (This process is now of limited industrial significance.)

atomization (thermal spraying). The division of molten material at the end of the wire or rod into fine particles.

autogenous weld. A fusion weld made without the addition of filler metal.

automatic brazing. Brazing with equipment which performs the brazing operation without constant observation and adjustment by a brazing operator. The equipment may or may not perform the loading and unloading of the work. See **machine brazing.**

automatic gas cutting. See preferred term **automatic oxygen cutting.**

automatic oxygen cutting. Oxygen cutting with equipment which performs the cutting operation without constant observation and adjustment of the controls by an operator. The equipment may or may not perform loading and unloading of the work. See **machine oxygen cutting.**

automatic welding. Welding with equipment which performs the welding operation without adjustment of the controls by a welding operator. The equipment may or may not perform the loading and unloading of the work. See **machine welding.**

auxiliary magnifier or enlarger (eye protection). An additional lens or plate, associated with eye protection equipment, used to magnify or enlarge the field of vision.

axis of a weld. A line through the length of a weld, perpendicular to and at the geometric center of its cross section. (See Figs. 1, 2, and 3, pp. 326-328.)

B

back bead. See preferred term **back weld.**

backfire. The momentary recession of the flame into the welding tip or cutting tip followed by immediate reappearance or complete extinction of the flame.

back gouging. The removal of weld metal and base metal from the other side of a partially welded joint to assure complete penetration upon subsequent welding from that side.

backhand welding. A welding technique in which the welding torch or gun is directed opposite to the progress of welding. Sometimes referred to as the "pull gun technique" in GMAW and FCAW. See **travel angle, work angle,** and **drag angle.**

backing. A material (base metal, weld metal, carbon, or granular material) placed at the root of a weld joint for the purpose of supporting molten weld metal.

backing bead. See preferred term **backing weld.**

backing filler metal. See **consumable insert.**

backing pass. A pass made to deposit a backing weld.

backing ring. Backing in the form of a ring, generally used in the welding of piping.

backing strap. See preferred term **backing strip.**

backing strip. Backing in the form of a strip.

backing weld. Backing in the form of a weld.

backstep sequence. A longitudinal sequence in which the weld bead increments are deposited in the direction opposite to the progress of welding the joint. See **block sequence, cascade sequence, continuous sequence, joint building sequence,** and **longitudinal sequence.**

backup (flash and upset welding). A locator used to transmit all or a portion of the upsetting force to the workpieces or to aid in preventing the workpieces from slipping during upsetting.

back weld. A weld deposited at the back of a single groove weld.

balling up. The formation of globules of molten brazing filler metal or flux due to lack of wetting of the base material.

bare electrode. See **electrode.**

bare metal arc welding (BMAW). An arc welding process which produces coalescence of metals by heating them with an electric arc between a bare or lightly coated metal electrode and the work. Neither shielding nor pressure is used and filler metal is obtained from the electrode. (This process is now obsolete in industrial applications.)

base metal (material). The metal (material) to be welded, brazed, soldered, or cut. See also **substrate.**

base metal test specimen. A test specimen composed wholly of base metal.

bead. See preferred term **weld bead.**

bead weld. See preferred term **surfacing weld.**

bevel. An angular type of edge preparation.

bevel angle. The angle formed between the prepared edge of a member and a plane perpendicular to the surface of the member.

bit (soldering). That part of the soldering iron, usually made of copper, which actually transfers heat (and sometimes solder) to the joint.

bit soldering. See preferred term **iron soldering.**

blacksmith welding. See preferred term **forge welding.**

blasting. A method of cleaning or surface roughening by a forcibly projected stream of sharp angular abrasive.

blind joint. A joint, no portion of which is visible.

block brazing (BB). A brazing process in which the heat required is obtained from heated blocks applied to the parts to be joined. (This process is not of major industrial significance.)

block sequence. A combined longitudinal and buildup sequence for a continuous multiple pass weld in which separated lengths are completely or partially built up in cross section before intervening lengths are deposited. See **backstep sequence, longitudinal sequence,** etc.

blowhole. See preferred term **porosity.**

blowpipe.

welding and cutting blowpipe. See preferred term **welding torch** or **cutting torch.**

brazing and soldering blowpipe. A device used to obtain a small, accurately directed flame, for fine work, such as in the dental and jewelry trades. Any flame may be used, a portion of it being blown to the desired location for the required time by the blowpipe which is usually mouth operated.

bond. See **adhesive bond, mechanical bond,** and **metallic bond.**

bond coat (thermal spraying). A preliminary (or prime) coat of material which improves adherence of the subsequent thermal spray deposit.

bonding force. The force that holds two atoms together; it results from a decrease in energy as two atoms are brought closer to one another.

bond line. In a weldment, the junction between weld metal (material), brazing filler metal or solder and base material, between thermal spray deposits and substrate, or between base metal (material) parts when filler metal is not used.

bottle. See preferred term **cylinder.**

boxing. The continuation of a fillet weld around a corner of a member as an extension of the principal weld.

brazeability. The capacity of a metal to be brazed under the fabrication conditions imposed into a specific suitably designed structure and to perform satisfactorily in the intended service.

braze. A weld produced by heating an assembly to suitable temperatures and by using a filler metal, having a liquidus above 450 °C (840 °F) and below the solidus of the base materials. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction.

brazement. An assembly whose component parts are joined by brazing.

brazer. One who performs a manual or semiautomatic brazing operation.

braze welding. A method of welding by using a filler metal, having a liquidus above 450 °C (840 °F) and below the solidus of the base metals. Unlike brazing, in braze welding, the filler metal is *not* distributed in the joint by capillary attraction.

brazing (B). A group of welding processes which produces coalescence of materials by heating them to a suitable temperature and by using a filler metal, having a liquidus above 450 °C (840 °F) and below the solidus of the base materials. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction.

brazing alloy. See preferred term **brazing filler metal.**

brazing filler metal. The metal which fills the capillary gap and has a liquidus above 450 °C (840 °F) but below the solidus of the base materials.

brazing operator. One who operates machine or automatic brazing equipment.

brazing procedure. The detailed methods and practices including all joint brazing procedures involved in the production of a brazement. See **joint brazing procedure.**

brazing sheet. Brazing filler metal in sheet form.

brazing technique. The details of a brazing operation which, within the limitations of the prescribed brazing procedure, are controlled by the brazer or the brazing operator.

brazing temperature. The temperature to which the base materials are heated to enable the filler metal to wet the base materials and form a brazed joint.

brazing temperature range. The temperature range within which brazing can be conducted.

bridge size (eye protection). The distance between lenses on the nose side of each eye, expressed in millimetres.

bronze welding. A term erroneously used to denote braze welding. See **braze welding.**

buildup sequence. See **joint buildup sequence.**

burner. See preferred term **oxygen cutter.**

burning. See preferred term **oxygen cutting.**

burning in. See preferred term **flow welding.**

burnoff rate. See preferred term **melting rate.**

burn-thru. A term erroneously used to denote excessive melt-thru or a hole. See **melt-thru.**

burn-thru weld. A term erroneously used to denote a seam weld or spot weld.

buttering. A form of surfacing in which one or more layers of weld metal are deposited on the groove face of one member (for example, a high alloy weld deposit on steel base metal which is to be welded to a dissimilar base metal). The buttering provides a suitable transition weld deposit for subsequent completion of the butt weld.

butt joint. A joint between two members aligned approximately in the same plane. (See Fig. 4, p. 329.)

button. That part of a weld, including all or part of the nugget, which tears out in the destructive testing of spot, seam, or projection welded specimens.

butt weld. An erroneous term for a weld in a butt joint. See **butt joint.**

C

carbon arc cutting (CAC). An arc cutting process in which metals are severed by melting them with the heat of an arc between a carbon electrode and the base metal.

carbon arc welding (CAW). An arc welding process which produces coalescence of metals by heating them with an arc between a carbon electrode and the work. No shielding is used. Pressure and filler metal may or may not be used.

carbon electrode. See **electrode.**

carbonizing flame. See preferred term **reducing flame.**

carburizing flame. See preferred term **reducing flame.**

carrier gas (thermal spraying). The gas used to carry powdered materials from the powder feeder or hopper to the gun.

cascade sequence. A combined longitudinal and buildup sequence during which weld beads are deposited in overlapping layers. See **backstep sequence, block sequence, buildup sequence, longitudinal sequence,** etc.

caulk weld. See preferred term **seal weld.**

ceramic rod flame spray gun. A flame spraying device using heat provided by an oxyfuel gas flame. The material to be sprayed is in ceramic rod form.

ceramic rod flame spraying. A method of flame spraying which provides heat through an oxyfuel gas flame and the material to be sprayed is in ceramic rod form.

chain intermittent fillet welding. Two lines of intermittent fillet welds on a joint in which the fillet weld increments on one side are approximately opposite to those on the other side of the joint.

chamfer. See preferred term **bevel.**

chemical flux cutting (FOC). An oxygen cutting process in which metals are severed using a chemical flux to facilitate cutting.

chill ring. See preferred term **backing ring.**

chill time. See preferred term **quench time.**

circular electrode. See **electrode—resistance welding electrode.**

circular resistance seam welding. See preferred term **transverse resistance seam welding.**

circumferential resistance seam welding. See preferred term **transverse resistance seam welding.**

clad brazing sheet. A metal sheet on which one or both sides are clad with brazing filler metal.

clad metal. A composite metal containing two or three layers that have been welded together. The welding may have been accomplished by roll welding, arc welding, casting, heavy chemical deposition, or heavy electroplating. See **cladding, surfacing.**

cladding. A relatively thick layer (> 1 mm

[0.04 in.]) of material applied by surfacing for the purpose of improved corrosion resistance or other properties (see **coating, surfacing, hardfacing).**

coalescence. The growing together or growth into one body of the materials being welded.

coated electrode. See preferred terms **covered electrode** and **lightly coated electrode.** See **electrode.**

coating. A relatively thin layer (< 1 mm [0.04 in.]) of material applied by surfacing for the purpose of corrosion prevention, resistance to high temperature scaling, wear resistance, lubrication, or other purposes. See **cladding, surfacing,** and **hardfacing.**

coating density (thermal spraying). The ratio of the determined density of a thermal sprayed coating to the theoretical density of the material used in the coating process. Usually expressed as percent of theoretical density.

coil without support. A filler metal package type consisting of a continuous length of electrode in coil form without an internal support. It is appropriately bound to maintain its shape.

coil with support. A filler metal package type consisting of a continuous length of electrode in coil form wound on an internal support which is a simple cylindrical section without flanges.

cold soldered joint. A joint with incomplete coalescence caused by insufficient application of heat to the base metal during soldering.

cold welding (CW). A solid state welding process in which pressure is used at room temperature to produce coalescence of metals with substantial deformation at the weld. Compare **hot pressure welding, diffusion welding,** and **forge welding.**

collar. The reinforcing metal of a nonpressure thermit weld.

collaring (thermal spraying). Adding a shoulder to a shaft or similar component as a protective confining wall for the thermal spray deposit.

commutator-controlled welding (resistance welding). The making of a number of spot or projection welds. Several electrodes, in simultaneous contact with the work, function progressively under the control of an electrical commutating device.

complete fusion. Fusion which has occurred over the entire base material surfaces intended for welding, and between all layers and passes.

complete joint penetration. Joint penetration in which the weld metal completely fills the groove and is fused to the base metal throughout its total thickness.

complete penetration. See preferred term **complete joint penetration.**

composite electrode. See **electrode.**

composite joint. A joint produced by welding used in conjunction with a non-welding process. (See **weldbonding.**)

concave fillet weld. A fillet weld having a concave face.

concave root surface. A root surface which is concave.

concavity. The maximum distance from the face of a concave fillet weld perpendicular to a line joining the toes.

concurrent heating. The application of supplemental heat to a structure during a welding or cutting operation.

cone. The conical part of an oxyfuel gas flame next to the orifice of the tip.

constricted arc (plasma arc welding and cutting). A plasma arc column that is shaped by a constricting nozzle orifice.

constricting nozzle (plasma arc welding and cutting). A water cooled copper nozzle surrounding the electrode and containing the constricting orifice.

constricting orifice (plasma arc welding and cutting). The hole in the constricting nozzle through which the arc passes.

consumable guide electroslag welding. A method of electroslag welding in which filler metal is supplied by an electrode and its guiding member. See **electroslag welding (ESW).**

consumable insert. Preplaced filler metal which is completely fused into the root of the joint and becomes part of the joint.

contact tube. A device which transfers current to a continuous electrode.

continuous sequence. A longitudinal sequence in which each pass is made continuously from one end of the joint to the other. See **backstep sequence, longitudinal sequence,** etc.

continuous weld. A weld which extends continuously from one end of a joint to the other. Where the joint is essentially circular, it extends completely around the joint.

convex fillet weld. A fillet weld having a convex face.

convex root surface. A root surface which is convex.

convexity. The maximum distance from the face of a convex fillet weld perpendicular to a line joining the toes.

cool time (resistance welding). The time interval between successive heat times in multiple-impulse welding or in the making of seam welds.

copper brazing. A term improperly used to denote brazing with a copper filler metal. See preferred terms **furnace brazing** and **braze welding.**

cored solder. A solder wire or bar containing flux as a core.

corner joint. A joint between two members located approximately at right angles to each other. (See Fig. 4, p. 329.)

corona (resistance welding). The area sometimes surrounding the nugget of a spot weld at the faying surfaces which provides a degree of solid state welding.

corrective lens (eye protection). A lens ground to the wearer's individual corrective prescription.

corrosive flux. A flux with a residue that chemically attacks the base metal. It may be composed of inorganic salts and acids, organic salts and acids, or activated rosins or resins.

covalent bond. A primary bond arising from the reduction in energy associated with overlapping half-filled orbitals of two atoms.

CO_2 welding. See preferred term **gas metal arc welding.**

covered electrode. See **electrode.**

cover lens (eye protection). A round cover plate.

cover plate (eye protection). A removable pane of colorless glass, plastic-coated glass, or plastic that covers the filter plate and protects it from weld spatter, pitting, or scratching when used in a helmet, hood, or goggle.

crack. A fracture-type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement.

crater. In arc welding, a depression at the termination of a weld bead or in the molten weld pool.

crater crack. A crack in the crater of a weld bead. (See Chapter 5, Fig. 5.45, p. 211.)

cross wire weld. A weld made between crossed wires or bars.

cup. See preferred term **nozzle.**

cutting attachment. A device for converting an oxyfuel gas welding torch into an oxygen cutting torch.

cutting head. The part of a cutting machine or automatic cutting equipment in which a cutting torch or tip is incorporated.

cutting nozzle. See preferred term **cutting tip.**

cutting process. A process which brings about the severing or removal of metals. See **arc cutting** and **oxygen cutting.**

cutting tip. That part of an oxygen cutting torch from which the gases issue.

cutting torch. A device used in oxygen cutting for controlling and directing the gases used for preheating and the oxygen used for cutting the metal.

cylinder. A portable container used for transportation and storage of a compressed gas.

cylinder manifold. See preferred term **manifold.**

D

defect. A discontinuity or discontinuities which by nature or accumulated effect (for example, total crack length) render a part or product unable to meet minimum applicable acceptance standards or specifications. This term designates rejectability. See **discontinuity** and **flaw.**

defective weld. A weld containing one or more defects.

deposit (thermal spraying). See preferred term **spray deposit.**

deposited metal. Filler metal that has been added during a welding operation.

deposition efficiency (arc welding). The ratio of the weight of deposited metal to the net weight of filler metal consumed, exclusive of stubs.

deposition efficiency (thermal spraying). The ratio usually expressed in percent of the weight of spray deposit to the weight of the material sprayed.

deposition rate. The weight of material deposited in a unit of time. It is usually expressed as kilograms per hour (kg/h) (pounds per hour [lb/h]).

deposition sequence. The order in which the increments of weld metal are deposited. See **longitudinal sequence, buildup sequence,** and **pass sequence.**

deposit sequence. See preferred term **deposition sequence.**

depth of fusion. The distance that fusion extends into the base metal or previous pass from the surface melted during welding.

detonation gun (thermal spraying). The device used in detonation flame spraying.

detonation flame spraying. A method of thermal spraying in which the controlled explosion of a mixture of fuel gas, oxygen, and powdered coating material is utilized to melt and propel the material to the workpiece.

die.

resistance welding die. A member usually shaped to the work contour to clamp the parts being welded and to conduct the welding current.

forge welding die. A device used in forge welding primarily to form the work while hot and apply the necessary pressure.

die welding. See preferred terms **forge welding** and **cold welding.**

diffusion aid. A solid filler metal applied to the faying surfaces to assist in diffusion welding.

diffusion bonding. See preferred term **diffusion welding.**

diffusion brazing (DFB). A brazing process which produces coalescence of metals by heating them to suitable temperatures and by using a filler metal or an *in situ* liquid phase. The filler metal may be distributed by capillary attraction or may be placed or formed at the faying surfaces. The filler metal is diffused with the base metal to the extent that the joint properties have been changed to approach those of the base metal.

diffusion welding (DFW). A solid state welding process which produces coalescence of the faying surfaces by the application of pressure and elevated temperature. The process does not involve macroscopic deformation, melting, or relative motion of parts. A solid filler metal (diffusion aid) may or may not be inserted between the faying surfaces. See also **forge welding, hot pressure welding,** and **cold welding.**

dilution. The change in chemical composition of a welding filler material caused by the admixture of the base material or previously deposited weld material in the deposited weld bead. It is normally measured by the percentage of base material or previously deposited weld material in the weld bead.

dip brazing (DB). A brazing process in which the heat required is furnished by a molten chemical or metal bath. When a molten chemical bath is used, the bath may act as a flux. When a molten metal bath is used, the bath provides the filler metal.

dip soldering (DS). A soldering process in which the heat required is furnished by a molten metal bath which provides the solder filler metal.

direct current electrode negative. The arrangement of direct current arc welding leads in which the work is the positive pole and the electrode is the negative pole of the welding arc. See also **straight polarity.**

direct current electrode positive. The arrangement of direct current arc welding leads in which the work is the negative pole and the electrode is the positive pole of the welding arc. See also **reverse polarity.**

direct current reverse polarity (DCRP). See **reverse polarity** and **direct current electrode positive.**

direct current straight polarity (DCSP). See **straight polarity** and **direct current electrode negative.**

discontinuity. An interruption of the typical structure of a weldment, such as a lack of homogeneity in the mechanical, metallurgical, or physical characteristics of the material or weldment. A discontinuity is not necessarily a defect. See **defect, flaw.**

doped solder. A solder containing a small amount of an element intentionally added to insure retention of one or more characteristics of the materials on which it is used.

double arcing (plasma arc welding and cutting). A condition in which the main arc does not pass through the constricting orifice but transfers to the inside surface of the nozzle. A secondary arc is simultaneously established between the outside surface of the nozzle and the workpiece. Double arcing usually damages the nozzle.

double-bevel-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

double-flare-bevel-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

double-flare-V-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

double-J-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

double-U-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

double-V-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

double-welded joint. In arc and oxyfuel gas welding, any joint welded from both sides.

dovetailing (thermal spraying). A method of surface roughening involving angular undercutting to interlock the spray deposit.

downhand. See preferred term **flat position.**

downslope time (resistance welding). The time during which the welding current is continuously decreased.

drag (thermal cutting). The offset distance between the actual and the theoretical exit points of the cutting oxygen stream measured on the exit surface of the material.

drag angle. The travel angle when the electrode is pointing backward. See also **backhand welding.**

Note: This angle can be used to define the position of welding guns, welding torches, high energy beams, welding rods, thermal cutting and thermal spraying torches, and thermal spraying guns.

drop-thru. An undesirable sagging or surface irregularity, usually encountered when brazing or welding near the solidus of the base metal caused by overheating with rapid diffusion or alloying between the filler metal and the base metal.

drum. A filler metal package type consisting of a continuous length of electrode wound or coiled within an enclosed cylindrical container.

duty cycle. The percentage of time during an arbitrary test period, usually 10 min, during which a power supply can be operated at its rated output without overloading.

dynamic electrode force. See **electrode force.**

E

edge joint. A joint between the edges of two or more parallel or nearly parallel members. (See Fig. 4, p. 329.)

edge preparation. The surface prepared on the edge of a member for welding.

edge weld. A weld in an edge joint. (See Fig. 4, p. 329.)

effective length of weld. The length of weld throughout which the correctly proportioned cross section exists. In a curved weld, it shall be measured along the axis of the weld.

effective throat. The minimum distance from the root of a weld to its face less any reinforcement.

electric arc gun (thermal spraying). A device where the material to be sprayed is in the form of two consumable electrodes. An arc is struck and maintained between the ends of the two electrodes, and provides the heat for melting.

electric arc spraying (EASP) (thermal spraying). A process using as a heat source, an electric arc between two consumable electrodes of a coating material, and a compressed gas which is used to atomize and propel the material to the substrate.

electric bonding (thermal spraying). See preferred term **surfacing.**

electric brazing. See preferred terms **resistance brazing** and **arc brazing.**

electrode.

arc welding electrode. A component of the welding circuit through which current is conducted between the electrode holder and the arc. See **arc welding.**

bare electrode. A filler metal electrode consisting of a single metal or alloy that has been produced into a wire, strip, or bar form and that has had no coating or covering applied to it other than that which was incidental to its manufacture or preservation.

carbon electrode. A non-filler material electrode used in arc welding or cutting, consisting of a carbon or graphite rod, which may be coated with copper or other coatings.

composite electrode. Any of a number of multicomponent filler metal electrodes in various physical forms such as stranded wires, tubes, and covered wire.

covered electrode. A composite filler metal electrode consisting of a core of a bare electrode or metal cored electrode to which a covering sufficient to provide a slag layer on the weld metal has been applied. The covering may contain materials providing such functions as shielding from the atmosphere, deoxidation, and arc stabilization and can serve as a source of metallic additions to the weld.

flux cored electrode. A composite filler metal electrode consisting of a metal tube or other hollow configuration containing ingredients to provide such functions as shielding atmosphere, deoxidation, arc stabilization and slag formation. Alloying materials may be included in the core. External shielding may or may not be used.

metal cored electrode. A composite filler metal electrode consisting of a metal tube or other hollow configuration containing alloying ingredients. Minor amounts of ingredients providing such functions as arc stabilization and fluxing of oxides may be included. External shielding gas may or may not be used.

stranded electrode. A composite filler metal electrode consisting of stranded wires which may mechanically enclose materials to improve properties, stabilize the arc, or provide shielding.

emissive electrode. A filler metal electrode consisting of a core of a bare electrode or a composite electrode to which a very light coating has been applied to produce a stable arc.

lightly coated electrode. A filler metal electrode consisting of a metal wire with a light coating applied subsequent to the drawing operation, primarily for stabilizing the arc.

metal electrode. A filler or non-filler metal electrode, used in arc welding or cutting, consisting of a metal wire or rod that has been manufactured by any method and that is either bare or covered with a suitable covering or coating.

tungsten electrode. A non-filler metal electrode used in arc welding or cutting, made principally of tungsten.

electroslag welding electrode. A filler metal component of the welding circuit through which current is conducted between the electrode guiding member and the molten slag.

