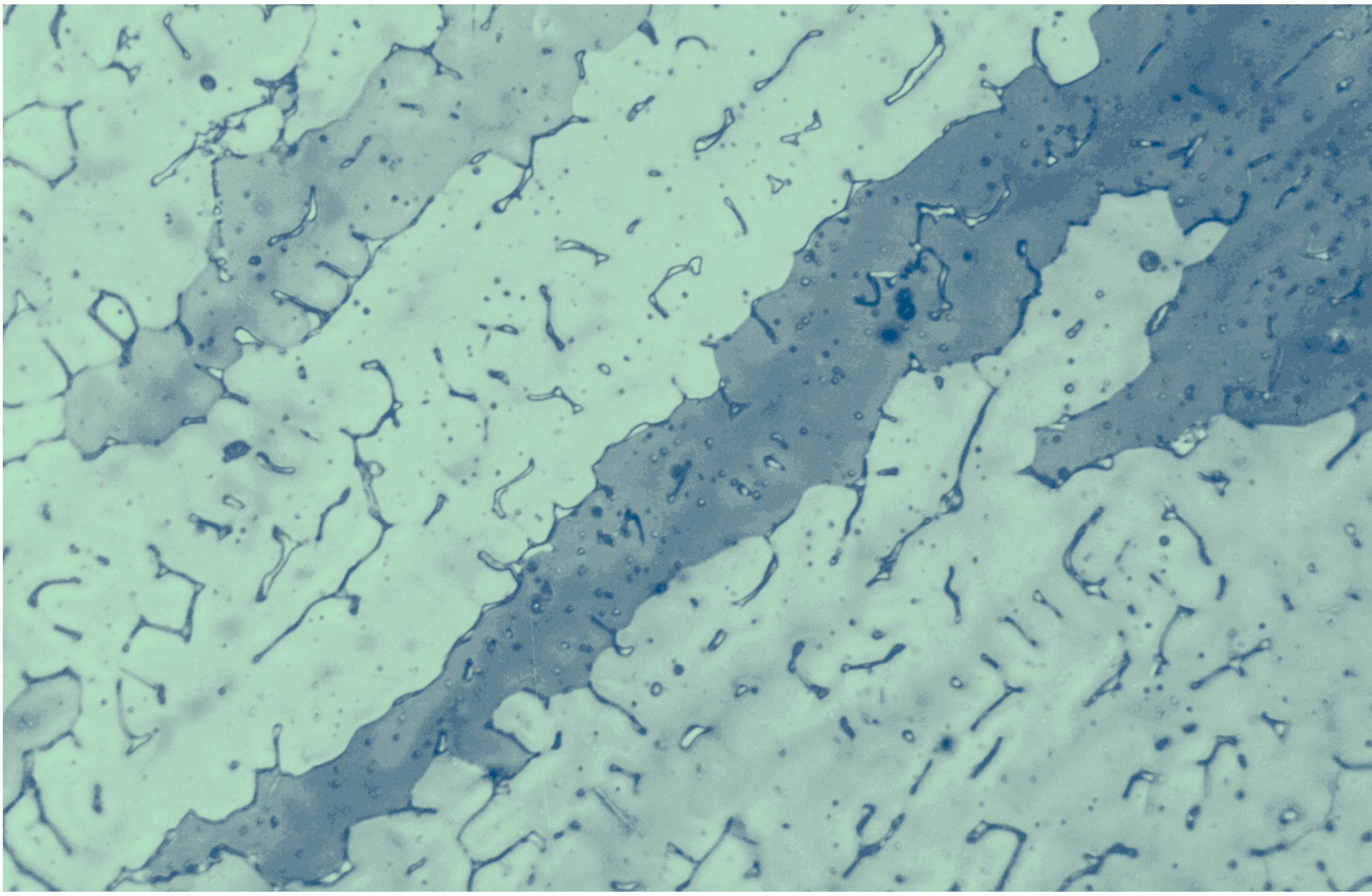
Interim reprint

AvestaPolarit Welding

Stainless steels



Stainless steels – their properties and their suitability for welding

AvestaPolarit
STAINLESS

INDEX

The revisions made to this brochure concern the cover, company name and logotype only, which now adhere to AvestaPolarit's graphic profile. In all other respects, the contents are identical with the information supplied in brochure 9473:2.