Note: Bare electrodes and composite electrodes as defined under "arc welding electrode" are used for electroslag welding. A consumable guide may also be used as part of the electroslag welding electrode system.

resistance welding electrode. The part or parts of a resistance welding machine through which the welding current and, in most cases, pressure, are applied directly to the work. The electrode may be in the form of a rotating wheel, rotating roll, bar, cylinder, plate, clamp, chuck, or modification thereof. See **resistance welding.**

electrode extension (gas metal arc welding, flux cored arc welding, submerged arc welding). The length of unmelted electrode extending beyond the end of the contact tube during welding.

electrode force.

dynamic electrode force (resistance welding). The force in newtons (pounds force) between the electrodes during the actual welding cycle in making spot, seam, or projection welds by resistance welding.

static electrode force (resistance welding). The force between the electrodes in making spot, seam, or projection welds by resistance welding under welding conditions, but with no current flowing and no movement in the welding machine.

theoretical electrode force (resistance welding). The force, neglecting friction and inertia, in making spot, seam, or projection welds by resistance welding, available at the electrodes of a resistance welding machine by virtue of the initial force application and the theoretical mechanical advantage of the system.

electrode holder. A device used for mechanically holding the electrode while conducting current to it.

electrode lead. The electrical conductor between the source of arc welding current and the electrode holder.

electrode setback (plasma arc welding and cutting). The distance the electrode is recessed behind the constricting orifice measured from the outer face of the nozzle.

electrode skid (resistance welding). The sliding of an electrode along the surface of the work during the making of spot, seam, or projection welds by resistance welding.

electrogas welding. See preferred terms **gas metal arc welding-electrogas** and **flux cored arc welding-electrogas.**

electron beam cutting (EBC). A cutting process which uses the heat obtained from a concentrated beam composed primarily of high velocity electrons which impinge upon the workpieces to be cut; it may or not use an externally supplied gas.

electron beam welding (EBW). A welding process which produces coalescence of metals with the heat obtained from a con-

electron beam welding (EBW). A welding process which produces coalescence of metals with the heat obtained from a concentrated beam composed primarily of high velocity electrons impinging upon the surfaces to be joined.

electronic heat control (resistance welding). A device for adjusting the heating value (rms value) of the current in making a resistance weld by controlling the ignition or firing of the electronic devices in an electronic contactor. The current is initiated each half-cycle at an adjustable time with respect to the zero point on the voltage wave.

electroslag welding (ESW). A welding process producing coalescence of metals with molten slag which melts the filler metal and the surfaces of the work to be welded. The molten weld pool is shielded by this slag which moves along the full cross section of the joint as welding progresses. The process is initiated by an arc which heats the slag. The arc is then extinguished and the conductive slag is maintained in a molten condition by its resistance to electric current passing between the electrode and the work. See **electroslag welding electrode** and **consumable guide electroslag welding.**

electroslag welding electrode. See **electrode.**

end return. See preferred term **boxing.**

erosion (brazing). A condition caused by dissolution of the base material by molten filler metal resulting in a postbraze reduction in the thickness of the base material. (See Chapter 5, Fig. 5.36d, p. 202.)

exhaust booth. A mechanically ventilated, semi-enclosed area in which an air flow across the work area is used to remove fumes, gases, and material particles.

explosion welding (EXW). A solid state welding process in which coalescence is effected by high-velocity movement together of parts to be joined produced by a controlled detonation.

eye size (eye protection). The nominal size of the lens-holding section of an eye frame expressed in millimetres.

F

face feed. The application of filler metal to the joint, usually by hand, during brazing and soldering.

face of weld. The exposed surface of a weld on the side from which welding was done. (See Fig. 6, p. 331.)

face reinforcement. Reinforcement of weld at the side of the joint from which welding was done. See also **root reinforcement.**

face shield (eye protection). A device positioned in front of the eyes and a portion of, or all of, the face, whose predominant function is protection of the eyes and face. See also **hand shield** and **helmet.**

faying surface. That mating surface of a member which is in contact or in close proximity with another member to which it is to be joined.

feed rate (thermal spraying). The rate at which a material passes through the gun in a unit of time. A synonym for **spray rate.**

ferrite number. An arbitrary, standardized value designating the ferrite content of an austenitic stainless steel weld metal. It should be used in place of percent ferrite or volume percent ferrite on a direct one to one replacement basis. See the latest edition of AWS A4.2, Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic Stainless Steel Weld Metal.

filler metal (material). The metal (material) to be added in making a welded, brazed, or soldered joint. See **electrode, welding rod, backing filler metal, brazing filler metal, diffusion aid, solder,** and **spray deposit.**

fillet weld. A weld of approximately triangular cross section joining two surfaces approximately at right angles to each other in a lap joint, T-joint or corner joint.

fillet weld size. See preferred term **size of weld.**

filter glass. See preferred term **filter plate.**

filter lens (eye protection). A round filter plate.

filter plate (eye protection). An optical material which protects the eyes against excessive ultraviolet, infrared, and visible radiation.

fines. Any or all material finer than a particular mesh under consideration.

fissure. A small crack-like discontinuity with only slight separation (opening displacement) of the fracture surfaces. The prefixes macro or micro indicate relative size.

fixture. A device designed to hold parts to be joined in proper relation to each other.

flame cutting. See preferred term **oxygen cutting.**

flame spraying (FLSP). A thermal spraying process in which an oxyfuel gas flame is the source of heat for melting the coating material. Compressed gas may or may not be used for atomizing and propelling the material to the substrate.

flange weld. A weld made on the edges of two or more members to be joined, at least one of which is flanged.

flare-bevel-groove weld. See **single-flare-bevel-groove weld** and **double-flare-bevel-groove weld.** (See Fig. 5, p. 330.)

flare-V-groove weld. See **single-flare-V-groove weld** and **double-flare-V-groove weld.** (See Fig. 5, p. 330.)

flash. The material which is expelled or squeezed out of a weld joint and which forms around the weld.

flashback. A recession of the flame into or back of the mixing chamber of the torch.

flashback arrester. A device to limit damage from a flashback by preventing propagation of the flame front beyond the point at which the arrester is installed.

flash coat. A thin coating usually less than 0.05 mm (0.002 in.) in thickness.

flash butt welding. See preferred term **flash welding.**

flashing time. The time during which the flashing action is taking place in flash welding.

flash-off time. See preferred term **flashing time.**

flash weld. A weld made by flash welding.

flash welding (FW). A resistance welding process which produces coalescence simultaneously over the entire area of abutting surfaces, by the heat obtained from resistance to electric current between the two surfaces, and by the application of pressure after heating is substantially completed. Flashing and upsetting are accompanied by expulsion of metal from the joint.

flat position. The welding position used to weld from the upper side of the joint; the face of the weld is approximately horizontal. (See Figs. 1, 2, and 3, pp. 326-328.)

flaw. A near synonym for **discontinuity** but with an undesirable connotation. See **defect, discontinuity.**

flowability. The ability of molten filler metal to flow or spread over a metal surface.

flow brazing (FLB). A brazing process which produces coalescence of metals by heating them with molten nonferrous filler metal poured over the joint until brazing temperature is attained. The filler metal is distributed in the joint by capillary attraction. (This process is not often used industrially.)

flow brightening (soldering). Fusion (melting) of a chemically or mechanically deposited metallic coating on a substrate.

flow welding (FLOW). A welding process which produces coalescence of metals by heating them with molten filler metal, poured over the surfaces to be welded until the welding temperature is attained and until the required filler metal has been added. The filler metal is not distributed in the joint by capillary attraction. (This process is of little industrial significance.)

flux. Material used to prevent, dissolve, or facilitate removal of oxides and other undesirable surface substances.

flux cored arc welding (FCAW). An arc welding process which produces coalescence of metals by heating them with an arc between a continuous filler metal (consumable) electrode and the work. Shielding is provided by a flux contained within the tubular electrode. Additional shielding may or may not be obtained from an externally supplied gas or gas mixture. See **flux cored electrode.**

flux cored arc welding-electrogas (FCAW-EG). A variation of the flux cored arc welding process in which molding shoes are used to confine the molten weld metal for vertical position welding. Additional shielding may or may not be obtained from an externally supplied gas or gas mixture.

flux cored electrode. See **electrode.**

flux cover. In metal bath dip brazing and dip soldering a cover of flux over the molten filler metal bath.

flux oxygen cutting. See preferred term **chemical flux cutting.**

focal point. See preferred term **focal spot.**

focal spot (electron beam welding and laser beam welding). A spot at which an energy beam has the most concentrated energy level and the smallest cross sectional area.

forehand welding. A welding technique in which the welding torch or gun is directed toward the progress of welding. See also **travel angle, work angle, push angle.**

forge-delay time (resistance welding). The time elapsing between the beginning of weld time or weld interval and the instant of application of forging force to the electrodes.

forge welding (FOW). A solid state welding process which produces coalescence of metals by heating them in air in a forge and by applying pressure or blows sufficient to cause permanent deformation at the interface. Compare **cold welding, roll welding, diffusion welding,** and **hot pressure welding.**

friction soldering. See preferred term **abrasion soldering.**

friction welding (FRW). A solid state welding process which produces coalescence of materials by the heat obtained from a mechanically induced sliding motion between rubbing surfaces. The work parts are held together under pressure.

fuel gases. Gases usually used with oxygen for heating such as acetylene, natural gas, hydrogen, propane, methylacetylene propadiene, and other synthetic fuels and hydrocarbons.

full fillet weld. A fillet weld whose size is equal to the thickness of the thinner member joined.

furnace brazing (FB). A brazing process in which the parts to be joined are placed in a furnace heated to a suitable temperature.

furnace soldering (FS). A soldering process in which the parts to be joined are placed in a furnace heated to a suitable temperature.

fused spray deposit (thermal spraying). A self-fluxing spray deposit which is subsequently heated to coalescence within itself and with the substrate.

fused zone. See preferred terms **fusion zone, nugget** and **bond line.**

fusing (thermal spraying). See preferred term **fusion.**

fusion. The melting together of filler metal and base metal (substrate), or of base metal only, which results in coalescence. See **depth of fusion.**

fusion face. A surface of the base metal which will be melted during welding.

fusion welding. Any welding process or method which uses fusion to complete the weld.

fusion zone. The area of base metal melted as determined on the cross section of a weld.

G

gas brazing. See preferred term **torch brazing.**

gas carbon arc welding (CAW-G). A carbon arc welding process variation which produces coalescence of metals by heating them with an electric arc between a single carbon electrode and the work. Shielding is obtained from a gas or gas mixture. (This process is not believed to be of major industrial significance.)

gas cutter. See preferred term **oxygen cutter.**

gas cutting. See preferred term **oxygen cutting.**

gas gouging. See preferred term **oxygen gouging.**

gas metal arc cutting (GMAC). An arc cutting process used to sever metals by melting them with the heat of an arc between a continuous metal (consumable) electrode and the work. Shielding is obtained entirely from an externally supplied gas or gas mixture.

gas metal arc welding (GMAW). An arc welding process which produces coalescence of metals by heating them with an arc between a continuous filler metal (consumable) electrode and the work. Shielding is obtained entirely from an externally supplied gas or gas mixture. Some methods of this process are called MIG or CO_2 welding.

gas metal arc welding-electrogas (GMAW-EG). A variation of the gas metal arc welding process using molding shoes to confine the molten weld metal for vertical position welding.

gas metal arc welding-pulsed arc (GMAW-P). A variation of the gas metal arc welding process in which the current is pulsed. See also **pulsed power welding.**

gas metal arc welding-short circuiting arc (GMAW-S). A variation of the gas metal arc welding process in which the consumable electrode is deposited during repeated short circuits. See also **short circuiting transfer.**

gas pocket. See preferred term **porosity.**

gas regulator. See preferred term **regulator.**

gas shielded arc welding. A general term used to describe gas metal arc welding, gas tungsten arc welding, and flux cored arc welding when gas shielding is employed.

gas shielded stud welding. See **stud arc welding.**

gas torch. See preferred terms **welding torch** and **cutting torch.**

gas tungsten arc cutting (GTAC). An arc cutting process in which metals are severed by melting them with an arc between a single tungsten (nonconsumable) electrode and the work. Shielding is obtained from a gas or gas mixture.

gas tungsten arc welding (GTAW). An arc welding process which produces coalescence of metals by heating them with an arc between a tungsten (nonconsumable) electrode and the work. Shielding is obtained from a gas or gas mixture. Pressure may or may not be used and filler metal may or may not be used. (This process has sometimes been called TIG welding.)

gas tungsten arc welding-pulsed arc (GTAW-P). A variation of the gas tungsten arc welding process in which the current is pulsed. See also **pulsed power welding.**

gas welding. See preferred term **oxyfuel gas welding (OFW).**

globular transfer (arc welding). A type of metal transfer in which molten filler metal is transferred across the arc in large droplets.

gouging. The forming of a bevel or groove by material removal. See also **back gouging, arc gouging,** and **oxygen gouging.**

gradated coating. A thermal sprayed deposit composed of mixed materials in successive layers which progressively change in composition from the constituent material of the substrate to the surface of the sprayed deposit.

grit. See preferred term **abrasive.**

groove. An opening or channel in the surface of a part or between two components which provides space to contain a weld.

groove and rotary roughening (thermal spraying). A method of surface roughening in which grooves are made and the original surface roughened and spread.

groove angle. The total included angle of the groove between parts to be joined by a groove weld.

groove face. That surface of a member included in the groove. (See Fig. 7, p. 332.)

groove radius. The radius used to form the shape of a J- or U- groove weld joint.

groove type. The geometric configuration of a groove.

groove weld. A weld made in the groove between two members to be joined. The standard types of groove welds are as follows (See Fig. 5, p. 330):

double-bevel-groove weld
double-flare-bevel-groove weld
double-flare-V-groove weld
double-J-groove weld
double-U-groove weld
double-V-groove weld
single-bevel-groove weld
single-flare-bevel-groove weld
single-flare-V-groove weld
single-J-groove weld

single-U-groove weld
single-V-groove weld
square-groove weld

ground connection. An electrical connection of the welding machine frame to the earth for safety. See also **work connection** and **work lead.**

ground lead. See preferred term **work lead.**

gun.

arc welding gun. In semiautomatic, machine, and automatic welding, a manipulating device to transfer current and guide the electrode into the arc. It may include provisions for shielding and arc initiation.

resistance welding gun. A manipulating device to transfer current and provide electrode force to the weld area (usually in reference to a portable gun).

thermal spraying gun. A thermal spraying device.

gun extension (thermal spraying). The extension tube attached in front of the thermal spraying device to permit spraying within confined areas or deep recesses.

H

hammer welding. See preferred terms **forge welding** and **cold welding.**

hand shield. A protective device, used in arc welding, for shielding the eyes, face, and neck. A hand shield is equipped with a suitable filter plate and is designed to be held by hand.

hard facing. A particular form of surfacing in which a coating or cladding is applied to a substrate for the main purpose of reducing wear or loss of material by abrasion, impact, erosion, galling, and cavitation. See **coating, cladding,** and **surfacing.**

hard solder. A term erroneously used to denote silver-base brazing filler metals.

hard surfacing. See preferred terms **surfacing** or **hard facing.**

head. See **welding head** and **cutting head.**

heat-affected zone. That portion of the base metal which has not been melted, but whose mechanical properties or microstructure have been altered by the heat of welding, brazing, soldering, or cutting. (See Chapter 2, Fig. 2.1, p. 37.)

heating gate. The opening in a thermit mold through which the parts to be welded are preheated.

heat time (resistance welding). The duration of current flow during any one impulse in multiple-impulse welding, or the duration of current flow when making a simple welding cycle.

helmet (eye protection). A protection device, used in arc welding, for shielding the eyes, face, and neck. A helmet is equipped with a suitable filter plate and is designed to be worn on the head.

high frequency resistance welding (HFRW). A resistance welding process which produces coalescence of metals with the heat generated from the resistance of the workpieces to a high frequency alternating current in the 10 to 500 kHz range and the rapid application of an upsetting force after heating is substantially completed. The path of the current in the work-piece is controlled by the use of the proximity effect (the feed current follows closely the return current conductor).

hold time (resistance welding). The duration of force application at the point of welding after the last impulse of current ceases.

holding time. In brazing and soldering, the amount of time a joint is held within a specified temperature range.

horizontal fixed position (pipe welding). In pipe welding the position of a pipe joint in which the axis of the pipe is approximately horizontal and the pipe is not rotated during welding. (See Fig. 1, p. 326-327.)

horizontal position.

fillet weld. The position in which welding is performed on the upper side of an approximately horizontal surface and against an approximately vertical surface. (See Figs. 1 and 3, pp. 326-328.)

groove weld. The position of welding in which the axis of the weld lies in an approximately horizontal plane and the face of the weld lies in an approximately vertical plane. (See Figs. 1 and 2, pp. 326-328.)

horizontal rolled position (pipe welding). The position of a pipe joint in which the axis of the pipe is approximately horizontal, and welding is performed in the flat position by rotating the pipe. (See Fig. 1, pp. 326-327.)

horn (resistance welding). An essentially cylindrical arm or extension of an arm of a resistance welding machine which transmits the electrode force and usually conducts the welding current. See **Arm.**

horn spacing (resistance welding). The distance between adjacent surfaces of the horns of a resistance welding machine.

hot isostatic pressure welding. A diffusion welding method which produces coalescence of materials by heating and applying hot inert gas under pressure.

hot pressure welding (HPW). A solid state welding process which produces coalescence of materials with heat and application of pressure sufficient to produce macrodeformation of the base material. Vacuum or other shielding media may be used. See also **forge welding** and **diffusion welding.**

hydrogen brazing. A term erroneously used to denote any brazing process which takes place in a hydrogen or hydrogen-containing atmosphere.

hydromatic welding. See preferred term **pressure-controlled welding.**

I

impulse (resistance welding). An impulse of welding current consisting of a single pulse or a series of pulses, separated only by an interpulse time.

inadequate joint penetration. Joint penetration which is less than that specified.

included angle. See preferred term **groove angle.**

incomplete fusion. Fusion which is less than complete. (See Chapter 5, Figs. 5.42, 5.43, and 5.44, p. 210.)

indentation. In a spot, seam, or projection weld, the depression on the exterior surface or surfaces of the base metal.

induction brazing (IB). A brazing process in which the heat required is obtained from the resistance of the work to induced electric current.

induction soldering (IS). A soldering process in which the heat required is obtained from the resistance of the work to induced electric current.

induction welding (IW). A welding process which produces coalescence of metals through the heat obtained from resistance of the work to induced electric current, with or without the application of pressure.

induction work coil. See preferred term **work coil.**

inert gas. A gas which does not normally combine chemically with the base metal or filler metal. See also **protective atmosphere.**

inert-gas metal arc welding. See preferred term **gas metal arc welding.**

inert-gas tungsten arc welding. See preferred term **gas tungsten arc welding.**

infrared brazing (IRB). A brazing process in which the heat required is furnished by infrared radiation.

infrared radiation. Electromagnetic energy with wavelengths from 770 to 12 000 nanometres.

infrared soldering (IRS). A soldering process in which the heat required is furnished by infrared radiation.

intergranular penetration. The penetration of a filler metal along the grain boundaries of a base metal.

intermediate flux. A soldering flux with a residue that generally does not attack the base metal. The original composition may be corrosive.

intermittent weld. A weld in which the continuity is broken by recurring unwelded spaces.

interpass temperature. In a multiple-pass weld, the temperature (minimum or maximum as specified) of the deposited weld metal before the next pass is started.

interpulse time (resistance welding). The time between successive pulses of current within the same impulse.

interrupted spot welding. See preferred term **multiple impulse welding.**

ionic bond. A primary bond arising from the electrostatic attraction between two oppositely charged ions.

iron soldering (INS). A soldering process in which the heat required is obtained from a soldering iron.

J

joint. The junction of members or the edges of members which are to be joined or have been joined. (See Fig. 4, p. 329.)

joint brazing procedure. The materials, detailed methods, and practices employed in the brazing of a particular joint.

joint buildup sequence. The order in which the weld beads of a multiple-pass weld are deposited with respect to the cross section of the joint. See **block sequence** and **longitudinal sequence.**

joint clearance. The distance between the faying surfaces of a joint. In brazing this distance is referred to as that which is present either before brazing, at the brazing temperature, or after brazing is completed.

joint design. The joint geometry together with the required dimensions of the welded joint.

joint efficiency. The ratio of the strength of a joint to the strength of the base metal (expressed in percent).

joint geometry. The shape and dimensions of a joint in cross section prior to welding.

joint penetration. The minimum depth a groove or flange weld extends from its face into a joint, exclusive of reinforcement. Joint penetration may include root penetration. See also **complete joint penetration, root penetration,** and **effective throat.**

joint welding procedure. The materials, detailed methods, and practices employed in the welding of a particular joint.

joint welding sequence. See preferred term **joint buildup sequence.**

K

kerf. The width of the cut produced during a cutting process.

keyhole. A technique of welding in which a concentrated heat source penetrates completely through a workpiece forming a hole at the leading edge of the molten weld metal. As the heat source progresses, the molten metal fills in behind the hole to form the weld bead.

keying (thermal spraying). See preferred term **mechanical bond.**

knee (resistance welding). The lower arm supporting structure in a resistance welding machine.

knurling (thermal spraying). See preferred terms **rotary roughening, groove and rotary roughening,** and **threading and knurling.**

L

lack of fusion. See preferred term **incomplete fusion.**

lack of joint penetration. See preferred term **inadequate joint penetration.**

lap joint. A joint between two overlapping members. (See Fig. 4, p. 329.)

land. See preferred term **root face.**

laser beam cutting (LBC). A cutting process which severs materials with the heat obtained from the application of a concentrated coherent light beam impinging on the workpiece to be cut. The process can be used with or without an externally supplied gas.

laser beam welding (LBW). A welding process which produces coalescence of materials with the heat obtained from the application of a concentrated coherent light beam impinging upon the members to be joined.

layer. A stratum of weld metal or surfacing material. The layer may consist of one or more weld beads laid side by side.

lead angle. See preferred term **travel angle.**

lead burning. An erroneous term used to denote the welding of lead.

leg of a fillet weld. The distance from the root of the joint to the toe of the fillet weld.

lens. See preferred term **filter lens.**

lightly coated electrode. See **electrode.**

liquation. The separation of a low melting constituent of an alloy from the remaining constituents, usually apparent in alloys having a wide melting range.

liquidus. The lowest temperature at which a metal or an alloy is completely liquid.

local preheating. Preheating a specific portion of a structure.

local stress relief heat treatment. Stress relief heat treatment of a specific portion of a structure.

locked-up stress. See preferred term **residual stress.**

longitudinal resistance seam welding. The making of a resistance seam weld in a direction essentially parallel to the throat depth of a resistance welding machine.

longitudinal sequence. The order in which the increments of a continuous weld are deposited with respect to its length. See **backstep sequence, block sequence,** etc.

low frequency cycle (resistance welding). One positive and one negative pulse of current within the same weld or heat time at a frequency lower than the power supply frequency from which it is obtained.

M

machine brazing. Brazing with equipment which performs the brazing operation under the constant observation and control of a brazing operator. The equipment may or may not perform the loading and unloading of the work. See **automatic brazing.**

machine oxygen cutting. Oxygen cutting with equipment which performs the cutting operation under the constant observation and control of an oxygen cutting operator. The equipment may or may not perform the loading and unloading of the work. See **automatic oxygen cutting.**

machine welding. Welding with equipment which performs the welding operation under the constant observation and control of a welding operator. The equipment may or may not perform the loading and unloading of the work. See **automatic welding.**

manifold. A multiple header for interconnection of gas or fluid sources with distribution points.

manual brazing. A brazing operation performed and controlled completely by hand. See **automatic brazing** and **machine brazing.**

manual oxygen cutting. A cutting operation performed and controlled completely by hand. See **automatic oxygen cutting** and **machine oxygen cutting.**

manual welding. A welding operation performed and controlled completely by hand. See **automatic welding, machine welding,** and **semiautomatic welding.**

mash resistance seam weld. A resistance seam weld made in a lap joint in which the thickness at the lap is reduced plastically to approximately the thickness of one of the lapped parts.

mask (thermal spraying). A device for protecting a surface from the effects of blasting or coating adherence or coalescence with the substrate. Masks are generally of two types: reusable or disposable.

matrix (thermal spraying). The major continuous substance of a thermal sprayed coating as opposed to inclusions or particles of materials having dissimilar characteristics.

mechanical bond (thermal spraying). The adherence of a thermal sprayed deposit to a roughened surface by the mechanism of particle interlocking.

melting range. The temperature range between solidus and liquidus.

melting rate. The weight or length of electrode melted in a unit of time.

melt-thru. Complete joint penetration for a joint welded from one side. Visible root reinforcement is produced.

metal arc cutting (MAC). Any of a group of arc cutting processes which sever metals by melting them with the heat of an arc between a metal electrode and the base metal. See **shielded metal arc cutting** and **gas metal arc cutting.**

metal arc welding. See **shielded metal arc welding, flux cored arc welding, gas metal arc welding, gas tungsten arc welding, submerged arc welding, plasma arc welding** and **stud arc welding.**

metal cored electrode. See **electrode.**

metal electrode. See **electrode.**

metallic bond. The principal bond which holds metals together and which is formed between base metals and filler metals in all welding processes. This is a primary bond arising from the increased spatial extension of the valence electron wave functions when an aggregate of metal atoms is brought close together. See **bonding force, covalent bond, ionic bond.**

metallizing. See preferred term **thermal spraying.**

metallurgical bond. See preferred term **metallic bond.**

metal powder cutting (POC). An oxygen cutting process which severs metals through the use of powder, such as iron, to facilitate cutting.

method. An orderly arrangement or set form of procedure to be used in the application of welding or allied processes.

MIG welding. See preferred terms **gas metal arc welding, flux cored arc welding.**

mixing chamber. That part of a welding or cutting torch in which a fuel gas and oxygen are mixed.

molten chemical-bath dip brazing. A method of dip brazing.

molten metal-bath dip brazing. A method of dip brazing.

molten metal flame spraying. A method of flame spraying in which the metallic material to be sprayed is in the molten condition.

molten weld pool. The liquid state of a weld prior to solidification as weld metal.

multiple-impulse welding (resistance welding). The making of welds by more than one impulse of current.

multiple-impulse weld timer (resistance welding). A device for multiple-impulse welding which controls only the heat time, the cool time, and the weld interval or the number of heat times.

multiport nozzle (plasma arc welding and cutting). A constricting nozzle containing two or more orifices located in a configuration to achieve a degree of control over the arc shape.

N

neutral flame. An oxyfuel gas flame in which the portion used is neither oxidizing nor reducing.

noncorrosive flux. A soldering flux which in neither its original nor residual form chemically attacks the base metal. It usually is composed of rosin or resin base materials.

nonsynchronous initiation (resistance welding). The initiation or termination of the welding transformer primary current at any random time with respect to the voltage wave.

nonsynchronous timing. See preferred term **nonsynchronous initiation.**

nontransferred arc (plasma arc welding and cutting, and thermal spraying). An arc established between the electrode and the constricting nozzle. The workpiece is not in the electrical circuit. See **transferred arc.**

nozzle. A device which directs shielding media.

nugget (resistance welding). The weld metal joining the parts in spot, roll spot, seam, or projection welds.

nugget size. The diameter or width of the nugget measured in the plane of the interface between the pieces joined.

O

off time (resistance welding). The time during which the electrodes are off the work. This term is generally used when the welding cycle is repetitive.

open-circuit voltage. The voltage between the output terminals of the welding machine when no current is flowing in the welding circuit.

orifice gas (plasma arc welding and cutting). The gas that is directed into the torch to surround the electrode. It becomes ionized in the arc to form the plasma, and issues from the orifice in the torch nozzle as the plasma jet.

orifice throat length (plasma arc welding and cutting). The length of the constricting orifice.

oven soldering. See preferred term **furnace soldering.**

overhead position. The position in which welding is performed from the underside of the joint. (See Figs. 1, 2, and 3, pp. 326-328).

overlap. The protrusion of weld metal beyond the toe, face, or root of the weld; in resistance seam welding, the area in the preceding weld remelted by the succeeding weld. (See Chapter 5, Figs. 5.46 and 5.47, p. 212.)

overlaying. See preferred term **surfacing.**

oxidizing flame. An oxyfuel gas flame having an oxidizing effect (excess oxygen).

oxyacetylene cutting (OFC-A). An oxyfuel gas cutting process used to sever metals by means of the chemical reaction of oxygen with the base metal at elevated temperatures. The necessary temperature is maintained by gas flames resulting from the combustion of acetylene with oxygen.

oxyacetylene welding (OAW). An oxyfuel gas welding process which produces coalescence of metals by heating them with a gas flame or flames obtained from the combustion of acetylene with oxygen. The process may be used with or without the application of pressure and with or without the use of filler metal.

oxyfuel gas cutting (OFC). A group of cutting processes used to sever metals by means of the chemical reaction of oxygen with the base metal at elevated temperatures. The necessary temperature is maintained by means of gas flames obtained from the combustion of a specified fuel gas and oxygen. See **oxygen cutting, oxyacetylene cutting, oxyhydrogen cutting, oxynatural gas cutting,** and **oxypropane cutting.**

oxyfuel gas welding (OFW). A group of welding processes which produces coalescence by heating materials with an oxyfuel gas flame or flames, with or without the application of pressure and with or without the use of filler metal.

oxyfuel gas spraying. See preferred term **flame spraying.**

oxygas cutting. See preferred term **oxygen cutting.**

oxygen arc cutting (AOC). An oxygen cutting process used to sever metals by means of the chemical reaction of oxygen with the base metal at elevated temperatures. The necessary temperature is maintained by an arc between a consumable tubular electrode and the base metal.

oxygen cutter. One who performs a manual oxygen cutting operation.

oxygen cutting (OC). A group of cutting processes used to sever or remove metals by means of the chemical reaction of oxygen with the base metal at elevated temperatures. In the case of oxidation-resistant metals the reaction is facilitated by the use of a chemical flux or metal powder. See **oxygen arc cutting, oxyfuel gas cutting, oxygen lance cutting, chemical flux cutting,** and **metal powder cutting.**

oxygen cutting operator. One who operates machine or automatic oxygen cutting equipment.

oxygen gouging. An application of oxygen cutting in which a bevel or groove is formed.

oxygen grooving. See preferred term **oxygen gouging.**

oxygen lance. A length of pipe used to convey oxygen to the point of cutting in oxygen lance cutting.

oxygen lance cutting (LOC). An oxygen cutting process used to sever metals with oxygen supplied through a consumable lance; the preheat to start the cutting is obtained by other means.

oxygen lancing. See preferred term **oxygen lance cutting.**

oxyhydrogen cutting (OFC-H). An oxyfuel gas cutting process used to sever metals by means of the chemical reaction of oxygen with the base metal at elevated temperatures. The necessary temperature is maintained by gas flames resulting from the combustion of hydrogen with oxygen.

oxyhydrogen welding (OHW). An oxyfuel gas welding process which produces coalescence of materials by heating them with a gas flame or flames obtained from the combustion of hydrogen with oxygen, without the application of pressure and with or without the use of filler metal.

oxynatural gas cutting (OFC-N). An oxyfuel gas cutting process used to sever metals by means of the chemical reaction of oxygen with the base metal at elevated temperatures. The necessary temperature is maintained by gas flames resulting from the combustion of natural gas with oxygen.

oxypropane cutting (OFC-P). An oxyfuel gas cutting process used to sever metals by means of the chemical reaction of oxygen with the base metal at elevated temperatures. The necessary temperature is maintained by gas flames resulting from the combustion of propane with oxygen.

P

parent metal. See preferred term **base metal.**

partial joint penetration. Joint penetration which is less than complete. See also **complete joint penetration.**

pass. A single progression of a welding or surfacing operation along a joint, weld deposit, or substrate. The result of a pass is a weld bead, layer, or spray deposit.

pass sequence. See **deposition sequence.**

paste brazing filler metal. A mixture of finely divided brazing filler metal with an organic or inorganic flux or neutral vehicle or carrier.

paste soldering filler metal. A mixture of finely divided metallic solder with an organic or inorganic flux or neutral vehicle or carrier.

peel test. A destructive method of inspection which mechanically separates a lap joint by peeling. (See Chapter 5, Fig. 5.11, p. 164.)

peening. The mechanical working of metals using impact blows.

penetration. See preferred terms **joint penetration** and **root penetration.**

percent ferrite. See preferred term **ferrite number.**

percussion weld. A weld made by percussion welding.

percussion welding (PEW). A resistance welding process which produces coalescence of the abutting members using heat from an arc produced by a rapid discharge of electrical energy. Pressure is applied percussively during or immediately following the electrical discharge.

permanent dipole bond. A secondary bond arising from the attraction between dipoles, the oppositely charged ends of which are electronegative and electropositive atoms.

pilot arc (plasma arc welding). A low current continuous arc between the electrode and the constricting nozzle to ionize the gas and facilitate the start of the main welding arc.

plano lens (eye protection). A lens which does not incorporate correction.

plasma. A gas that has been heated to an at least partially ionized condition, enabling it to conduct an electric current.

plasma arc cutting (PAC). An arc cutting process which severs metal by melting a localized area with a constricted arc and removing the molten material with a high velocity jet of hot, ionized gas issuing from the orifice.

plasma arc welding (PAW). An arc welding process which produces coalescence of metals by heating them with a constricted arc between an electrode and the workpiece (transferred arc) or the electrode and the constricting nozzle (nontransferred arc). Shielding is obtained from the hot, ionized gas issuing from the orifice which may be supplemented by an auxiliary source of shielding gas. Shielding gas may be an inert gas or a mixture of gases. Pressure may or may not be used, and filler metal may or may not be supplied.

plasma spray gun (thermal spraying). A device which generates a plasma to provide a heat source.

plasma metallizing. See preferred term **plasma spraying.**

plasma spraying (PSP). A thermal spraying process in which a nontransferred arc is utilized as the source of heat for melting and propelling the coating material to the workpiece.

platen (resistance welding). A member with a substantially flat surface to which dies, fixtures, backups, or electrode holders are attached, and which transmits the electrode force or upsetting force. One platen usually is fixed and the other moveable.

platen force (resistance welding). The force available at the moveable platen to cause upsetting in flash or upset welding. This force may be dynamic, theoretical, or static.

platen spacing. The distance between adjacent surfaces of the platens in a resistance welding machine.

plenum chamber. See **plenum.**

plenum (plasma arc welding and cutting, and thermal spraying). The space between the inside wall of the constricting nozzle and the electrode.

plug weld. A circular weld made through a hole in one member of a lap or T-joint fusing that member to the other. The walls of the hole may or may not be parallel and the hole may be partially or completely filled with weld metal. (A fillet welded hole or a spot weld should not be construed as conforming to this definition.)

poke weld. See preferred term **push weld.**

poke welding. See preferred term **push welding.**

polarity. See **direct current electrode negative, direct current electrode positive, straight polarity,** and **reverse polarity.**

porosity. Cavity type discontinuities formed by gas entrapment during solidification.

positioned weld. A weld made in a joint which has been so placed as to facilitate making the weld.

position of welding. See **flat, horizontal, vertical,** and **overhead positions** and **horizontal rolled, horizontal fixed,** and **vertical pipe welding positions.** (See Figs. 1, 2, and 3, pp. 326-328.)

postheat current (resistance welding). The current through the welding circuit during postheat time in resistance welding.

postheating. The application of heat to an assembly after a welding, brazing, soldering, thermal spraying, or cutting operation. See **postweld heat treatment.**

postheat time (resistance welding). The time from the end of weld heat time to the end of weld time.

postweld heat treatment. Any heat treatment subsequent to welding.

postweld interval (resistance welding). The total time elapsing between the end of welding current and the start of hold time.

powder cutting. See preferred terms **chemical flux cutting** and **metal powder cutting.**

powder feeder (thermal spraying). A device for supplying powdered materials to thermal spraying equipment.

powder flame spraying (thermal spraying). A method of flame spraying in which the material to be sprayed is in powder form.

powder flame spray gun (thermal spraying). A flame spraying device in which an oxyfuel gas flame is the heat source and the material to be sprayed is in powder form.

powder metallizing. See preferred term **powder flame spraying.**

precoating. Coating the base metal in the joint by dipping, electroplating, or other applicable means prior to soldering or brazing.

preform. Brazing or soldering filler metal fabricated in a shape or form for a specific application.

preheat. See preferred term **preheat temperature.**

preheat current (resistance welding). An impulse or series of current impulses which occurs prior to and is separated from welding current.

preheating. The application of heat to the base metal immediately before welding, brazing, soldering, thermal spraying, or cutting.

preheat temperature. A specified temperature that the base metal must attain in the welding, brazing, soldering, thermal spraying, or cutting area immediately before these operations are performed.

preheat time (resistance welding). A portion of the preweld interval during which preheat current occurs.

pressure-controlled welding (resistance welding). The making of a number of spot or projection welds with several electrodes functioning progressively under the control of a pressure-sequencing device.

pressure gas welding (PGW). An oxyfuel gas welding process which produces coalescence simultaneously over the entire area of abutting surfaces by heating them with gas flames obtained from the combustion of a fuel gas with oxygen and by the application of pressure, without the use of filler metal.

pressure welding. See preferred terms **solid state welding, hot pressure welding, forge welding, diffusion welding, pressure gas welding,** and **cold welding.**

pretinning. See preferred term **precoating.**

preweld interval (resistance welding). The time elapsing between the end of squeeze time and the beginning of welding current in making spot welds and in projection or upset welding. In flash welding, it is the time during which the material is preheated.

procedure. The detailed elements (with prescribed values or ranges of values) of a process or method used to produce a specific result.

procedure qualification. The demonstration that welds made by a specific procedure can meet prescribed standards.

progressive block sequence. A block sequence during which successive blocks are completed progressively along the joint, either from one end to the other or from the center of the joint toward either end.

projection weld. A weld made by projection welding.

projection welding (RPW). A resistance welding process which produces coalescence of metals with the heat obtained from resistance to electric current through the work parts held together under pressure by electrodes. The resulting welds are localized at predetermined points by projections, embossments or intersections.

protective atmosphere. A gas envelope surrounding the part to be brazed, welded, or thermal sprayed, with the gas composition controlled with respect to chemical composition, dew point, pressure, flow rate, etc. Examples are inert gases, combusted fuel gases, hydrogen, and vacuum.

puddle. See preferred term **molten weld pool.**

pull gun technique. See preferred term **backhand welding.**

pulsation welding. See preferred term **multiple-impulse welding.**

pulsation weld timer. See preferred term **multiple-impulse weld timer.**

pulse (resistance welding). A current of controlled duration through a welding circuit.

pulsed power welding. Any arc welding method in which the power is cyclically programmed to pulse so that effective but short duration values of a parameter can be utilized. Such short duration values are significantly different from the average value of the parameter. Equivalent terms are pulsed voltage or pulsed current welding; see also **pulsed spray welding.**

pulsed spray welding. An arc welding method in which the current is pulsed to utilize the advantages of the spray mode of metal transfer at average currents equal to or less than the globular to spray transition current.

pulse time (resistance welding). The duration of a pulse.

push angle. The travel angle when the electrode is pointing forward. See also **forehand welding.**

Note: This angle can be used to define the position of welding guns, welding torches, high energy beams, welding rods, thermal cutting and thermal spraying torches, and thermal spraying guns.

push weld (resistance welding). A spot or projection weld made by push welding.

push welding (resistance welding). The making of a spot or projection weld by manually applying force to one electrode and using the work or a backing as the other electrode.

Q

qualification. See preferred terms **welder performance qualification** and **procedure qualification.**

quench time (resistance welding). The time from the end of weld time to the beginning of temper time.