STAINLESS STEELS

Their properties and their suitability for welding

by Björn Holmberg, M.Sc.

INTRODUCTION

When we speak of stainless steels in everyday speech, we mean steels alloyed with at least 12% chromium. As a result of reactions with the oxygen in the air, a protective oxide film forms on this alloy and prevents further rapid oxidation. Modern-day stainless steels are also usually alloyed with nickel and molybdenum, which further enhances their corrosion resistance properties.

The purpose of this lecture is to:

- shed light on the importance of microstructure for the corrosion resistance properties, physical properties and mechanical properties of the steels and provide information on their weldability
- give advice on the selection of filler metals for different steel grades
- inform briefly on different filler metal forms
- provide practical advice for the welding of stainless steels.

COMPOSITION AND MECHANICAL PROPERTIES

The mechanical properties, corrosion resistance and weldability of a steel are largely determined by its microstructure. This is in turn determined chiefly by the chemical composition of the steel. Steels are divided into different groups in the following tables (page 2) based on the predominant microstructure.

Austenitic steels

This type of stainless steel is dominant in the market. The group includes the very common AISI 304 and AISI 316 steels, but also the higher-alloy AISI 310S and ASTM N08904. Austenitic steels are characterized by their high content of austenite-formers, especially nickel. They are also alloyed with chromium, molybdenum and sometimes with copper, titanium, niobium and nitrogen. Alloying with nitrogen raises the yield strength of the steels.

Austenitic stainless steels have a very wide range of applications, e.g. in the chemical industry and the food processing industry. The molybdenum-free steels also have very good high-temperature properties and are therefore used in furnaces and heat exchangers. Their good impact strength at low temperatures is often exploited in apparatus such as vessels for cryogenic liquids.

Austenitic steels cannot be hardened by heat treatment. They are normally supplied in the quench-annealed state, which means that they are soft and highly formable. Their hardness and strength are increased by cold working. Certain steel grades are therefore supplied in the cold-stretched or hard-rolled condition.

Ferritic steels

These steels are, in principle, ferritic at all temperatures. This is achieved by a low content of austenite-formers, mainly nickel, and a high content of ferrite-formers, mainly chromium.

The older type, such as AISI 430, was mainly used for household utensils and other purposes where corrosion conditions were not particularly demanding. Steels with a high chromium content, such as AISI 446 with 27% chromium, are used at high temperatures where their resistance to sulphurous flue gases is an advantage. However, the risk of 475°C embrittlement and precipitation of brittle sigma phase in high-chromium steels must always be taken into consideration. Today's ferritic steels, such as S44400 with extremely low carbon and nitrogen contents, find greatest use where there is a risk of stress corrosion cracking.

Ferritic steels have a slightly higher yield strength (Rp 0.2) than austenitic steels, but they have less elongation at fracture. Another characteristic that distinguishes ferritic steel from austenitic material is that ferritic steels have much lower strain hardening.

Ferritic-austenitic steels

This group of steels is intermediate in terms of structure and alloy content between ferritic and austenitic steels. The main characteristic that differentiates ferritic-austenitic steels from austenitic and ferritic steels is that they have a higher yield strength and tensile strength. They are therefore often used in dynamically stressed machine parts, e.g. suction rolls for paper machines. New areas of application are within the oil, gas and petrochemical sector, seawater-bearing systems and the offshore industry.

Martensitic steels

Martensitic steels have the highest strength but also the lowest corrosion resistance of the stainless steels. Martensitic steels with high carbon contents may be regarded as tool steels.

Owing to their high strength in combination with some corrosion resistance, martensitic steels are suitable for applications which subject the material to both corrosion and wear. An example is in hydro-electric turbines.

Martensitic-austenitic steels

A martensitic-austenitic structure is obtained by increasing the nickel content slightly compared with the martensitic steels. These steels also often have a slightly lower carbon content. The range of applications is largely the same as for martensitic steels.