R

random sequence. See preferred term **wandering sequence.**

rate of deposition. See **deposition rate.**

rate of flame propagation. The speed at which a flame travels through a mixture of gases.

reaction flux (soldering). A flux composition in which one or more of the ingredients reacts with a base metal upon heating to deposit one or more metals.

reaction soldering. A soldering method in which a reaction flux is used.

reaction stress. The residual stress which could not otherwise exist if the members or parts being welded were isolated as free bodies without connection to other parts of the structure.

reactor (arc welding). A device used in arc welding circuits for the purpose of minimizing irregularities in the flow of welding current.

reducing atmosphere. A chemically active protective atmosphere which at elevated temperature will reduce metal oxides to their metallic state. (Reducing atmosphere is a relative term and such an atmosphere may be reducing to one oxide but not to another oxide.)

reducing flame. A gas flame having a reducing effect. (Excess fuel gas.)

reflow soldering. A nonpreferred term used to describe soldering processes in which preplaced solder is melted to produce a soldered joint or coated surface.

reflowing (soldering). See preferred term **flow brightening.**

regulator. A device for controlling the delivery of gas at some substantially constant pressure.

reinforcement of weld. Weld metal in excess of the quantity required to fill a joint. See **face reinforcement** and **root reinforcement.**

residual stress. Stress remaining in a structure or member as a result of thermal or mechanical treatment or both. Stress arises in fusion welding primarily because the melted material contracts on cooling from the solidus to room temperature. (See Chapter 6, starting on p. 221.)

resistance brazing (RB). A brazing process in which the heat required is obtained from the resistance to electric current in a circuit of which the work is a part.

resistance butt weld. See preferred terms **upset weld** and **flash weld.**

resistance butt welding. See preferred terms **upset welding** and **flash welding.**

resistance seam weld timer. In resistance seam welding, a device which controls the heat times and the cool times.

resistance seam welding (RSEW). A resistance welding process which produces coalescence at the faying surfaces by the heat obtained from resistance to electric current through the work parts held together under pressure by electrodes. The resulting weld is a series of overlapping resistance spot welds made progressively along a joint by rotating the electrodes.

resistance soldering (RS). A soldering process in which the heat required is obtained from the resistance to electric current in a circuit of which the work is a part.

resistance spot welding (RSW). A resistance welding process which produces coalescence at the faying surfaces in one spot by the heat obtained from the resistance to electric current through the work parts held together under pressure by electrodes. The size and shape of the individually formed welds are limited primarily by the size and contour of the electrodes.

resistance welding electrode. See **electrode.**

resistance welding (RW). A group of welding processes which produces coalescence of metals with the heat obtained from resistance of the work to electric current in a circuit of which the work is a part, and by the application of pressure. See **resistance welding electrode.**

reverse polarity. The arrangement of direct current arc welding leads with the work as the negative pole and the electrode as the positive pole of the welding arc. A synonym for **direct current electrode positive.**

roll resistance spot welding. The making of separated resistance spot welds with one or more rotating circular electrodes. The rotation of the electrodes may or may not be stopped during the making of a weld.

roll welding (ROW). A solid state welding process which produces coalescence of metals by heating and by applying pressure with rolls sufficient to cause deformation at the faying surfaces. See also **forge welding.**

root. See preferred terms **root of joint** and **root of weld.**

root crack. A crack in the weld or heat-affected zone occurring at the root of a weld.

root edge. A root face of zero width. See **root face.** (See Fig. 7, p. 332.)

root face. That portion of the groove face adjacent to the root of the joint. (See Fig. 7, p. 332.)

root gap. See preferred term **root opening.**

root of joint. That portion of a joint to be welded where the members approach closest to each other. In cross section the root of the joint may be either a point, a line or an area.

root of weld. The points, as shown in cross section, at which the back of the weld intersects the base metal surfaces.

root opening. The separation between the members to be joined at the root of the joint.

root penetration. The depth that a weld extends into the root of a joint measured on the center line of the root cross section.

root radius. See preferred term **groove radius.**

root reinforcement. Reinforcement of weld at the side other than that from which welding was done.

root surface. The exposed surface of a weld on the side other than that from which welding was done. (See Fig. 6, p. 331.)

rotary roughening (thermal spraying). A method of surface roughening in which a revolving roughening tool is pressed against the surface being prepared, while either the work, or the tool, or both move.

rough threading (thermal spraying). A method of surface roughening which consists of cutting threads with the sides and tops of the threads jagged and torn.

S

salt-bath dip brazing. See preferred term **molten chemical-bath dip brazing.**

sandwich braze. A brazed assembly of dissimilar materials using a preplaced shim, other than the filler metals, as a transition layer to minimize thermal stresses.

scarf. See preferred term **edge preparation.**

seal coat (thermal spraying). Material applied to infiltrate the pores of a thermal spray deposit.

seal weld. Any weld designed primarily to provide a specific degree of tightness against leakage.

seam weld. A continuous weld made between or upon overlapping members, in which coalescence may start and occur on the faying surfaces, or may have proceeded from the surface of one member. The continuous weld may consist of a single weld bead or a series of overlapping spot welds.

seam welding. The making of seam welds.

secondary circuit. That portion of a welding machine which conducts the secondary current between the secondary terminals of the welding transformer and the electrodes, or electrode and work.

selective block sequence. A block sequence in which successive blocks are completed in a certain order selected to create a predetermined stress pattern.

self-fluxing alloys (thermal spraying). Certain materials that "wet" the substrate and coalesce when heated to their melting point, without the addition of a fluxing agent.

semiautomatic arc welding. Arc welding with equipment which controls only the filler metal feed. The advance of the welding is manually controlled.

semiautomatic brazing. Brazing with equipment which controls only the brazing filler metal feed. The advance of the brazing is manually controlled.

semiblind joint. A joint in which one extremity of the joint is not visible.

sequence timer (resistance welding). A device for controlling the sequence and duration of any or all of the elements of a complete welding cycle except weld time or heat time.

sequence weld timer (resistance welding). A device which performs the functions of a sequence timer and the functions of either a weld timer or a multiple-impulse weld timer.

series submerged arc welding (SAW-S). A submerged arc welding process variation in which electric current is established between two (consumable) electrodes which meet just above the surface of the work. The work is not in the electrical circuit.

series welding (resistance welding). The making of two spot or seam welds or two or more projection welds simultaneously with three electrodes forming a series circuit.

shadow mask (thermal spraying). Method of partially shielding an area during the thermal spraying operation, thus permitting some overspray to produce a feathering at the coating edge.

sheet separation (resistance welding). The gap surrounding the weld, between faying surfaces, after the joint has been welded in spot, seam, or projection welding.

shielded carbon arc welding (CAW-S). A carbon arc welding process variation which produces coalescence of metals by heating them with an electric arc between a carbon electrode and the work. Shielding is obtained from the combustion of a solid material fed into the arc or from a blanket of flux on the work or both. Pressure may or may not be used and filler metal may or may not be used.

shielded metal arc cutting (SMAC). A metal arc cutting process in which metals are severed by melting them with the heat of an arc between a covered metal electrode and the base metal.

shielded metal arc welding (SMAW). An arc welding process which produces coalescence of metals by heating them with an arc between a covered metal electrode and the work. Shielding is obtained from decomposition of the electrode covering. Pressure is not used and filler metal is obtained from the electrode.

shielding gas. Protective gas used to prevent atmospheric contamination.

short circuiting arc welding. See **gas metal arc welding-short circuit arc (GMAW-S).**

short circuiting transfer (gas metal arc welding). A type of metal transfer in which melted material from a consumable electrode is deposited during repeated short circuits. (See Chapter 2, Fig. 2.18, p. 64.)

shoulder. See preferred term **root face.**

shrinkage stress. See preferred term **residual stress.**

shrinkage void. A cavity-type discontinuity normally formed by shrinkage during solidification.

sieve analysis. A method of determining particle size distribution, usually expressed as the weight percentage retained upon each of a series of standard screens of decreasing mesh size.

silver soldering, silver alloy brazing. Nonpreferred terms used to denote brazing with a silver-base filler metal. See preferred terms **furnace brazing, induction brazing,** and **torch brazing.**

single-bevel-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

single-flare-bevel-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

single-flare-V-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

single-impulse welding (resistance welding). The making of spot, projection, or upset welds by a single impulse of current. When alternating current is used, an impulse may consist of a fraction of a cycle or a number of cycles.

single-J-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

single port nozzle. A constricting nozzle containing one orifice, located below and concentric with the electrode.

single-U-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

single-V-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

single-welded joint. In arc and gas welding, any joint welded from one side only.

size of weld.

groove weld. The joint penetration (depth of bevel plus the root penetration when specified). The size of a groove weld and its effective throat are one and the same.

fillet weld.

For equal leg fillet welds, the leg lengths of the largest isosceles right triangle which can be inscribed within the fillet weld cross section.

For unequal leg fillet welds, the leg lengths of the largest right triangle which can be inscribed within the fillet weld cross section.

Note: When one member makes an angle with the other member greater than 105 degrees, the leg length (size) is of less significance than the effective throat which is the controlling factor for the strength of a weld.

flange weld. The weld metal thickness measured at the root of the weld.

skip sequence. See preferred term **wandering sequence.**

skull. The unmelted residue from a liquated filler metal.

slag inclusion. Nonmetallic solid material entrapped in weld metal or between weld metal and base metal.

slot weld. A weld made in an elongated hole in one member of a lap or T-joint joining that member to that portion of the surface of the other member which is exposed through the hole. The hole may be open at one end and may be partially or completely filled with weld metal. (A fillet welded slot should not be construed as conforming to this definition.)

slugging. The act of adding a separate piece or pieces of material in a joint before or during welding that results in a welded joint not complying with design, drawing, or specification requirements.

soft solder. See preferred term **solder.**

solder. A filler metal used in soldering which has a liquidus not exceeding 450 °C (840 °F).

solderability. The capacity of a material to be soldered under the fabrication conditions imposed upon a specific, suitably designed structure.

soldering (S). A group of welding processes which produces coalescence of materials by heating them to a suitable temperature and by using a filler metal having a liquidus not exceeding 450 °C (840 °F) and below the solidus of the base materials. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction.

soldering gun. An electrical soldering iron with a pistol grip and a quick heating, relatively small bit.

soldering iron. A soldering tool having an internally or externally heated metal bit usually made of copper.

solid state welding (SSW). A group of welding processes which produces coalescence at temperatures essentially below the melting point of the base materials being joined, without the addition of a brazing filler metal. Pressure may or may not be used.

solidus. The highest temperature at which a metal or alloy is completely solid.

spacer strip. A metal strip or bar prepared for a groove weld, and inserted in the root of a joint to serve as a backing and to maintain root opening during welding. It can also bridge an exceptionally wide gap due to poor fitup.

spatter. In arc and gas welding, the metal particles expelled during welding and which do not form a part of the weld.

spatter loss. Metal lost due to spatter.

spit. See preferred term **flash.**

spool. A type of filler metal package consisting of a continuous length of electrode wound on a cylinder (called the barrel) which is flanged at both ends. The flange extends below the inside diameter of the barrel and contains a spindle hole.

spot weld. A weld made between or upon overlapping members in which coalescence may start and occur on the faying surfaces or may proceed from the surface of one member. The weld cross section (plan view) is approximately circular. See **arc spot weld and resistance spot welding.**

spot welding. The making of spot welds.

spray deposit (thermal spraying). The coating applied by a thermal spraying process.

spraying sequence (thermal spraying). The order in which different layers of similar or different materials are applied in a planned relationship, such as overlapped, superimposed, or at certain angles.

spray rate. A synonym for feed rate. See **feed rate.**

spray torch (thermal spraying). A device for the application of self-fluxing alloys.

spray transfer (arc welding). A type of metal transfer in which molten filler metal is propelled axially across the arc in small droplets (See Chapter 2, Fig. 2.14, p. 60.)

square-groove weld. A type of groove weld. (See Fig. 5, p. 330.)

squeeze time (resistance welding). The time interval between the initial application of the electrode force on the work and the first application of current in making spot and seam welds and in projection or upset welding.

stack cutting. Thermal cutting of stacked metal plates arranged so that all the plates are severed by a single cut.

staggered intermittent fillet welding. Two lines of intermittent fillet welding on a joint in which the fillet weld increments in one line are staggered with respect to those in the other line.

static electrode force. See **electrode force.**

stepback sequence. See preferred term **backstep sequence.**

step brazing. The brazing of successive joints on a given part with filler metals of successively lower brazing temperatures so as to accomplish the joining without disturbing the joints previously brazed. A similar result can be achieved at a single brazing temperature if the remelt temperature of prior joints is increased by metallurgical interaction.

step soldering. The soldering of successive joints on a given part with solders of successively lower soldering temperatures so as to accomplish the joining without disturbing the joints previously soldered.

stick electrode. See **electrode: covered electrode.**

stick electrode welding. See preferred term **shielded metal arc welding.**

stickout. See preferred term **electrode extension.**

stitch welding. The use of intermittent welds to join two or more parts.

stopoff. A material used on the surfaces adjacent to the joint to limit the spread of soldering or brazing filler metal.

stored energy welding. The making of a weld with electrical energy accumulated electrostatically, electromagnetically or electrochemically at a relatively low rate and made available at the required welding rate.

straight polarity. The arrangement of direct current arc welding leads in which the work is the positive pole and the electrode is the negative pole of the welding arc. A synonym for **direct current electrode negative.**

stranded electrode. See **electrode.**

stress corrosion cracking. Failure of metals by cracking under combined action of corrosion and stress, residual or applied. In brazing, the term applies to the cracking of stressed base metal due to the presence of a liquid filler metal. (See Chapter 5, Fig. 5.36k. p. 202.)

stress relief cracking. Intergranular cracking in the heat-affected zone or weld metal that occurs during the exposure of weldments to elevated temperatures during postweld heat treatment or high temperature service.

stress relief heat treatment. Uniform heating of a structure or a portion thereof to a sufficient temperature to relieve the major portion of the residual stresses, followed by uniform cooling.

stringer bead. A type of weld bead made without appreciable weaving motion. See also **weave bead.**

stud arc welding (SW). An arc welding process which produces coalescence of metals by heating them with an arc between a metal stud, or similar part, and the other work part. When the surfaces to be joined are properly heated, they are brought together under pressure. Partial shielding may be obtained by the use of a ceramic ferrule surrounding the stud. Shielding gas or flux may or may not be used.

stud welding. A general term for the joining of a metal stud or similar part to a workpiece. Welding may be accomplished by arc, resistance, friction or other suitable process with or without external gas shielding.

submerged arc welding (SAW). An arc welding process which produces coalescence of metals by heating them with an arc or arcs between a bare metal electrode or electrodes and the work. The arc is shielded by a blanket of granular, fusible material on the work. Pressure is not used and filler metal is obtained from the electrode and sometimes from a supplementary welding rod.

substrate. Any base material to which a thermal sprayed coating or surfacing weld is applied.

suck-back. See preferred term **concave root surface.**

surface preparation. The operations necessary to produce a desired or specified surface condition.

surface roughening. A group of procedures for producing irregularities on a surface. See **blasting, dovetailing, groove and rotary roughening, rotary roughening, rough threading,** and **threading and knurling.**

surfacing. The deposition of filler metal (material) on a base metal (substrate) to obtain desired properties or dimensions.

surfacing weld. A type of weld composed of one or more stringer or weave beads deposited on an unbroken surface to obtain desired properties or dimensions.

sweat soldering. A soldering method in which two or more parts which have been precoated with solder are reheated and assembled into a joint without the use of additional solder.

synchronous initiation (resistance welding). The initiation and termination of each half-cycle of welding-transformer primary current so that all half-cycles of such current are identical in making spot and seam welds or in making projection welds.

synchronous timing. See preferred term **synchronous initiation.**

T

tack weld. A weld made to hold parts of a weldment in proper alignment until the final welds are made.

taps. Connections to a transformer winding which are used to vary the transformer turns ratio, thereby controlling welding voltage and current.

temper time (resistance welding). That part of the postweld interval following quench time to the beginning of hold time in resistance welding.

temporary weld. A weld made to attach a piece or pieces to a weldment for temporary use in handling, shipping, or working on the weldment.

theoretical electrode force. See **electrode force.**

theoretical throat. See **throat of a fillet weld.**

thermal cutting. A group of cutting processes which melt the metal (material) to be cut. See **arc cutting, oxygen cutting, electron beam cutting,** and **laser beam cutting.**

thermal spraying (THSP). A group of welding or allied processes in which finely divided metallic or nonmetallic materials are deposited in a molten or semi-molten condition to form a coating. The coating material may be in the form of powder, ceramic rod, wire or molten materials. See **flame spraying, plasma spraying,** and **electric arc spraying.**

thermal stresses. Stresses in metal resulting from nonuniform temperature distributions.

thermit crucible. The vessel in which the thermit reaction takes place.

thermit mixture. A mixture of metal oxide and finely divided aluminum with the addition of alloying metals as required.

thermit mold. A mold formed around the parts to be welded to receive the molten metal.

thermit reaction. The chemical reaction between metal oxide and aluminum which produces superheated molten metal and aluminum oxide slag.

thermit welding (TW). A welding process which produces coalescence of metals by heating them with superheated liquid metal from a chemical reaction between a metal oxide and aluminum, with or without the application of pressure. Filler metal, when used, is obtained from the liquid metal.

thermocompression bonding. See preferred term **hot pressure welding.**

threading and knurling (thermal spraying). A method of surface roughening in which spiral threads are prepared followed by upsetting with a knurling tool.

throat depth (resistance welding). The distance from the center line of the electrodes or platens to the nearest point of interference for flat sheets in a resistance welding machine. In the case of a resistance seam welding machine with a universal head, the throat depth is measured with the machine arranged for transverse welding.

throat height (resistance welding). The unobstructed dimension between arms throughout the throat depth in a resistance welding machine.

throat of a fillet weld.

theoretical throat. The distance from the beginning of the root of the joint perpendicular to the hypotenuse of the largest right triangle that can be inscribed within the fillet weld cross section.

actual throat. The shortest distance from the root of a fillet weld to its face.

effective throat. The minimum distance minus any reinforcement from the root of a weld to its face.

throat of a groove weld. See preferred term **size of weld.**

throat opening. See preferred term **horn spacing.**

TIG welding. See preferred term **gas tungsten arc welding.**

tinning. See preferred term **precoating.**

tip skid. See preferred term **electrode skid.**

T-joint. A joint between two members located approximately at right angles to each other in the form of a T. (See Fig. 4, p. 329.)

toe crack. A crack in the base metal occurring at the toe of a weld. (See Chapter 5, Fig. 5.45, p. 211.)

toe of weld. The junction between the face of a weld and the base metal. (See Fig. 6, p. 331.)

torch. See preferred terms **welding torch, cutting torch, spray torch.**

torch brazing (TB). A brazing process in which the heat required is furnished by a fuel gas flame.

torch soldering (TS). A soldering process in which the heat required is furnished by a fuel gas flame.

torch standoff distance. The distance between a nozzle and a workpiece.

torch tip. See preferred terms **welding tip** or **cutting tip.**

transferred arc (plasma arc welding). A plasma arc established between the electrode and the workpiece.

transverse resistance seam welding. The making of a resistance seam weld in a direction essentially at right angles to the throat depth of a resistance seam welding machine.

travel angle. The angle that the electrode makes with a reference line perpendicular to the axis of the weld in the plane of the weld axis. See also **drag angle** and **push angle.** Note: This angle can be used to define the position of welding guns, welding torches, high energy beams, welding rods, thermal cutting and thermal spraying torches, and thermal spraying guns.

travel angle (pipe). The angle that the electrode makes with a reference line extending from the center of the pipe through the puddle in the plane of the weld axis. Note: This angle can be used to define the position of welding guns, welding torches, high energy beams, welding rods, thermal cutting and thermal spraying torches, and thermal spraying guns.

tungsten electrode. See **electrode: tungsten electrode.**

twin carbon arc brazing (TCAB). A brazing process which produces coalescence of metals by heating them with an electric arc between two carbon electrodes. The filler metal is distributed in the joint by capillary attraction.

twin carbon arc welding (CAW-T). A carbon arc welding process variation which produces coalescence of metals by heating them with an electric arc between two carbon electrodes. No shielding is used. Pressure and filler metal may or may not be used.

U

ultrasonic coupler (ultrasonic soldering and ultrasonic welding). Elements through which ultrasonic vibration is transmitted from the transducer to the tip.

ultrasonic soldering. A soldering method in which high frequency vibratory energy is transmitted through molten solder to remove undesirable surface films and thereby promote wetting of the base metal. This operation is usually accomplished without a flux.

ultrasonic welding (USW). A solid state welding process which produces coalescence of materials by the local application of high frequency vibratory energy as the work parts are held together under pressure.

ultra-speed welding. See preferred term **commutator-controlled welding.**

underbead crack. A crack in the heat-affected zone generally not extending to the surface of the base metal. (See Chapter 5, Fig. 5.45, p. 211.)

undercut. A groove melted into the base metal adjacent to the toe or root of a weld and left unfilled by weld metal. (See Chapter 5, Fig. 5.46, p. 212.)

underfill. A depression on the face of the weld or root surface extending below the surface of the adjacent base metal.

unipolarity operation. A resistance welding machine operation in which succeeding welds are made with pulses of the same polarity.

upset. Bulk deformation resulting from the application of pressure in welding. The upset may be measured as a percent increase in interfacial area, a reduction in length, or a percent reduction in thickness (for lap joints).

upset butt welding. See preferred term **upset welding.**

upsetting force. The force exerted at the faying surfaces during upsetting.

upsetting time. The time during upsetting.

upset weld. A weld made by upset welding.

upset welding (UW). A resistance welding process which produces coalescence simultaneously over the entire area of abutting surfaces or progressively along a joint, by the heat obtained from resistance to electric current through the area where those surfaces are in contact. Pressure is applied before heating is started and is maintained throughout the heating period.

upslope time (resistance welding). The time during which the welding current continuously increases from the beginning of welding current.

V

van der Waals bond. A secondary bond arising from the fluctuating-dipole nature of an atom with all occupied electron shells filled.

vacuum brazing. A nonpreferred term used to denote various brazing processes which take place in a chamber or retort below atmospheric pressure.

vertical position. The position of welding in which the axis of the weld is approximately vertical. (See Figs. 1, 2, and 3, pp. 326-328.)

vertical position (pipe welding). The position of a pipe joint in which welding is performed in the horizontal position and the pipe may or may not be rotated. (See Fig. 1, pp. 326-327.)

voltage regulator. An automatic electrical control device for maintaining a constant voltage supply to the primary of a welding transformer.

W

wandering sequence. A longitudinal sequence in which the weld bead increments are deposited at random.

water wash (thermal spraying). The forcing of exhaust air and fumes from a spray booth through water so that the vented air is free of thermal sprayed particles or fumes.

wave soldering (WS). An automatic soldering process where work parts are automatically passed through a wave of molten solder. See also **dip soldering.**

wax pattern (thermit welding). Wax molded around the parts to be welded to the form desired for the completed weld.

weave bead. A type of weld bead made with transverse oscillation.

weld. A localized coalescence of metals or nonmetals produced either by heating the materials to suitable temperatures, with or without the application of pressure, or by the application of pressure alone, and with or without the use of filler material.

weldability. The capacity of a material to be welded under the fabrication conditions imposed into a specific, suitably designed structure and to perform satisfactorily in the intended service.

weld bead. A weld deposit resulting from a pass. See **stringer bead** and **weave bead.**

weldbonding. A joining method which combines resistance spot welding or resistance seam welding with adhesive bonding. The adhesive may be applied to a faying surface before welding or may be applied to the areas of sheet separation after welding.

weld crack. A crack in weld metal.

weld-delay time (resistance welding). The amount of time the beginning of welding current is delayed with respect to the initiation of the forge-delay timer in order to synchronize the forging force with welding current flow.

welder. One who performs a manual or semiautomatic welding operation. (Sometimes erroneously used to denote a welding machine.)

welder certification. Certification in writing that a welder has produced welds meeting prescribed standards.

welder performance qualification. The demonstration of a welder's ability to produce welds meeting prescribed standards.

welder registration. The act of registering a welder certification or a photostatic copy thereof.

weld gage. A device designed for checking the shape and size of welds.

weld-heat time (resistance welding). The time from the beginning of welding current to the beginning of postheat time.

welding. A materials joining process used in making welds. (See the Master Chart of Welding and Allied Processes.)

welding current. The current in the welding circuit during the making of a weld. In resistance welding, the current used during a preweld or postweld interval is excluded.

welding cycle (resistance welding). The complete series of events involved in the making of a weld.

welding electrode. See preferred term **electrode.**

welding force. See preferred terms **electrode force** and **platen force.**

welding generator. A generator used for supplying current for welding.

welding goggles. See **goggle.**

welding ground. See preferred term **work connection.**

welding head. The part of a welding machine or automatic welding equipment in which a welding gun or torch is incorporated.

welding leads. The work lead and electrode lead of an arc welding circuit.

welding machine. Equipment used to perform the welding operation. For example, spot welding machine, arc welding machine, seam welding machine, etc.

welding operator. One who operates machine or automatic welding equipment.

welding pressure. The pressure exerted during the welding operation on the parts being welded. See also **electrode force** and **platen force.**

welding procedure. The detailed methods and practices including all joint welding procedures involved in the production of a weldment. See **joint welding procedure.**

welding process. A materials joining process which produces coalescence of materials by heating them to suitable temperatures, with or without the application of pressure or by the application of pressure alone, and with or without the use of filler metal. (See the Master Chart of Welding and Allied Processes.)

welding rectifier. A device in a welding machine for converting alternating current to direct current.

welding rod. A form of filler metal used for welding or brazing which does not conduct the electrical current.

welding sequence. The order of making the welds in a weldment.

welding technique. The details of a welding procedure which are controlled by the welder or welding operator.

welding tip. A welding torch tip designed for welding.

welding torch. A device used in oxyfuel gas welding or torch brazing for mixing and controlling the flow of gases.

welding transformer. A transformer used for supplying current for welding. See also **reactor** (arc welding).

welding wheel. See preferred term **electrode.**

welding wire. See preferred terms **electrode** and **welding rod.**

weld interval (resistance welding). The total of all heat and cool time when making one multiple-impulse weld.

weld interval timer (resistance welding). A device which controls heat and cool times and weld interval when making multiple-impulse welds singly or simultaneously.

weld length. See preferred term **effective length of weld.**

weld line. See preferred term **bond line.**

weldment. An assembly whose component parts are joined by welding.

weld metal. That portion of a weld which has been melted during welding.

weld metal area. The area of the weld metal as measured on the cross section of a weld.

weldor. See preferred term **welder.**

weld penetration. See preferred terms **joint penetration** and **root penetration.**

weld size. See preferred term **size of weld.**

weld time (resistance welding). The time that welding current is applied to the work in making a weld by single-impulse welding or flash welding.

weld timer. A device which controls only the weld time in resistance welding.

wetting. The bonding or spreading of a liquid filler metal or flux on a solid base metal.

wiped joint. A joint made with solder having a wide melting range and with the heat supplied by the molten solder poured onto the joint. The solder is manipulated with a hand-held cloth or paddle so as to obtain the required size and contour.

wire flame spray gun. A flame spraying device using heat provided by an oxyfuel gas flame and metallic material in wire or rod form for spraying.

wire flame spraying. A method of flame spraying using metallic material in wire or rod form for spraying.

wire feed speed. The rate of speed in mm/s or in./min at which a filler metal is consumed in arc welding or thermal spraying.

wire straightener. A device used for controlling the cast of coiled wire to enable it to be easily fed into the gun.

work angle. The angle that the electrode makes with the referenced plane or surface of the base metal in a plane perpendicular to the axis of the weld. See also **drag angle** and **push angle.**

Note: This angle can be used to define the position of welding guns, welding torches, high energy beams, welding rods, thermal cutting and thermal spraying torches, and thermal spraying guns.

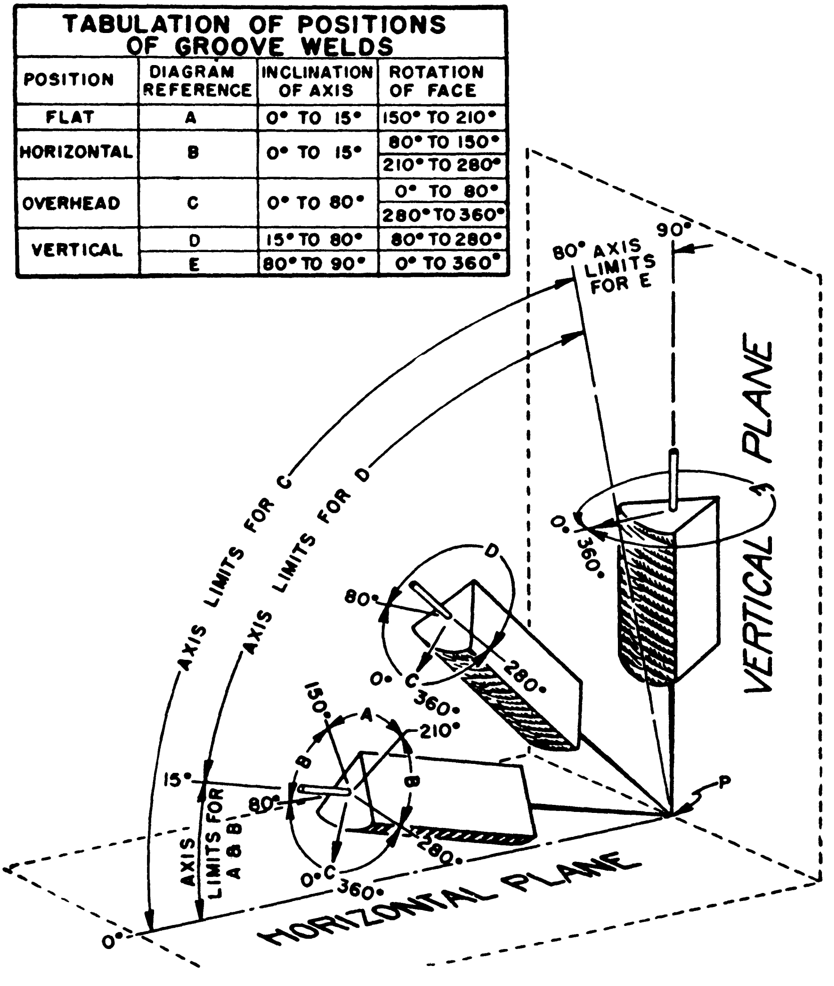
work angle (pipe). The angle that the electrode makes with the referenced plane or surface of the pipe in a plane extending from the center of the pipe through the puddle.

Note: This angle can be used to define the position of welding guns, welding torches, high energy beams, welding rods, thermal cutting and thermal spraying torches, and thermal spraying guns.

work coil. The inductor used when welding, brazing or soldering with induction heating equipment.

work connection. The connection of the work lead to the work.

work lead. The electric conductor between the source of arc welding current and the work.



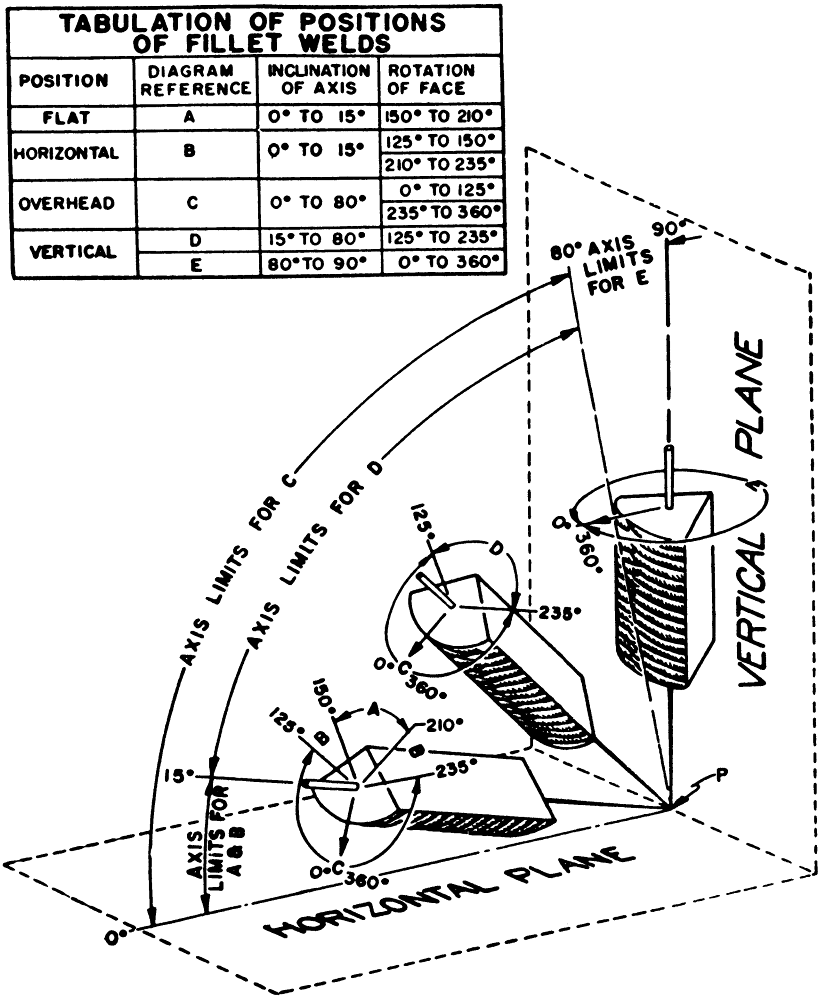
TABULATION OF POSITIONS OF GROOVE WELDS

POSITION	DIAGRAM REFERENCE	INCLINATION OF AXIS	ROTATION OF FACE
FLAT	A	0° TO 15°	150° TO 210°
HORIZONTAL	B	0° TO 15°	80° TO 150° 210° TO 280°
OVERHEAD	C	0° TO 80°	0° TO 80° 280° TO 360°
VERTICAL	D	15° TO 80°	80° TO 280°
	E	80° TO 90°	0° TO 360°

NOTES:

1. The horizontal reference plane is taken to lie always below the weld under consideration.
2. Inclination of axis is measured from the horizontal reference plane toward the vertical.
3. Angle of rotation of face is determined by a line perpendicular to the theoretical face of the weld which passes through the axis of the weld. The reference position (0°) of rotation of the face invariably points in the direction opposite to that in which the axis angle increases. The angle of rotation of the face of weld is measured in a clockwise direction from this reference position (0°) when looking at point P.

Fig. 1—Positions of welds—Part 1.



TABULATION OF POSITIONS OF FILLET WELDS

POSITION	DIAGRAM REFERENCE	INCLINATION OF AXIS	ROTATION OF FACE
FLAT	A	0° TO 15°	150° TO 210°
HORIZONTAL	B	0° TO 15°	125° TO 150° 210° TO 235°
OVERHEAD	C	0° TO 80°	0° TO 125° 235° TO 360°
VERTICAL	D	15° TO 80°	125° TO 235°
	E	80° TO 90°	0° TO 360°

NOTE: FOR GROOVE WELDS IN PIPE THE FOLLOWING DEFINITIONS SHALL APPLY:

Horizontal fixed position: When the axis of the pipe does not deviate by more than 30° from the horizontal plane and the pipe is not rotated during welding.

Horizontal rolled position: When the axis of the pipe does not deviate by more than 30° from the horizontal plane, the pipe is rotated during welding, and the weld metal is deposited within an arc not to exceed 15° on either side of a vertical plane passing through the axis of the pipe.

Vertical position: When the axis of the pipe does not deviate by more than 10° from the vertical position. (The pipe may or may not be rotated during welding.)*

*Positions in which the axis of the pipe deviates by more than 10° and less than 60° from the vertical shall be considered intermediate.

Fig. 1—Positions of welds—Part 2.

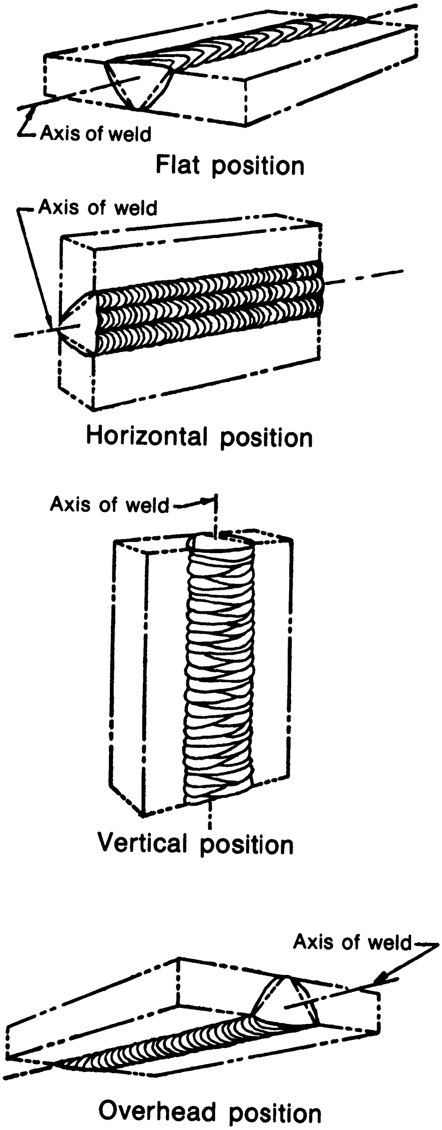


Fig. 2—Positions of welding for groove welds.

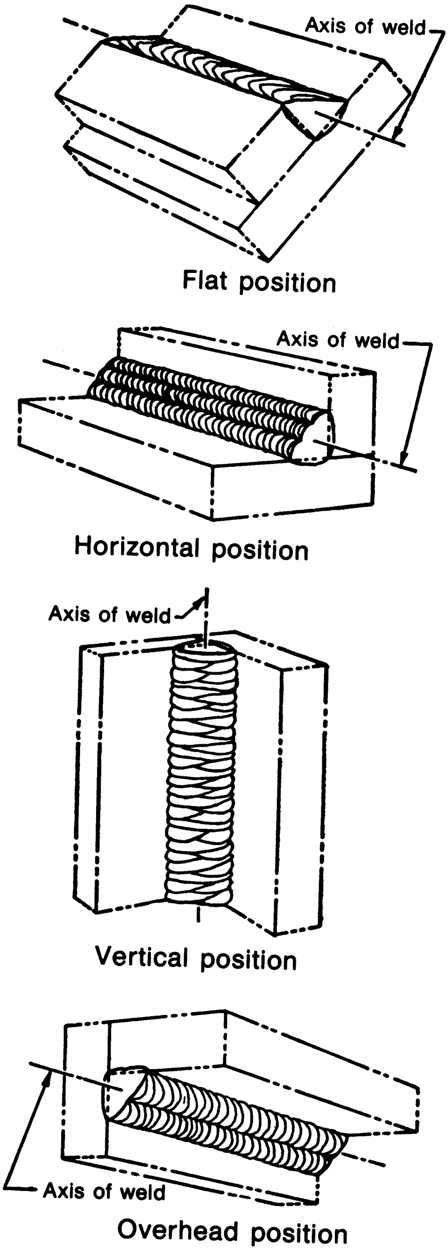
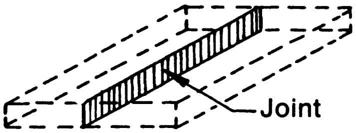


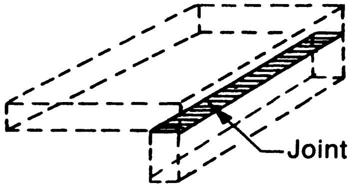
Fig. 3—Positions of welding for fillet welds.



Applicable welds

- Square-Groove
- V-Groove
- Bevel-Groove
- U-Groove
- J-Groove
- Flare-V-Groove
- Flare-Bevel-Groove
- Edge-Flange

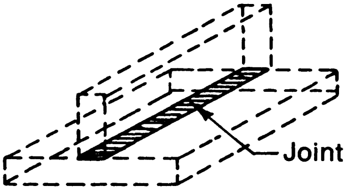
Butt joint



Applicable welds

- Fillet
- Square-Groove
- V-Groove
- Bevel-Groove
- U-Groove
- J-Groove
- Flare-V-Groove
- Flare-Bevel-Groove
- Edge-Flange
- Corner-Flange
- Spot
- Projection
- Seam

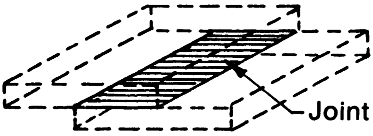
Corner joint



Applicable welds

- Fillet
- Plug
- Slot
- Square-Groove
- Bevel-Groove
- J-Groove
- Flare-Bevel-Groove
- Spot
- Projection
- Seam

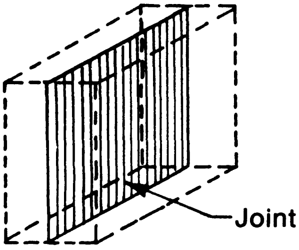
T-joint



Applicable welds

- Fillet
- Plug
- Slot
- Bevel-Groove
- J-Groove
- Flare-Bevel-Groove
- Spot
- Projection
- Seam

Lap joint



Applicable welds

- Plug
- Slot
- Square-Groove
- Bevel-Groove
- V-Groove
- U-Groove
- J-Groove
- Edge-Flange
- Corner-Flange
- Spot
- Projection
- Seam
- Edge

Edge joint

Fig. 4—Types of joints.

Square-Groove weld

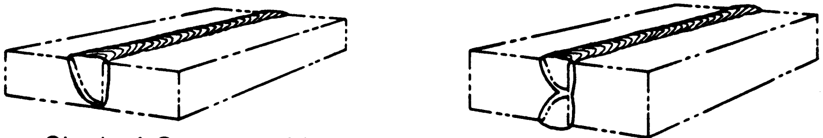
Square-Groove weld

Single-Bevel-Groove weld

Double-Bevel-Groove weld

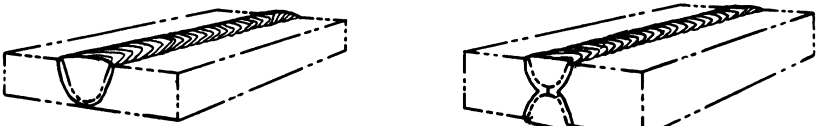
Single-V-Groove weld

Double-V-Groove weld



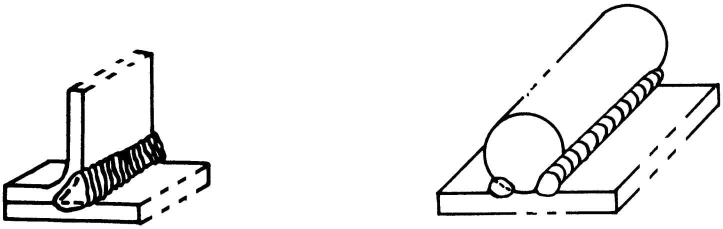
Single-J-Groove weld

Double-J-Groove weld



Single-U-Groove weld

Double-U-Groove weld



Single-Flare-Bevel-Groove weld

Double-Flare-Bevel-Groove weld

Single-Flare-V-Groove weld

Double-Flare-V-Groove weld

Fig. 5—Types of groove welds.

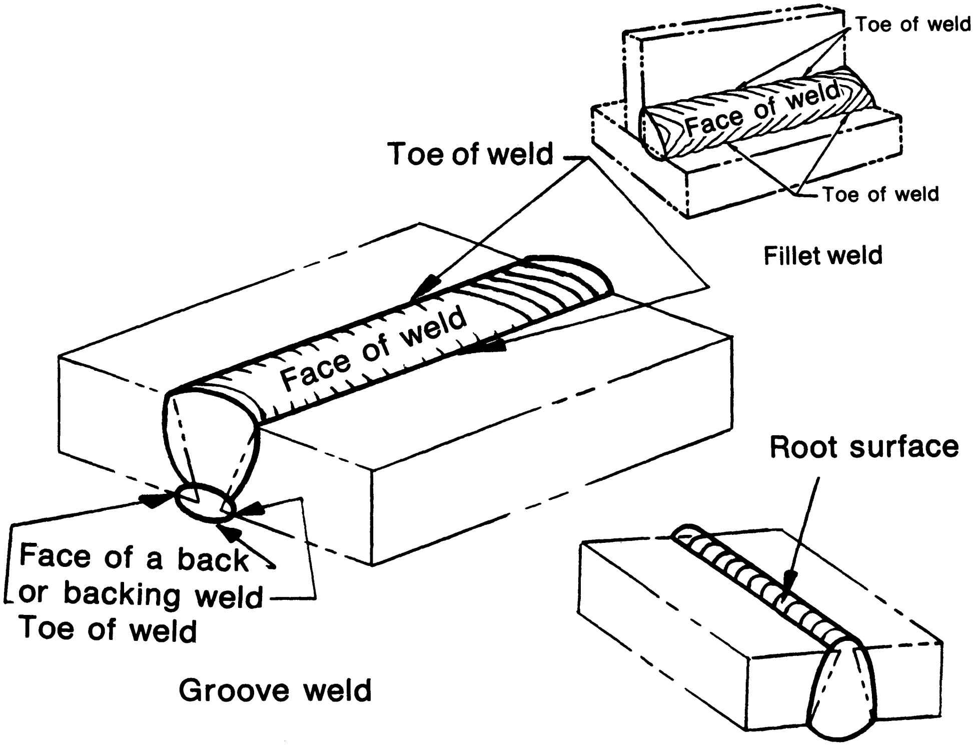


Fig. 6—Face, root surface, and toe of weld.