Table 1

Microstructure	Type	C % (max.)	Cr %	Ni %	Mo %	Other elements %
Ferritic	430	0.10	16.0-18.0	max. 0.5	–	–
	S44400	0.025	17.0-19.0	max. 0.5	2.0-2.5	Ti-stab.
Ferritic-austenitic (Duplex steels)	329	0.10	24.0-27.0	4.5- 6.0	1.3-1.8	
	S31803	0.03	21.0-23.0	4.5- 6.5	2.5-3.5	N=0.10-0.20
Austenitic	304	0.05	17.0-19.0	8.0-11.0	–	
	321	0.08	17.0-19.0	9.0-12.0	–	Ti-stab.
	316	0.05	16.0-18.5	10.5-14.0	2.5-3.0	
	304L	0.030	17.0-19.0	9.0-12.0	–	
	316L	0.030	16.0-18.5	11.5-14.5	2.5-3.0	
	310S	0.08	24.0-26.0	19.0-22.0		
	317L	0.030	17.5-19.5	14.0-17.0	3.0-4.0	
	N08904	0.025	19.0-21.0	24.0-26.0	4.0-5.0	Cu 1.2-2.0
Martensitic	420	0.4	12.0-14.0	max. 1.0	–	–
Martensitic-austenitic	–	0.1	12.0-14.0	5.0- 6.0	–	–

Table 2

Microstructure	Type	Rp 0.2 N/mm^2 (min.)	Rm N/mm^2	A_5 % (min.)	Hardness HB (max.)
Ferritic	430	250	440-640	18	200
	S44400	340	440-640	25	210
Ferritic-austenitic*	329	440	590-780	20	260
	S31803	480	680-880	25	290
Austenitic	304	210	490-690	45	200
	321	210	490-690	40	210
	316	220	490-640	45	200
	304L	190	460-640	45	190
	316L	210	490-690	45	200
	310S	–	max. 780	–	220
	317L	220	490-640	45	200
	N08904	220	500-750	35	220
Martensitic	420 **	450	650-850	15	220
Martensitic-austenitic	– **	620	830-1030	15	320

* Due to the high mechanical strength of ferritic-austenitic steels, machining and joint preparation may demand certain consideration. The use of planar machines or lathes has proven to be the easiest method of joint preparation. If the milling method is to be used, feed and cutting speeds should be reduced by a minimum 20% compared to conventional cutting data for austenitic stainless steels.

** quenched and tempered condition.

PHYSICAL PROPERTIES

Stainless steels differ from unalloyed materials with respect to thermal expansion, thermal conductivity and electrical conductivity, as illustrated below for several different steels.

Table 3

Steel type	Type	α x10^{-6}°C	λ W/m C	Ω nΩm	E kN/mm^2
Carbon steels	1016	13	47	150	205
Ferritic	S44400	12.5	24	600	225
Ferritic-austenitic	329	13.5	20	850	205
Austenitic	304	19.5	15	700	200

α = coefficient of thermal expansion at 20-800°C
λ = thermal conductivity at 20°C
Ω = electrical resistance at 20°C
E = modulus of elasticity at 20°C

The differences have to be taken into consideration by both designer and welder. The high thermal expansion and low thermal conductivity of the austenitic steels lead to higher shrinkage stresses in the weld than when carbon and ferritic steels are used. Thin sections of austenitic steels may therefore be deformed when an abnormally high heat input is used.

CORROSION RESISTANCE PROPERTIES

Austenitic steels

These steels are mainly used in wet environments. With increasing chromium and molybdenum contents, the steels become increasingly resistant to aggressive solutions. The higher nickel content reduces the risk of stress corrosion cracking. Austenitic steels are more or less resistant to general corrosion, crevice corrosion and pitting, depending on the quantity of alloying elements. Resistance to pitting and crevice corrosion is very important if the steel is to be used in chloride-containing environments. Resistance to pitting and crevice corrosion increases with increasing contents of chromium, molybdenum and nitrogen.

The rich chloride content of seawater makes it a particularly harsh environment which can attack stainless steel by causing pitting and crevice corrosion. However, two stainless steel grades designed to cope with this environment have been developed by AvestaPolarit, 254 SMO (ASTM S31254) and 654 SMO (ASTM S32654). 254 SMO has a long record of successful installations for seawater handling within offshore, desalination, and coastal located process industries. Some crevice corrosion has still been reported and for more severe situations, i.e. severe crevice geometries and elevated temperatures, the natural selection should be 654 SMO.