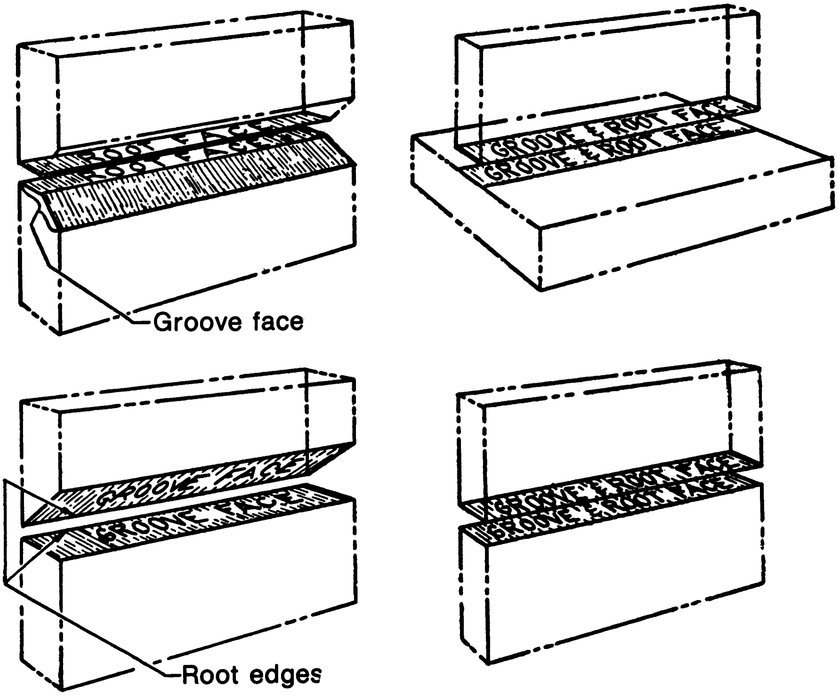


Fig. 7—Groove face, root face, and root edge.

Table A—Designation of welding and allied processes by letters

Welding and Allied Processes	Letter Designation	Welding and Allied Processes	Letter Designation
adhesive bonding	ABD	high frequency resistance welding	HFRW
arc welding	AW	percussion welding	PEW
atomic hydrogen welding	AHW	projection welding	RPW
bare metal arc welding	BMAW	resistance seam welding	RSEW
carbon arc welding	CAW	resistance spot welding	RSW
flux cored arc welding	FCAW	upset welding	UW
gas metal arc welding	GMAW	soldering	S
gas tungsten arc welding	GTAW	dip soldering	DS
plasma arc welding	PAW	furnace soldering	FS
shielded metal arc welding	SMAW	induction soldering	IS
stud arc welding	SW	infrared soldering	IRS
submerged arc welding	SAW	iron soldering	INS
arc welding process variations		resistance soldering	RS
flux cored arc welding-electrogas	FCAW-EG	torch soldering	TS
gas carbon arc welding	CAW-G	wave soldering	WS
gas metal arc welding-electrogas	GMAW-EG	solid state welding	SSW
gas metal arc welding-pulsed arc	GMAW-P	cold welding	CW
gas metal arc welding-short circuiting arc	GMAW-S	diffusion welding	DFW
		explosion welding	EXW
gas tungsten arc welding-pulsed arc	GTAW-P	forge welding	FOW
series submerged arc welding	SAW-S	friction welding	FRW
shielded carbon arc welding	CAW-S	hot pressure welding	HPW
twin carbon arc welding	CAW-T	roll welding	ROW
brazing	B	ultrasonic welding	USW
arc brazing	AB	thermal cutting	TC
block brazing	BB	arc cutting	AC
diffusion brazing	DFB	air carbon arc cutting	AAC
dip brazing	DB	carbon arc cutting	CAC
flow brazing	FLB	gas metal arc cutting	GMAC
furnace brazing	FB	gas tungsten arc cutting	GTAC
induction brazing	IB	metal arc cutting	MAC
infrared brazing	IR	plasma arc cutting	PAC
resistance brazing	RB	shielded metal arc cutting	SMAC
torch brazing	TB	electron beam cutting	EBC
twin carbon arc brazing	TCAB	laser beam cutting	LBC
other processes		oxygen cutting	OC
electron beam welding	EBW	chemical flux cutting	FOC
electroslag welding	ESW	metal powder cutting	POC
flow welding	FLOW	oxyfuel gas cutting	OFC
induction welding	IW	oxyacetylene cutting	OFC-A
laser beam welding	LBW	oxyhydrogen cutting	OFC-H
thermit welding	TW	oxynatural gas cutting	OFC-N
		oxypropane cutting	OFC-P
oxyfuel gas welding	OFW	oxygen arc cutting	AOC
air acetylene welding	AAW	oxygen lance cutting	LOC
oxyacetylene welding	OAW	thermal spraying	THSP
oxyhydrogen welding	OHW	electric arc spraying	EASP
pressure gas welding	PGW	flame spraying	FLSP
resistance welding	RW	plasma spraying	PSP
flash welding	FW		

Table A1—Suffixes for optional use in applying welding and allied processes

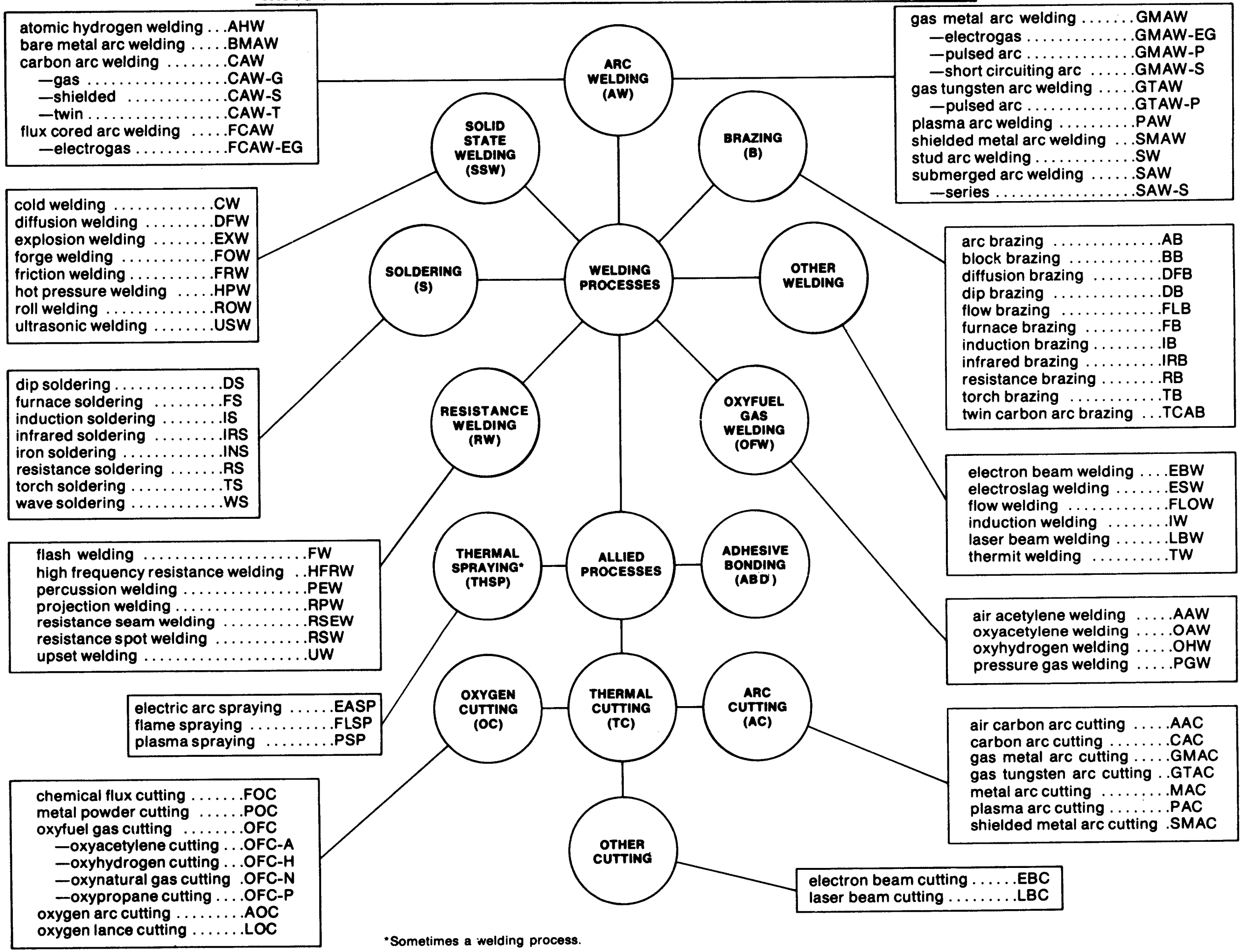
Automatic	AU	Manual	MA
Machine	ME	Semiautomatic	SA

Table B—Alphabetical cross-reference to table A*

Welding and Allied Processes	Letter Designation	Welding and Allied Processes	Letter Designation
air carbon arc cutting	AAC	induction brazing	IB
air acetylene welding	AAW	iron soldering	INS
adhesive bonding	ABD	infrared brazing	IRB
arc cutting	AC	infrared soldering	IRS
arc brazing	AB	induction soldering	IS
atomic hydrogen welding	AHW	induction welding	IW
oxygen arc cutting	AOC	laser beam cutting	LBC
arc welding	AW	laser beam welding	LBW
brazing	B	oxygen lance cutting	LOC
block brazing	BB	metal arc cutting	MAC
bare metal arc welding	BMAW	oxyacetylene welding	OAW
carbon arc cutting	CAC	oxygen cutting	OC
carbon arc welding	CAW	oxyfuel gas cutting	OFC
gas carbon arc welding	CAW-G	oxyacetylene cutting	OFC-A
shielded carbon arc welding	CAW-S	oxyhydrogen cutting	OFC-H
twin carbon arc welding	CAW-T	oxynatural gas cutting	OFC-N
cold welding	CW	oxypropane cutting	OFC-P
dip brazing	DB	oxyfuel gas welding	OFW
diffusion brazing	DFB	oxyhydrogen welding	OHW
diffusion welding	DFW	plasma arc cutting	PAC
dip soldering	DS	plasma arc welding	PAW
electric arc spraying	EAS	percussion welding	PEW
electron beam cutting	EBC	pressure gas welding	PGW
electron beam welding	EBW	metal powder cutting	POC
electroslag welding	ESW	plasma spraying	PS
explosion welding	EXW	resistance brazing	RB
furnace brazing	FB	projection welding	RPW
flux cored arc welding	FCAW	resistance soldering	RS
flux cored arc welding-electrogas	FCAW-EG	resistance seam welding	RSEW
flow brazing	FLB	resistance spot welding	RSW
flow welding	FLOW	roll welding	ROW
flame spraying	FLS	resistance welding	RW
chemical flux cutting	FOC	soldering	S
forge welding	FOW	submerged arc welding	SAW
friction welding	FRW	series submerged arc welding	SAW-S
furnace soldering	FS	shielded metal arc cutting	SMAC
flash welding	FW	shielded metal arc welding	SMAW
gas metal arc cutting	GMAC	solid state welding	SSW
gas metal arc welding	GMAW	stud arc welding	SW
gas metal arc welding-electrogas	GMAW-EG	torch brazing	TB
gas metal arc welding-pulsed arc	GMAW-P	thermal cutting	TC
gas metal arc welding-short circuiting arc	GMAW-S	twin carbon arc brazing	TCAB
		thermal spraying	THS
gas tungsten arc cutting	GTAC	torch soldering	TS
gas tungsten arc welding	GTAW	thermit welding	TW
gas tungsten arc welding-pulsed arc	GTAW-P	ultrasonic welding	USW
high frequency resistance welding	HFRW	upset welding	UW
hot pressure welding	HPW	wave soldering	WS

*See Table A1 for suffixes which may be used if desired to indicate the methods of applying the above processes.

MASTER CHART OF WELDING AND ALLIED PROCESSES



*Sometimes a welding process.

Appendix
B
Metric Practice Guide

Appendix B was prepared to guide Handbook readers in the use of metric units for welding. Acquiring familiarity with these units is essential in light of their rapidly expanding use by American industry as a replacement for U. S. customary units. In fact, measurement practices all over the world are currently in various stages of transition, a condition that is expected to continue during the next several years. This transition includes a change from both the U. S. customary units and the noncoherent metric units to the International System of Units, officially abbreviated SI, from the French "Le Systême Internationale d'Unités." SI is the primary system of measurements in this volume of the *Welding Handbook*.

This appendix is an extraction from the AWS document, Metric Practice Guide for the Welding Industry, A2.3-75, prepared by the AWS Committee on Definitions, Symbols, and Metric Practice. For more complete coverage of the SI system and methods of handling the transition period, Handbook readers should refer to A2.3-75 or later revision.

Appendix
B
Metric Practice Guide

1. Scope

This metric practice guide defines the International System of Units (SI). It contains the base units, supplementary units, derived SI units, and rules for their use in AWS documents and by the welding industry. It also contains factors and rules for converting from U.S. customary units to SI units and recommendations to industry for managing the transition.

2. Features of SI

SI is a modernized metric system of measurement. It was formally established in 1960 as the International System of Units and is officially recognized by all industrial nations. It has features that make it superior to the U.S. customary system and to other metric systems. These features are:

2.1 Absolute Base. An absolute base is one in which force is not defined by action of gravity. An absolute system has several advantages, the greatest being simplicity of calculation. In SI units, a force of one newton gives a mass of one kilogram an acceleration of one metre per second squared. In contrast, in European metric practice, a force of one kilogram force (gravitational system) accelerates the same mass 9.806 650 metres per second squared, whereas in U.S. customary units, one pound force accelerates a mass of one slug 32.174 feet per second squared. There's added confusion in the United States because the pound is used for either force or mass, although properly the poundal should be used for force when the pound is used for mass, or the pound should be used for force when the slug is used for mass.

2.2 Coherence. Coherence is the characteristic which relates any derived unit to any other, or to the base units from which it is formed, without the use of conversion factors.

In SI units, a force of one newton applied through a distance of one metre does work equivalent to one joule, which equals the work produced by one watt of power in one second.

In U.S. customary units, a force of one pound applied through a distance of one inch produces energy equivalent to 0.000 107 Btu, which is the same as produced by one horsepower in 0.000 505 hours. Coherence is a valuable characteristic in engineering calculations, and lends itself to simplifying even elementary use of measurement units. A disadvantage is that some of the derived units become awkward in size. This has caused much controversy, such as, the disagreement concerning the bar as a unit of pressure.

Though the bar is compatible with units of the International System, being equal to 100 000 newtons per metre squared, it is not coherent with the system because it introduces a conversion factor. It is this SI characteristic of coherence which has made the well known calorie a unit that cannot be incorporated into SI because a conversion factor would be required.

2.3 Unique Units. Another desirable characteristic of SI is its use of only one unit for each physical quantity. The SI units for force, energy, and power are the same regardless of whether the process is mechanical, electrical, or thermal. Power, whether in engines or air conditioners, is measured in watts. By contrast, the customary system has 9 commonly used units for area, 25 units for energy, 26 units for length, and so on.

2.4 Decimal System. SI is a decimal system, and thus easier to use because it is easier to work in multiples of ten and in decimal notation than in the fractions and decimalized fraction equivalents common to the customary system.

The above combination of features makes SI an excellent system suitable for all kinds of measurements. Though there remain areas that can and no doubt will be improved, the SI System is practical for universal application and is rapidly becoming the commonly used world measurement system.

3. SI Units and Symbols

SI consists of seven base units, two supplementary units, a series of derived units consistent with the base and supplementary units, and a series of prefixes for the formation of multiples of the various units.

3.1 Base Units. SI base units and their symbols are:

Quantity	Unit	Symbol	Quantity	Unit	Symbol
length	metre*	m	thermodynamic temperature	kelvin	K
mass	kilogram	kg	luminous intensity	candela	cd
time	second	s	amount of substance	mole	mol
electric current	ampere	A			

The National Bureau of Standards defines the SI base units as follows:

metre*. The length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton-86 atom.

kilogram. The mass equal to the mass of the international prototype of the kilogram.

second. The duration equal to 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

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*The spelling of metre and litre is derived from the European origin of SI. Many U. S. authorities prefer the traditional American spelling—meter and liter—and until the question is settled the reader is likely to encounter both spellings in AWS documents and elsewhere. In this volume of the *Welding Handbook*, the re spelling of these words is used.

ampere. That constant current which, if maintained in two straight parallel conductors of infinite length, of negligible cross section, and placed one metre apart in a vacuum, would produce between these conductors a force equal to 2 x 10^{-7} newton per metre of length.

kelvin. The thermodynamic temperature that is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

candela. The luminous intensity, in the perpendicular direction, of a surface of 1/600 000 metre squared of a blackbody at the temperature of freezing platinum under a pressure of 101 325 newtons per metre squared.

mole. The amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon-12 (when the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles).

3.2 Supplementary Units. The supplementary units consist of two purely geometric units, the radian and the steradian, as follows:

radian. The plane angle between two radii of a circle that cut off on the circumference an arc equal in length to the radius. Symbol: rad

steradian. The solid angle which, having its vertex in the center of a sphere, cuts off an area of the surface of a sphere equal to that of a square with sides of length equal to the radius of the sphere. Symbol: sr

3.3 Derived Units. Any additional quantity can be measured using combinations of the base and supplementary units just given. Some examples are:

Quantity	Unit	Symbol	Formula
acceleration—linear	metre per second squared		m/s^2
—angular	radian per second squared		rad/s^2
area	metre squared		m^2
capacitance	farad	F	$A \cdot s/V$
conductivity (thermo)	watt per metre kelvin		$W/m \cdot K$
density	kilogram per metre cubed		kg/m^3
electromotive force	volt	V	W/A
electricity (quantity)	coulomb	C	$A \cdot s$
energy, work, heat, and impact strength	joule	J	$N \cdot m$
field strength, electric	volt per metre		V/m

(Derived Units Continued)

Quantity	Unit	Symbol	Formula
force	newton	N	$kg \cdot m/s^2$
frequency	hertz	Hz	s^{-1}
inductance	henry	H	$V \cdot s/A$
luminous flux	lumen	lm	$cd \cdot sr$
illumination	lux	lx	lm/m^2
magnetic flux	weber	Wb	$V \cdot s$
magnetic flux density, magnetic induction	tesla	T	Wb/m^2
power	watt	W	J/s
pressure, stress	pascal	Pa	N/m^2
resistance	ohm	Ω	V/A
velocity—linear	metre per second		m/s
—angular	radian per second		rad/s
volume	metre cubed		m^3

3.4 Prefixes. SI prefixes should be used to indicate orders of magnitude, thus simplifying numeric terms and providing a convenient substitute for writing powers of ten as generally preferred in computation. For example, 16 800 metres or 16.8 x 10^3 metres becomes 16.8 kilometres. See 8.1 for use of prefixes.

Exponential Expression	Multiplication Factor	Prefix	Symbol
10^{12}	1 000 000 000 000	tera	T
10^9	1 000 000 000	giga	G
10^6	1 000 000	mega	M
10^3	1 000	kilo	k
10^2	100	hecto*	h
10	10	deka*	da
10^{-1}	0.1	deci*	d
10^{-2}	0.01	centi*	c
10^{-3}	0.001	milli	m
10^{-6}	0.000 001	micro	μ
10^{-9}	0.000 000 001	nano	n
10^{-12}	0.000 000 000 001	pico	p
10^{-15}	0.000 000 000 000 001	femto	f
10^{-18}	0.000 000 000 000 000 001	atto	a

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*Not recommended. Prefixes should be selected in steps of 10^3 so that the resultant number before the prefix is between 0.1 and 1000 (see 8.1).

4. Other Units Used with SI

There are certain units which, although not part of SI, are in widespread use and are acceptable for use with SI.

Unit	Symbol	Value in SI units
minute	min	1 min = 60 s
hour	h	1 h = 60 min = 3600 s
day	d	1 d = 24 h = 86 400 s
degree (angular)	deg	1 deg = (π / 180) rad = 0.0175 rad
bar	bar	1 bar = 0.1 MPa = 10^5 Pa
litre	l*	1 l = 0.001 m^3 = 1 dm^3
degree Celsius	°C	1 °C = 1 K (interval)
knot		1 nautical mile per hour = 0.5144 m/s
nautical mile		1 nautical mile = 1.852 km
angstrom	Å	1 Å = 0.1 nm = 10^{-10} m
atmosphere	atm	1 atm = 101 325 Pa
hectare	ha	1 ha = 1 hm^2 = 10^4 m^2

*The lower case "ell" is the recognized symbol for litre but on most typewriters (and typesetting machines) the lower case "ell" and the figure one are nearly identical. Accordingly, it is preferable to spell the word in full. However, ml may be used for millilitre, because confusion would no longer be possible.

5. Nonrecommended Units

Some metric units have been used in particular applications, but the International Committee of Weights and Measures considers that they should not be used with SI. Some of these units are:

Unit	Value in SI units	Unit	Value in SI units
calorie**	1 cal = 4.184 J	kilogram force	1 kgf = 9.806 650 N
dyne	1 dyn = 10^{-5} N	micron	1 μ = 10^{-6} m
erg	1 erg = 10^{-7} J	torr	1 torr = 133.32 Pa

**thermochemical

6. Units Pertaining to Welding

The following chart shows the recommended SI units to be used in welding nomenclature. The selection of these terms was based on use of (1) SI base units where practicable, (2) numbers of reasonable size, and (3) accepted units currently in use or anticipated to be used.

Factors for converting from the commonly used U.S. customary units to these recommended units are given in 7.2.

Units Pertaining to Welding

Property	Unit	Symbol
area dimensions	millimetre squared	mm^2
current density	ampere per millimetre squared	A/mm^2
deposition rate	kilogram per hour	kg/h
electrical resistivity	ohm metre	Ω · m
electrode force (upset, squeeze, hold)	newton	N
flow rate (gas and liquid)	litre per minute	litre per min
fracture toughness	meganewton metre $^{-3/2}$	MN · m $^{-3/2}$
impact strength	joule	J = N · m
linear dimensions	millimetre	mm
power density	watt per metre squared	W/m^2
pressure (gas and liquid)	pascal	Pa = N/m^2
tensile strength	pascal	Pa = N/m^2
thermal conductivity	watt per metre kelvin	W/m · K
travel speed	millimetre per second	mm/s
volume dimensions	millimetre cubed	mm^3
wire feed rate	millimetre per second	mm/s

7. Conversions

7.1 General

Property	To Convert From	To	Multiply By
acceleration (angular)	revolution per minute squared	rad/s^2	1.745 329 x10^{-3}
acceleration (linear)	in./min^2	m/s^2	7.055 556 x 10^{-6}
	ft/min^2	m/s^2	8.466 667 x 10^{-5}
	in./min^2	mm/s^2	7.055 556 x 10^{-3}
	ft/min^2	mm/s^2	8.466 667 x 10^{-2}
	ft/s^2	m/s^2	3.048 000 x 10^{-1}
angle, plane	deg	rad	1.745 329 x 10^{-2}
	minute	rad	2.908 882 x 10^{-4}
	second	rad	4.848 137 x 10^{-6}

(General Conversions, Continued)

Property	To Convert From	To	Multiply By
area	in.^{2}	m^2	6.451 600 x 10^{-4}
	ft^2	m^2	9.290 304 x 10^{-2}
	yd^2	m^2	8.361 274 x 10^{-1}
	in.^{2}	mm^2	6.451 600 x 10^2
	ft^2	mm^2	9.290 304 x 10^4
	acre (U.S. Survey)	m^2	4.046 873 x 10^3
density	pound mass per inch cubed	kg/m^3	2.767 990 x 10^4
	pound mass per foot cubed	kg/m^3	1.601 846 x 10
energy, work, heat, & impact energy	foot pound force	J	1.355 818
	foot poundal	J	4.214 011 x 10^{-2}
	Btu*	J	1.054 350 x 10^3
	calorie*	J	4.184 000
	watt hour	J	3.600 000 x 10^3
force	kilogram force	N	9.806 650
	pound force	N	4.448 222
impact strength	(see energy)		
length	in.	m	2.540 000 x 10^{-2}
	ft	m	3.048 000 x 10^{-1}
	yd	m	9.144 000 x 10^{-1}
	rod (U.S. Survey)	m	5.029 210
	mile (U.S. Survey)	km	1.609 347
mass	pound mass (avdp)	kg	4.535 924 x 10^{-1}
	tonne (metric)	kg	1.000 000 x 10^3
	ton (short, 2000 lbm)	kg	9.071 847 x 10^2
	slug	kg	1.459 390 x 10
power	horsepower (550 ft · lbf/s)	W	7.456 999 x 10^2
	horsepower (electric)	W	7.460 000 x 10^2
	Btu/min*	W	1.757 250 x 10
	calorie per minute*	W	6.973 333 x 10^{-2}
	foot-pound force per minute	W	2.259 697 x 10^{-2}
pressure and stress	pound force per inch squared	Pa	6.894 757 x 10^3
	bar	Pa	1.000 000 x 10^5
	atmosphere	Pa	1.013 250 x 10^5
	kip/in.^{2}	Pa	6.894 757 x 10^6

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*thermochemical

(General Conversions, Continued)

Property	To Convert From	To	Multiply By
temperature	degree Celsius, t_C	K	$t_K = t_C + 273.15$
	degree Fahrenheit, t_F	K	$t_K = (t_F + 459.67)/1.8$
	degree Rankine, t_R	K	$t_K = t_R/1.8$
	degree Fahrenheit, t_F	°C	$t_C = (t_F - 32)/1.8$
	kelvin, t_K	°C	$t_C = t_K - 273.15$
tensile strength	(see pressure)		
torque	inch pound force	N · m	1.129 848 x 10^{-1}
	foot pound force	N · m	1.355 818
velocity (angular)	revolution per minute	rad/s	1.047 198 x 10^{-1}
	degree per minute	rad/s	2.908 882 x 10^{-4}
	revolution per minute	deg/min	3.600 000 x 10^{2}
velocity (linear)	in./min	m/s	4.233 333 x 10^{-4}
	ft/min	m/s	5.080 000 x 10^{-3}
	in./min	mm/s	4.233 333 x 10^{-1}
	ft/min	mm/s	5.080 000
	mile/hour	km/h	1.609 344
volume	in.^{3}	m^3	1.638 706 x 10^{-5}
	ft^3	m^3	2.831 685 x 10^{-2}
	yd^3	m^3	7.645 549 x 10^{-1}
	in.^{3}	mm^3	1.638 706 x 10^{4}
	ft^3	mm^3	2.831 685 x 10^{7}
	in.^{3}	litre	1.638 706 x 10^{-2}
	ft^3	litre	2.831 685 x 10
	gallon	litre	3.785 412

7.2 Special Conversions for Welding. Preferred units are given in parentheses.

Property	To Convert From	To	Multiply By
area dimensions (mm^2)	in.^{2}	mm^2	6.451 600 x 10^2
	mm^2	in.^{2}	1.550 003 x 10^{-3}
current density (A/mm^2)	A/in.^{2}	A/mm^2	1.550 003 x 10^{-3}
	A/mm^2	A/in.^{2}	6.451 600 x 10^2
deposition rate (kg/h)	lb/h	kg/h	0.45*
	kg/h	lb/h	2.2*
electrical resistivity (Ω·m)	Ω·cm	Ω·m	1.000 000 x 10^{-2}
	Ω·m	Ω·cm	1.000 000 x 10^2
electrode force (N)	pound-force	N	4.448 222
	kilogram-force	N	9.806 650
	N	lbf	2.248 089 x 10^{-1}
flow rate (litre per minute)	ft^3/h	litre per minute	4.719 475 x 10^{-1}
	gallon per hour	litre per minute	6.309 020 x 10^{-2}
	gallon per minute	litre per minute	3.785 412
	cm^3/min	litre per minute	1.000 000 x 10^{-3}
	litre per minute	ft^3/h	2.118 880
	cm^3/min	ft^3/h	2.118 880 x 10^{-3}
fracture toughness (MN m$^{-3/2}$)	ksi · in.$^{1/2}$	MN · m$^{-3/2}$	1.098 855
	MN ·m$^{-3/2}$	ksi · in.$^{1/2}$	0.910 038
heat input (J/m)	J/in.	J/m	3.937 008 x 10
	J/m	J/in.	2.540 000 x 10^{-2}
linear measurements (mm)	in.	mm	2.540 000 x 10
	ft	mm	3.048 000 x 10^2
	mm	in.	3.937 008 x 10^{-2}
	mm	ft	3.280 840 x 10^{-3}
power density (W/m^2)	W/in.^{2}	W/m^2	1.550 003 x 10^3
	W/m^2	W/in.^{2}	6.451 600 x 10^{-4}

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*Approximate conversion.

(Conversions for Welding, Continued)

Property	To Convert From	To	Multiply By
pressure (gas & liquid) (Pa)	psi	Pa	6.894 757 x 10^{3}
	lb/ft^{2}	Pa	4.788 026 x 10^{1}
	N/mm^{2}	Pa	1.000 000 x 10^{6}
	Pa	psi	1.450 377 x 10^{-4}
	Pa	lb/ft^{2}	2.088 543 x 10^{-2}
	Pa	N/mm^{2}	1.000 000 x 10^{-6}
	torr (mm Hg at 0 °C)	Pa	1.333 22 x 10^{2}
	micron (μm Hg at 0 °C)	Pa	1.333 22 x 10^{-1}
	Pa	torr	7.500 64 x 10^{-3}
	Pa	micron	7.500 64
tensile strength (Pa)	psi	Pa	6.894 757 x 10^{3}
	lb/ft^{2}	Pa	4.788 026 x 10^{1}
	N/mm^{2}	Pa	1.000 000 x 10^{6}
	Pa	psi	1.450 377 x 10^{-4}
	Pa	lb/ft^{2}	2.088 543 x 10^{-2}
	Pa	N/mm^{2}	1.000 000 x 10^{-6}
thermal conductivity (W/m · K)	cal/cm·s·°C	W/m · K	4.184 000 x 10^{2}
travel speed, wire feed speed (mm/s)	in./min	mm/s	4.233 333 x 10^{-1}
	mm/s	in./min	2.362 205

7.3 SI Equivalents for Electrode and Fillet Sizes. The following SI values are approximate equivalents for conversion on drawings, specifications, and so forth. These values are for conversion only and are not intended for new designs where a more rational series for sizing may be used.

Electrode Sizes

in.	mm
0.030	0.76
0.035	0.89
0.040	1.02
0.045	1.14
1/16	1.59
5/64	1.98
3/32	2.38
1/8	3.18
5/32	3.97
3/16	4.76
1/4	6.35

Fillet Sizes

in.	mm
1/8	3
5/32	4
3/16	5
1/4	6
5/16	8
3/8	10
7/16	11
1/2	13
5/8	16
3/4	19
7/8	22
1	25

7.4 Rules for Conversion and Rounding

Conversion and rounding are necessary only during a transition period. In manufacturing practice, this occurs most frequently when designing is done in SI units and fabrication must be done in conventional units. In this case the conversion is from SI to U.S. customary units. The necessity for conversion and rounding disappears when all steps can be done in one system.

Exact conversion from one system to another usually results in numbers which are inconvenient to use. Also, the intended precision is exaggerated when the conversion results in more decimal places than are necessary.

The degree of accuracy of the converted number is based on the intended or necessary precision of the product. The precision must be determined by the designer or user. The guidelines given herein may then be applied to arrive at appropriate numerical equivalents.

7.4.1 Inch-Millimetre Conversion. Exact conversion from inches to millimetres often results in unnecessarily long decimal numbers. Showing more decimal places than necessary leads to misinterpretation, uses valuable space, and increases the possibility of error. The numbers should be rounded to eliminate insignificant decimal places, consistent with the accuracy required. The rounding of equivalent millimetre dimensions should be handled as described here.

7.4.1.1 Nominal Dimensions. The closest practical indication of equivalent inch and millimetre values occurs when the millimetre value is shown to one less decimal place than its inch equivalent. For example, 0.365 in. equals 9.27 mm. However, fractional inch conversions may exaggerate the intended precision. For example, the rule may not be applicable when changing 1⅞ in. to 47.63 mm unless the precision of 1⅞ in. was 1.875 inches. Some dimensions must be converted more accurately to insure interchangeability of parts. The methods described in 7.4.3 will accomplish this requirement.

7.4.1.2 Tolerances. The following round off criteria should be used when it is necessary to insure the physical and functional interchangeability of parts made and inspected using either system of measurement, and when inch dimensions are converted to millimetre equivalents and shown on dual dimensioned drawings:

(1) *Basic and Maximum-Minimum Dimensions.* Basic dimensions are inherently precise and should be converted exactly. When the function of a feature requires that the maximum and minimum limits in millimetres be within the inch limits, maximum limits are rounded down and minimum limits are rounded up.

(2) *Dimensions Without Tolerance.* Untoleranced dimensions are converted to exact millimetre equivalents and rounded to equivalent or better precision, depending on the purpose of the dimension.

(3) *Toleranced Dimensions.* The normal practice for toleranced dimensions is to use Method A as described in 7.4.1.2.2. However, when the function of a feature requires that the millimetre equivalents must be within the inch dimension tolerance limits in all cases, Method B is used as described in 7.4.1.2.3.

7.4.1.2.1 Number of Decimal Places in Tolerances. Table 1 lists the criteria for retaining decimal places in millimetre equivalents of inch tolerances. The number of decimal places is determined by the inch tolerance span.

7.4.1.2.2 Round-Off Method A. This method produces rounded millimetre limits which will not vary from the inch limits by more than 5.0 percent. Thus, for a dimension with a tolerance of 0.001 in., the maximum amount that the rounded millimetre can be greater or less than the inch limits is 0.000 050 inch. To determine the millimetre equivalents of inch dimensions by Method A, these steps should be followed:

(1) The maximum and minimum limits in inches should be determined.

(2) The tolerance span in inches should be determined.

(3) The inch limit dimensions should be converted to millimetre values using exact millimetre equivalents.

(4) Based on the tolerance span in inches, the number of decimal places to be retained should be established using Table 1 and the millimetre values rounded according to the rounding rules given in 7.4.3. See the example in Table 2.

7.4.1.2.3 Round-Off Method B. This method is used when the resulting millimetre values must be within the inch value limits. In extreme cases this method may result in the lower limit millimetre value being greater than the lower inch value by a maximum of five percent. Similarly, the upper limit millimetre value may be smaller than the upper inch by a maximum of five percent. Thus, the tolerance span may be reduced by up to ten percent of the original design inch tolerance; however, it is very unlikely that the five percent maximum will occur at both limits simultaneously. To determine the millimetre equivalents of inch dimensions by Method B, these steps should be followed:

(1) The maximum and minimum limits in inches should be determined.

(2) The tolerance span in inches should be determined.

(3) The inch tolerances should be converted to exact millimetre equivalents.

(4) Based on the tolerance span in inches, the number of decimal places to be retained in the millimetre values should be established using Table 1.

(5) If rounding is required, millimetre values should be rounded to fall within the inch tolerance limits; that is, to the next lower value for the upper limit and to the next higher value for the lower limit. See the example in Table 2.

7.4.2 Other Conversions. To establish meaningful and equivalent converted values, a careful determination must be made of the number of significant digits to be retained so as not to sacrifice or exaggerate the precision of the value. To convert a pressure of 1000 psi to 6.894 757 MPa is not practical because the value does not warrant expressing the conversion using six decimal places.* The intended precision of a value can be established from

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*Applying the policy of 7.4.2.4, a practical conversion is 7 MPa.

Table 1—Millimetre value round-off using inch tolerance span

Inch tolerance span		Round off millimetre value to these decimal places	
At Least	Less Than		
0.000 04	0.0004	4 places	0.00XX
0.0004	0.004	3 places	0.0XX
0.004	0.04	2 places	0.XX
0.04	0.4	1 place	X.X
0.4 and over		Whole number	XX

Example: The span of a $^{+0.005}_{-0.003}$ in. tolerance is 0.008. Since 0.008 is between 0.004 and 0.04, two decimal places are retained in individually converting 0.005 and 0.003.

Table 2—Comparison of round-off Methods A and B

Inch Dimension:	1.934-1.966 in.
Tolerance Span:	0.032 in.
Conversion:	1.934 in. = 49.1236 mm (exactly) 1.966 in. = 49.9364 mm (exactly)
Table 1:	0.032 lies between 0.004 and 0.04; therefore, the millimetre values are to be rounded to two decimal places.
Method A:	Rounding off 49.1236 and 49.9364 to two decimal places via the method shown in 7.4.3 gives 49.12 mm and 49.94 mm, respectively.
	Method A gives a tolerance span of 0.82 mm.
Method B:	Rounding to within the inch tolerance limits requires the 49.1236 mm limit to be rounded up, giving 49.13 mm as the lower limit, and the 49.9364 mm limit to be rounded down, giving 49.93 mm as the upper limit.
	Method B gives a tolerance span of 0.80 mm.

The tolerance span of 0.032 in. equals 0.8128 mm. In this example, Method A would increase the tolerance span by 0.0072 mm (0.88 percent), whereas Method B would decrease the tolerance span by 0.0128 mm (1.6 percent).

the specified tolerance or by an understanding of the equipment, process, or accuracy of the measuring device.

7.4.2.1 Values With a Specified Tolerance. A tolerance on a value provides a good indication of the intended precision. A general rule for determining the intended precision of a toleranced value is to assume that it is one-tenth of the total tolerance. Since the intended precision of the converted value should be no greater than that of the original, the total tolerance is divided by ten and converted. The proper significant digits are retained in both the converted value and the converted tolerance so that the last significant digit retained is in units no larger than one-tenth the converted tolerance. The following examples illustrate this rule:

(1) 200 ± 15 psi pressure converted to Pa. Total tolerance is 30 psi, divided by 10 is 3 psi, which converted is about 20.7 kPa. The units to use equal 10 kPa (rather than 100 kPa or 1 kPa) since 10 kPa is the largest unit smaller than 20.7 kPa, which is one-tenth the converted tolerance.
200+ 15 psi = 1378.9514 ±103.421 355 kPa which rounds to 1380 ± 100 kPa = 1.38 ± 0.10 MPa.

(2) 25 ± 0.1 oz of alcohol converted to litres. Total tolerance is 0.2 oz, divided by 10 is 0.02 oz, converted is about 0.6 ml.

Units to use: 0.1 ml (rather than 10 ml or 1 ml).
25 ± 0.1 oz = 739.34 ± 2.957 ml which rounds to 739.3 ± 3.0 ml

7.4.2.2 Values With no Specified Tolerance. If a value is shown without a tolerance, the intended precision relates to the number of significant digits shown by assuming that the value has been rounded from a greater number of digits. The intended precision is established as being plus or minus one-half unit of the last significant digit in which the value is stated. However, as the last significant digit moves away from the decimal point, the intended precision may become distorted if this rule is used indiscriminately. In these cases the intended precision is estimated as being some digit closer to the decimal point based on the nature of the value's use. Since the intended precision of the converted value should be no greater than that of the original, the intended precision is established and converted. The proper significant digits are retained in the converted value so that the last significant digit retained is in units no larger than the converted intended precision. The following examples illustrate this policy:

(1) 157 miles (rounded from any value between 156.5 and 157.5 miles) to kilometres. Total intended precision is 1 mile, which is about 1.6 km.

Units to use: 1 km
157 miles = 252.613 km, which rounds to 253 km

(2) 50 000 psi tensile strength converted to pascals. Total estimated precision is 500 psi (3.4 MPa) from the nature of use and the precision of the measuring equipment.

Units to use: 1 MPa
50 000 psi = 344.7379 MPa, which rounds to 345 MPa
(See also 7.4.2.4 for less precise conversion.)

(3) An electrical lead 8 ft long, converted to metres. The total intended precision is 1 ft, or about 0.3 m.

Units to use: 0.1 m
8 ft = 2.4384 m, which rounds to 2.4 m

7.4.2.3 Temperature. All temperatures expressed in whole numbers of degrees Fahrenheit are converted to the nearest 0.1 kelvin or degree Celsius. Fahrenheit temperatures indicated to be approximate, maximum, or minimum, or to have a tolerance of ± 5 °F or more, are converted to the nearest whole number in kelvin or degrees Celsius. Fahrenheit temperatures having a tolerance of plus or minus 100 °F or more are converted to the nearest 10 kelvin or degrees Celsius.

EXAMPLE: 100 ± 5 °F = 38 ± 3 °C = 311 ± 3 K
1000 ± 100 °F = 540 ± 30 °C = 810 ± 30 K

7.4.2.4 Pressure or Stress Conversion. In most cases stress values are converted from ksi to the nearest one megapascal. Pressure or stress values having an uncertainty of more than two percent may be converted without rounding by the approximate factors:

1 psi = 7 kPa   1 ksi = 7 MPa

7.4.3 Round Off Rules. When the next digit beyond the last digit to be retained is less than five, the last digit retained is not changed.

EXAMPLE: 4.463 25 rounded to three decimal places is 4.463

7.4.3.1 When the digits beyond the last digit to be retained amount to more than five followed by zeros, the last digit retained is increased by one.

EXAMPLE: 8.376 52 rounded to three decimal places is 8.377

7.4.3.2 Where the digit beyond the last digit to be retained is exactly five followed by zeros (expressed or implied), the last digit to be retained, if even, is unchanged but, if odd, is increased by one.

EXAMPLE: 4.365 00 becomes 4.36 when rounded to two decimal places
4.355 00 also becomes 4.36 when rounded to two decimal places

7.4.3.3 The final rounded value is obtained from the precise value to be rounded, not from a series of successive roundings. To maintain precision during conversion, the millimetre equivalent value is carried out to at least one extra decimal place. Generally, it is best to use exact values and round off only the final result.