Most molybdenum-free steels can be used at high temperatures in contact with hot gases. An adhesive oxide layer then forms on the surface of the steel. It is important that the oxide is impervious so that further oxidation is prevented and the oxide film adheres tightly to the steel. At very high temperatures, the oxide begins to come loose (scaling temperature). This temperature increases with increasing chromium content. A common high-temperature steel is 310S. Another steel that has proved to be very good at high temperatures is Avesta Polarit 253 MA. Due to a balanced composition and the addition of cerium, among other elements, the steel can be used at temperatures of up to 1150-1200°C in air.

Ferritic steels

The modern molybdenum-alloyed ferritic steels have largely the same corrosion resistance as AISI 316 but are superior to most austenitic steels in terms of their resistance to stress corrosion cracking. A typical application example for these steels is hot-water heaters.

For chlorine-containing environments, where there is a particular risk of pitting, e.g. in seawater, the high-alloy steel S44635 (25Cr 4Ni 4Mo) can be used.

Ferritic steels with high chromium contents have good high-temperature properties. As mentioned previously, the steels readily form brittle sigma phase within the temperature range 550-950°C, but this is of minor importance as long as the product, e.g. a furnace, operates at its service temperature. AISI 446 with 27 % chromium has a scaling temperature in air of about 1070°C.

Ferritic-austenitic steels (duplex/super duplex)

The most widely exploited property of this category of steels is their good resistance to stress corrosion cracking. They are quite superior to common austenitic steels in this respect. Today’s modern steels with correctly balanced compositions, for example AvestaPolarit 2205 (UNS S31803), also possess good pitting properties and are not sensitive to intergranular corrosion after welding, as were the “old” ferritic-austenitic steels.

The latest developed duplex stainless steels with very high Cr, Mo and N-contents (super duplex = Avesta Polarit SAF 2507) have better corrosion resistance than the 2205-type and are in many cases comparable to the 6-Mo steels (254 SMO).

Martensitic and austenitic steels

Compared with the steels discussed above, these steels have much poorer corrosion resistance properties owing to lower contents of chromium and molybdenum.

WELDABILITY

The Schaeffler-de-Long diagram

An aid in determining which structural constituents can occur in a weld metal is the Schaeffler-de-Long diagram. With knowledge of the properties of different phases, it is possible to judge the extent to which they affect the service life of the weldment. The diagram can be used for rough estimates of the weldability of different steel grades as well as when welding dissimilar steels to each other. See page 4.

A new method of determining the ferrite content from the chemical composition of the weld metals has been developed by Sievert et al. See page 4.

Austenitic steels

The steels of type 304, 316, 304L and 316L have very good weldability. The old problem of intergranular corrosion after welding is very seldom encountered today. The steels suitable for wet corrosion either have carbon contents below 0.05% or are niobium or titanium stabilized. They are also very unsusceptible to hot cracking, mainly because they solidify with a high ferrite content. The higher-alloy steels such as 310S and N08904 solidify with a fully austenitic structure when welded. They should therefore be welded using a controlled heat input. Steel and weld metal with high chromium and molybdenum contents may undergo precipitation of brittle sigma phase in their microstructure if they are exposed to high temperatures for a certain length of time. The transformation from ferrite to sigma or directly from austenite to sigma proceeds most rapidly within the temperature range 750-850°C. Welding with a high heat input leads to slow cooling, especially in light-gauge weldments. The weld’s holding time between 750-850°C then increases, and along with it the risk of sigma phase formation.

The fully austenitic steel AvestaPolarit 254 SMO should be welded like all other fully austenitic steels, in other words with some caution to reduce the risk of hot cracking. For further information on the welding of Avesta Polarit 254 SMO, see separate brochure.

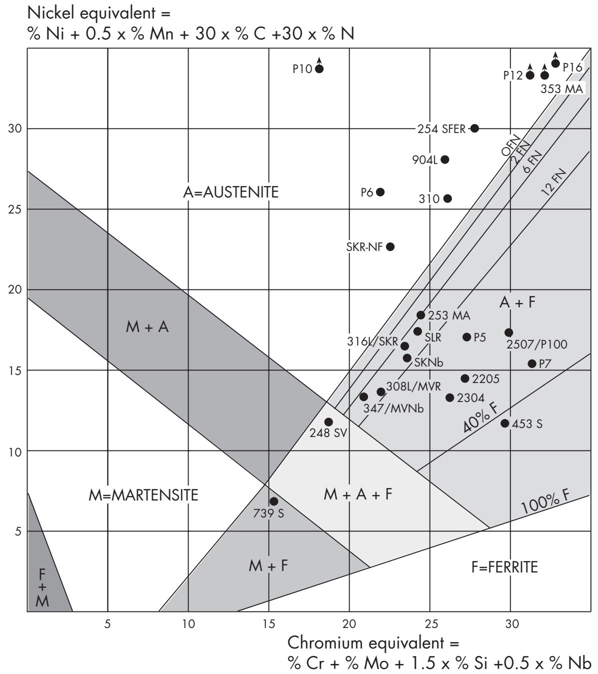
Ferritic steels

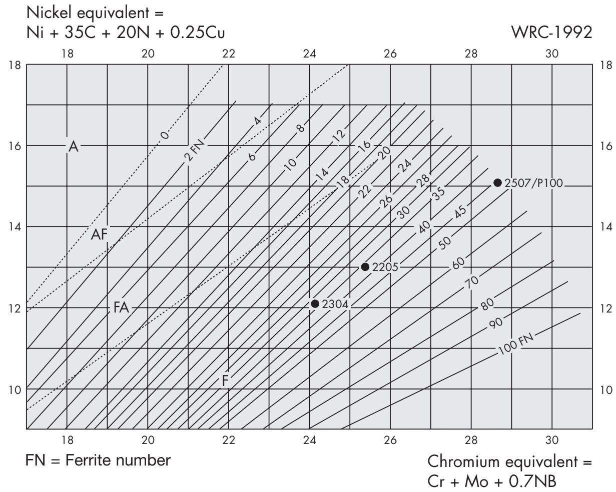
These steels are generally more difficult to weld than austenitic steels. This is the main reason they are not used to the same extent as austenitic steels. The older types, such as AISI 430, had greatly reduced ductility in the weld. This was mainly due to strong grain growth in the heat-affected zone (HAZ), but also to precipitation of martensite in the HAZ. They were also susceptible to intergranular corrosion after welding. These steels are therefore often welded with preheating and postweld annealing. Today’s ferritic steels of type S44400 and S44635 have considerably better weldability due to low carbon and nitrogen contents and stabilization with titanium/niobium. However, there is always a risk of unfavourable grain enlargement if they are not welded under controlled conditions using a low heat input. They do not normally have to be annealed after welding.

These steels are welded with matching or austenitic superalloyed filler metal (such as Avesta P5).

Ferritic-austenitic steels

Today’s ferritic-austenitic steels have considerably better weldability than earlier grades. They can be welded more or less as common austenitic steels. Besides being susceptible to intergranular corrosion, the old steels were also susceptible to ferrite grain growth in the HAZ and poor ferrite to austenite transformation, resulting in reduced ductility. Today’s steels, which have a higher nickel content and are alloyed with nitrogen, exhibit austenite transformation in the HAZ that is sufficient in most cases. However, extremely rapid cooling after welding, for example in a tack or in a strike mark, can lead to an unfavourably high ferrite content. Extremely high heat input can also lead to heavy ferrite grain growth in the HAZ.





$$\text{Heat input} = \eta \times \frac{U \cdot I}{1000 \cdot v}$$

η = constant dependent on welding method (0.7-1.0)

U = voltage (V)

I = current (A)

v = welding speed (mm/s)

When welding UNS S31803 (AvestaPolarit 2205) in a conventional way (0.6-2.0 kJ/mm) and using filler metals at the same time, a satisfactory ferrite-austenite balance can be obtained. For the new super duplex stainless steel (AvestaPolarit SAF 2507) a somewhat different heat input is recommended (0.2-1.5 kJ/mm). The reason for lowering the minimum value is that this steel has a much higher nitrogen content than 2205. The nitrogen favours a fast reformation of austenite which is important when welding with a low heat input. The maximum level is lowered in order to minimize the risk of secondary phases.

The steels are welded with ferritic-austenitic or austenitic filler metals. Welding without filler metal is not recommended without subsequent quench annealing. Nitrogen affects not only the microstructure, but also the weld pool penetration. Increased nitrogen content reduces the penetration into the parent metal. To avoid porosity in TIG-welding it is recommended to produce thin beads. To achieve the highest possible pitting corrosion resistance at the root side in ordinary 2205 weld metals, the root gas should be Ar + N_2 or Ar + N_2 + H_2. The use of H_2 in the shielding gas is not recommended when welding super duplex steels. When welding 2205 with plasma, a shielding gas containing Ar + 5% H_2 is sometimes used in combination with filler metal and followed by quench annealing. For further information on the welding of AvestaPolarit 2205 and AvestaPolarit SAF 2507, see separate brochures.