8. Style and Usage

8.1 Application and Usage of Prefixes

8.1.1 Prefixes should be used with SI units to indicate orders of magnitude. Prefixes provide convenient substitutes for using powers of 10, and they eliminate insignificant digits.

Correct	Incorrect
12.3 km	12 300 m 12.3 x 10^3 m

8.1.2 Prefixes in steps of 1000 are recommended. The use of the prefixes hecto, deka, deci, and centi should be avoided.

Correct	Incorrect
mm, m, km	hm, dam, dm, cm

8.1.3 Prefixes should be chosen so that the numerical value lies between 0.1 and 1000.

8.1.3.1 For special situations such as tabular presentations, the same unit, multiple or submultiple may be used even though the numerical value exceeds the range of 0.1 to 1000.

8.1.4 Multiple and hyphenated prefixes should not be used.

Correct	Incorrect
pF, GF, GW	μμ F, Mkg, kMW, G-W

8.1.5 It is generally desirable to use only base and derived units in the denominator. Prefixes are used with the numerator unit to give numbers of appropriate size (see 8.1.3).

Preferred	Nonpreferred
200 J/kg, 5 Mg/m^3	0.2 J/g, 1 kg/mm

8.1.6 Prefixes are to be attached to the base SI units with the exception of the base unit for mass, the kilogram, which contains a prefix. In this case the required prefix is attached to gram.

8.1.7 Prefixes should not be mixed unless magnitudes warrant a difference.

Correct	Incorrect
5 mm long x 10 mm high	5 mm long x 0.1 m high

Exception
4 mm diam x 50 m long

8.2 Use of Nonpreferred Units

8.2.1 The mixing of units from different systems should be avoided.

Correct	Incorrect
kilogram per metre cubed (kg/m^3)	kilogram per gallon (kg/gal)

8.2.2 The use of non-SI units should be limited to those which have been approved by the National Bureau of Standards such as for temperature, time, and angle (see list in Section 4).

8.2.2.1 Other non-SI units should not be used (see list in Section 5).

8.3 Mass, Force, and Weight. The unit of mass is the kilogram. The kilogram-force is non-SI and should not be used.

The unit of force is the newton (N).

Correct	Incorrect
N/m^2 or Pa, N · m/s or W	kgf/m^2

The common term "weight" should not be used in technical literature.

8.4 Temperature. The SI unit for temperature is the kelvin. The degree Celsius is, however, widely used in engineering work and may be used where considered necessary or desirable for clearer understanding. The degree Celsius was formerly called the "degree centigrade." The degree Fahrenheit should not be used.

8.5 Time. The SI unit for time is the second. The use of minute, hour, and day is permissible but not preferred.

8.6 Angles. The SI unit for plane angles is the radian. The SI unit for solid angles is the steradian. The degree (deg) may be used where appropriate or convenient and should be decimalized.

EXAMPLE: 5.8 deg

Angular minutes and seconds should be avoided.

8.7 Stress and Pressure. The SI unit for pressure and stress is the pascal, which is newton per metre squared (N/m^2). The bar is an acceptable but nonpreferred unit of pressure.

Other pressure and stress terms such as the following shall not be used.

Incorrect

kilogram-force per square centimetre (kgf/cm^2)
torr
pound-force per square inch (psi)

8.8 Capitalization. Celsius is the only SI unit name which is always capitalized. Other SI unit names are capitalized only at the beginning of a sentence. Examples: newton, pascal, metre, kelvin, hertz, degree Celsius.

SI unit symbols are not capitalized except for the several units derived from a proper name.

EXAMPLE: (1) A (ampere), K (kelvin), W (watt), N (newton), J (joule), etc.
(2) m (metre), kg (kilogram), etc.

Only three prefix symbols are capitalized, namely, T (tera), G (giga), and M (mega).

8.9 Plurals. Unit symbols are the same for singular and plural. Unit names form their plurals in the usual manner.

EXAMPLE: 50 newtons (50 N) 25 grams (25 g)

8.10 Punctuation. Periods are not to be used after SI unit symbols except at the end of a sentence.

Periods (not commas) are used as decimal markers. Periods are not used in unit symbols or in conjunction with prefixes.

Correct	Incorrect
5.7 mm	5.7 m.m.

A raised dot is used to indicate the product of two unit symbols. A space is used between unit names to indicate the product.

EXAMPLE: metre second (m · s) kilogram metre kg · m)

A slash or solidus (/) or a negative exponent is used as follows to indicate the quotient of two unit symbols.

(1) Only one solidus should be used in a combination.

(2) A solidus and a negative exponent can be used together, even together with parentheses, for complicated cases.

(3) Numerical values are to be used so that the denominator is unity.

Correct	Incorrect
m/s, m · s^{-1}, 4 m/s, m/s^2, m · kg/(s^3 · A)	m/0.1 s, m/s/s, m · kg/s^3/A, kg/s/m^2

The word "per" is used to indicate the quotient of two unit names.

EXAMPLE: metre per second squared (m/s^2)

An exponent is used with unit symbols to show powers.

EXAMPLE: m^3

The words "squared" and "cubed" are used with unit names to indicate powers.

EXAMPLE: metre squared (m^2) metre cubed (m^3)

8.11 Number Grouping

8.11.1 Numbers made up of five or more digits should be written with a space separating each group of three digits counting both to the left and right of the decimal point. With four digit numbers, the spacing is optional.

8.11.2 Commas will not be used between the groups of three digits.

Correct	Incorrect
1 420 462.1; 0.045 62 1452 or 1 452	1,420,462.1; 0.04562

8.12 Miscellaneous Styling

8.12.1 A space is to be used between the numerical value and the unit symbol.

Correct	Incorrect
4 mm	4mm

8.12.2 Unit symbols and names are never used together in a single expression:

Correct	Incorrect
metre per second (m/s)	metre/s

8.12.3 Numbers are expressed as decimals, not as fractions. The decimal should be preceded by a zero when the number is less than unity.

Correct	Incorrect
0.5 kg, 1.74 m	1/2 kg, .5 kg, 1 ¾ m

8.12.4 SI unit symbols should be printed in upright type rather than slanted, script, etc.

8.12.5 Typed rather than hand-drawn prefixes should be used when possible. The spelled word may be used in preference to the use of hand-drawn symbols.

8.12.6 When it is necessary or desirable to use U.S. customary units in an equation or table, SI units or quantities should be restated in a separate equation, table or column in a table. As an alternate, a note may be added to the equation or table giving the factors to be used in converting the calculated result in U.S. customary to preferred SI units. The SI equivalents may follow and be inserted in parentheses.

COMMONLY USED METRIC CONVERSIONS

Inch-Millimetre Conversion

1 in. = 25.4 mm exactly

To convert inches to millimetres, multiply the inch value by 25.4.
To convert millimetres to inches, divide the millimetre value by 25.4.

Inch and Millimetre Decimal Equivalents of Fractions of an Inch

Inch		Millimetre	Inch		Millimetre
Fraction	Decimal		Fraction	Decimal	
1/64	0.015 625	0.396 875	33/64	0.515 625	13.096 875
1/32	0.031 250	0.793 750	17/32	0.531 250	13.493 750
3/64	0.046 875	1.190 625	35/64	0.546 875	13.890 625
1/16	0.062 500	1.587 500	9/16	0.562 500	14.287 500
5/64	0.078 125	1.984 375	37/64	0.578 125	14.684 375
3/32	0.093 750	2.381 250	19/32	0.593 750	15.081 250
7/64	0.109 375	2.778 125	39/64	0.609 375	15.478 125
1/8	0.125 000	3.175 000	5/8	0.625 000	15.875 000
9/64	0.140 625	3.571 875	41/64	0.640 625	16.271 875
5/32	0.156 250	3.968 750	21/32	0.656 250	16.668 750
11/64	0.171 875	4.365 625	43/64	0.671 875	17.065 625
3/16	0.187 500	4.762 500	11/16	0.687 500	17.462 500
13/64	0.203 125	5.159 375	45/64	0.703 125	17.859 375
7/32	0.218 750	5.556 250	23/32	0.718 750	18.256 250
15/64	0.234 375	5.953 125	47/64	0.734 375	18.653 125
1/4	0.250 000	6.350 000	3/4	0.750 000	19.050 000
17/64	0.265 625	6.746 875	49/64	0.765 625	19.446 875
9/32	0.281 250	7.143 750	25/32	0.781 250	19.843 750
19/64	0.296 875	7.540 625	51/64	0.796 875	20.240 625
5/16	0.312 500	7.937 500	13/16	0.812 500	20.637 500
21/64	0.328 125	8.334 375	53/64	0.828 125	21.034 375
11/32	0.343 750	8.731 250	27/32	0.843 750	21.431 250
23/64	0.359 375	9.128 125	55/64	0.859 375	21.828 125
3/8	0.375 000	9.525 000	7/8	0.875 000	22.225 000
25/64	0.390 625	9.921 875	57/64	0.890 625	22.621 875
13/32	0.406 250	10.318 750	29/32	0.906 250	23.018 750
27/64	0.421 875	10.715 625	59/64	0.921 875	23.415 625
7/16	0.437 500	11.112 500	15/16	0.937 500	23.812 500
29/64	0.453 125	11.509 375	61/64	0.953 125	24.209 375
15/32	0.468 750	11.906 250	31/32	0.968 750	24.606 250
31/64	0.484 375	12.303 125	63/64	0.984 375	25.003 125
1/2	0.500 000	12.700 000	1	1.000 000	25.400 000

Pressure and Stress Equivalents—Pounds-Force per Square Inch and Thousand Pounds-Force per square Inch to Megapascals

This table may be used to obtain SI equivalents of values expressed in psi or ksi. SI values are usually expressed in kPa when original value is in psi and in MPa when original value is in ksi.

This table may be extended to values below 1 or above 100 psi (or ksi) by manipulation of the decimal point and addition.

1 psi = 6894.757 Pa

To convert psi to pascals, multiply the psi value by 6.894 757 x 10^3.
To convert pascals to psi, divide the pascal value by 6.894 757 x 10^3.

psi ksi	0	1	2	3	4	5	6	7	8	9
					kPa MPa					
0	0.0000	6.8948	13.7895	20.6843	27.5790	34.4738	41.3685	48.2633	55.1581	62.0528
10	68.9476	75.8423	82.7371	89.6318	96.5266	103.4214	110.3161	117.2109	124.1056	131.0004
20	137.8951	144.7899	151.6847	158.5794	165.4742	172.3689	179.2637	186.1584	193.0532	199.9480
30	206.8427	213.7375	220.6322	227.5270	234.4217	241.3165	248.2113	255.1060	262.0008	268.8955
40	275.7903	282.6850	289.5798	296.4746	303.3693	310.2641	317.1588	324.0536	330.9483	337.8431
50	344.7379	351.6326	358.5274	365.4221	372.3169	379.2116	386.1064	393.0012	399.8959	406.7907
60	413.6854	420.5802	427.4749	434.3697	441.2645	448.1592	455.0540	461.9487	468.8435	475.7382
70	482.6330	489.5278	496.4225	503.3173	510.2120	517.1068	524.0015	530.8963	537.7911	544.6858
80	551.5806	558.4753	565.3701	572.2648	579.1596	586.0544	592.9491	599.8439	606.7386	613.6334
90	620.5281	627.4229	634.3177	641.2124	648.1072	655.0019	661.8967	668.7914	675.6862	682.5810
100	689.4757									

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CONVERSIONS FOR FAHRENHEIT—CELSIUS TEMPERATURE SCALES

Find the number to be converted in the center (boldface) column. If converting Fahrenheit degrees, read the Celsius equivalent in the column headed "°C." If converting Celsius degrees, read the Fahrenheit equivalent in the column head "°F."

°C		°F	°C		°F	°C		°F	°C		°F
—273	**—459**		—40	**—40**	—40	24.4	**76**	168.8	199	**390**	734
—268	**—450**		—34	**—30**	—22	25.6	**78**	172.4	204	**400**	752
—262	**—440**		—29	**—20**	— 4	26.7	**80**	176.0	210	**410**	770
—257	**—430**		—23	**—10**	14	27.8	**82**	179.6	216	**420**	788
—251	**—420**		—17.8	**0**	32	28.9	**84**	183.2	221	**430**	806
—246	**—410**		—16.7	**2**	35.6	30.0	**86**	186.8	227	**440**	824
—240	**—400**		—15.6	**4**	39.2	31.1	**88**	190.4	232	**450**	842
—234	**—390**		—14.4	**6**	42.8	32.2	**90**	194.0	238	**460**	860
—229	**—380**		—13.3	**8**	46.4	33.3	**92**	197.6	243	**470**	878
—223	**—370**		—12.2	**10**	50.0	34.4	**94**	201.2	249	**480**	896
—218	**—360**		—11.1	**12**	53.6	35.6	**98**	204.8	254	**490**	914
—212	**—350**		—10.0	**14**	57.2	36.7	**98**	208.4	260	**500**	932
—207	**—340**		— 8.9	**16**	60.8	37.8	**100**	212.0	266	**510**	950
—201	**—330**		— 7.8	**18**	64.4	43	**110**	230	271	**520**	968
—196	**—320**		— 6.7	**20**	68.0	49	**120**	248	277	**530**	986
—190	**—310**		— 5.6	**22**	71.6	54	**130**	266	282	**540**	1004
—184	**—300**		— 4.4	**24**	75.2	60	**140**	284	288	**550**	1022
—179	**—290**		— 3.3	**26**	78.8	66	**150**	302	293	**560**	1040
—173	**—280**		— 2.2	**28**	82.4	71	**160**	320	299	**570**	1058
—168	**—270**	—454	— 1.1	**30**	86.0	77	**170**	338	304	**580**	1076
—162	**—260**	—436	0.0	**32**	89.6	82	**180**	356	310	**590**	1094
—157	**—250**	—418	1.1	**34**	93.2	88	**190**	374	316	**600**	1112
—151	**—240**	—400	2.2	**36**	96.8	93	**200**	392	321	**610**	1130
—146	**—230**	—382	3.3	**38**	100.4	99	**210**	410	327	**620**	1148
—140	**—220**	—364	4.4	**40**	104.0	100	**212**	414	332	**630**	1166
—134	**—210**	—346	5.6	**42**	107.6	104	**220**	428	338	**640**	1184
—129	**—200**	—328	6.7	**44**	111.2	110	**230**	446	343	**650**	1202
—123	**—190**	—310	7.8	**46**	114.8	116	**240**	464	349	**660**	1220
—118	**—180**	—292	8.9	**48**	118.4	121	**250**	482	354	**670**	1238
—112	**—170**	—274	10.0	**50**	122.0	127	**260**	500	360	**680**	1256
—107	**—160**	—256	11.1	**52**	125.6	132	**270**	518	366	**690**	1274
—101	**—150**	—238	12.2	**54**	129.2	138	**280**	536	371	**700**	1292
— 96	**—140**	—220	13.3	**56**	132.8	143	**290**	554	377	**710**	1310
— 90	**—130**	—202	14.4	**58**	136.4	149	**300**	572	382	**720**	1328
— 84	**—120**	—184	15.6	**60**	140.0	154	**310**	590	388	**730**	1346
— 79	**—110**	—166	16.7	**62**	143.6	160	**320**	608	393	**740**	1364
— 73	**—100**	—148	17.8	**64**	147.2	166	**330**	626	399	**750**	1382
— 68	**— 90**	—130	18.9	**66**	150.8	171	**340**	644	404	**760**	1400
— 62	**— 80**	—112	20.0	**68**	154.4	177	**350**	662	410	**770**	1418
— 57	**— 70**	— 94	21.1	**70**	158.0	182	**360**	680	416	**780**	1436
— 51	**— 60**	— 76	22.2	**72**	161.6	188	**370**	698	421	**790**	1454
— 46	**— 50**	— 58	23.3	**74**	165.2	193	**380**	716	427	**800**	1472

TEMPERATURE CONVERSION TABLE *(Continued)*

°C		°F	°C		°F	°C		°F	°C		°F
432	**810**	1490	738	**1360**	2480	1043	**1910**	3470	1349	**2460**	4460
438	**820**	1508	743	**1370**	2498	1049	**1920**	3488	1354	**2470**	4478
443	**830**	1526	749	**1380**	2516	1054	**1930**	3506	1360	**2480**	4496
449	**840**	1544	754	**1390**	2534	1060	**1940**	3524	1366	**2490**	4514
454	**850**	1562	760	**1400**	2552	1066	**1950**	3542	1371	**2500**	4532
460	**860**	1580	766	**1410**	2570	1071	**1960**	3560	1377	**2510**	4550
466	**870**	1598	771	**1420**	2588	1077	**1970**	3578	1382	**2520**	4568
471	**880**	1616	777	**1430**	2606	1082	**1980**	3596	1388	**2530**	4586
477	**890**	1634	782	**1440**	2624	1088	**1990**	3614	1393	**2540**	4604
482	**900**	1652	788	**1450**	2642	1093	**2000**	3632	1399	**2550**	4622
488	**910**	1670	793	**1460**	2660	1099	**2010**	3650	1404	**2560**	4640
493	**920**	1688	799	**1470**	2678	1104	**2020**	3668	1410	**2570**	4658
499	**930**	1706	804	**1480**	2696	1110	**2030**	3686	1416	**2580**	4676
504	**940**	1724	810	**1490**	2714	1116	**2040**	3704	1421	**2590**	4694
510	**950**	1742	816	**1500**	2732	1121	**2050**	3722	1427	**2600**	4712
516	**960**	1760	821	**1510**	2750	1127	**2060**	3740	1432	**2610**	4730
521	**970**	1778	827	**1520**	2768	1132	**2070**	3758	1438	**2620**	4748
527	**980**	1796	832	**1530**	2786	1138	**2080**	3776	1443	**2630**	4766
532	**990**	1814	838	**1540**	2804	1143	**2090**	3794	1449	**2640**	4784
538	**1000**	1832	843	**1550**	2822	1149	**2100**	3812	1454	**2650**	4802
543	**1010**	1850	849	**1560**	2840	1154	**2110**	3830	1460	**2660**	4820
549	**1020**	1868	854	**1570**	2858	1160	**2120**	3848	1466	**2670**	4838
554	**1030**	1886	860	**1580**	2876	1166	**2130**	3866	1471	**2680**	4856
560	**1040**	1904	866	**1590**	2894	1171	**2140**	3884	1477	**2690**	4874
566	**1050**	1922	871	**1600**	2912	1177	**2150**	3902	1482	**2700**	4892
571	**1060**	1940	877	**1610**	2930	1182	**2160**	3920	1488	**2710**	4910
577	**1070**	1958	882	**1620**	2948	1188	**2170**	3938	1493	**2720**	4928
582	**1080**	1976	888	**1630**	2966	1193	**2180**	3956	1499	**2730**	4946
588	**1090**	1994	893	**1640**	2984	1199	**2190**	3974	1504	**2740**	4964
593	**1100**	2012	899	**1650**	3002	1204	**2200**	3992	1510	**2750**	4982
599	**1110**	2030	904	**1660**	3020	1210	**2210**	4010	1516	**2760**	5000
604	**1120**	2048	910	**1670**	3038	1216	**2220**	4028	1521	**2770**	5018
610	**1130**	2066	916	**1680**	3056	1221	**2230**	4046	1527	**2780**	5036
616	**1140**	2084	921	**1690**	3074	1227	**2240**	4064	1532	**2790**	5054
621	**1150**	2102	927	**1700**	3092	1232	**2250**	4082	1538	**2800**	5072
627	**1160**	2120	932	**1710**	3110	1238	**2260**	4100	1543	**2810**	5090
632	**1170**	2138	938	**1720**	3128	1243	**2270**	4118	1549	**2820**	5108
638	**1180**	2156	943	**1730**	3146	1249	**2280**	4136	1554	**2830**	5126
643	**1190**	2174	949	**1740**	3164	1254	**2290**	4154	1560	**2840**	5144
649	**1200**	2192	954	**1750**	3182	1260	**2300**	4172	1566	**2850**	5162
654	**1210**	2210	960	**1760**	3200	1266	**2310**	4190	1571	**2860**	5180
660	**1220**	2228	966	**1770**	3218	1271	**2320**	4208	1577	**2870**	5198
666	**1230**	2246	971	**1780**	3236	1277	**2330**	4226	1582	**2880**	5216
671	**1240**	2264	977	**1790**	3254	1282	**2340**	4244	1588	**2890**	5234
677	**1250**	2282	982	**1800**	3272	1288	**2350**	4262	1593	**2900**	5252
682	**1260**	2300	988	**1810**	3290	1293	**2360**	4280	1599	**2910**	5270
688	**1270**	2318	993	**1820**	3308	1299	**2370**	4298	1604	**2920**	5288
693	**1280**	2336	999	**1830**	3326	1304	**2380**	4316	1610	**2930**	5306
699	**1290**	2354	1004	**1840**	3344	1310	**2390**	4334	1616	**2940**	5324
704	**1300**	2372	1010	**1850**	3362	1316	**2400**	4352	1621	**2950**	5342
710	**1310**	2390	1016	**1860**	3380	1321	**2410**	4370	1627	**2960**	5360
716	**1320**	2408	1021	**1870**	3398	1327	**2420**	4388	1632	**2970**	5378
721	**1330**	2426	1027	**1880**	3416	1332	**2430**	4406	1638	**2980**	5396
727	**1340**	2444	1032	**1890**	3434	1338	**2440**	4424	1643	**2990**	5414
732	**1350**	2462	1038	**1900**	3452	1343	**2450**	4442	1649	**3000**	5432

$^\circ C = 5/9\,(^\circ F - 32) \qquad ^\circ F = 9/5\,^\circ C + 32$

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