Martensitic and martensitic-austenitic steels

The quantity of martensite and its hardness are the main causes of the weldability problems encountered with these steels. The fully martensitic steels are air-hardening. The steels are therefore very susceptible to hydrogen embrittlement. By welding at an elevated temperature (= the steel's Ms temperature), the HAZ can be kept austenitic and tough throughout the welding process. After cooling, the formed martensite must always be tempered at about 650-850°C, preferably as a concluding heat treatment. However, the weld must first have been allowed to cool to below about 150°C.

Martensitic-austenitic steels, such as 13Cr/6Ni and 16Cr/5Ni/2Mo, can often be welded without preheating and without postweld annealing. Steels of the 13Cr/4Ni type with a low austenite content must, however, be preheated to a working temperature of about 100°C. If optimal strength properties are desired, they can be heat treated at 600°C after welding. The steels are welded with matching or austenitic filler metals.

FILLER METALS FOR STAINLESS STEELS

Austenitic filler metals

A. Weld metals with up to 40% ferrite.

Most common stainless steels are welded with filler metals that produce weld metal with 2-12 FN* at room temperature. The reason for this is that the risk of hot cracking can be greatly reduced with a few per cent ferrite in the metal, since ferrite has much better solubility of impurities than austenite. These filler metals have very good weldability. Heat treatment is generally not required.

High-alloy filler metals with chromium equivalents of more than about 20 can, if the weld metal is heat treated at 550-950°C, give rise to embrittling sigma phase. High molybdenum contents in the filler metal, in combination with ferrite, can cause sigma phase during welding if a high heat input is used. Multipass welding has the same effect. Sigma phase reduces ductility and can promote hot cracking. Heat input should be limited for these filler metals. Nitrogen-alloyed filler metals produce weld metals that do not precipitate sigma phase as readily.

---

* FN = Ferrite Number, which is an international measure of the ferrite content of the weld metal at room temperature.
For ferrite contents of 0-6%, FN = % ferrite.
For contents between 6 and 25%, FN is a unit or so higher.
For contents over about 25 %, only the % concept is used.

An extension of the FN scale to levels above 25 FN is being discussed within IIW. The designation EFN (E = Extended) is then used.

Non stabilized filler metals, with carbon contents higher than 0.05%, can give rise to chromium carbides in the weld metal, resulting in poorer wet corrosion properties. Today's non stabilized filler metals, however, generally have no more than 0.04% carbon unless they are intended for high-temperature applications.

Superalloyed filler metals with high ferrite numbers (15-40%) are often used in mixed weld connections between low-alloy and stainless steel. Weldability is very good. By using such filler metals, mixed weld metals of the 18/8 type can be obtained. The use of filler metals of the ordinary 18/8 type for welding low-alloy to stainless steel can, owing to dilution, result in a brittle martensitic-austenitic weld metal.

Other applications for superalloyed filler metals are in the welding of ferritic and ferritic-austenitic steels. The most highly alloyed, with 29Cr9Ni, are often used where the weld is exposed to heavy wear or for welding of difficult-to-weld steels, such as 14% Mn steel, tool steel and spring steel.

B. Fully austenitic weld metals

Sometimes ferrite-free metals are required. The reason is that there is usually a risk of selective corrosion of the ferrite. Fully austenitic weld metals are naturally more susceptible to hot cracking than weld metals with a few per cent ferrite. In order to reduce the risk, they are often alloyed with manganese and the level of trace elements is minimized. Large weld pools also increase the risk of hot cracks.

A large fully austenitic weld pool solidifies slowly with a coarse structure and a small effective grain boundary area. A small weld pool solidifies quickly, resulting in a more fine-grained structure. Since trace elements are often precipitated at the grain boundaries, the precipitations are larger in a coarse structure, which increases the risk that the precipitations will weaken the grain boundaries to such an extent that microfissures form. Many microfissures can combine to form visible hot cracks.

Fully austenitic filler metals should therefore be welded with low heat input. Since the filler metal generally has lower trace element contents than the parent metal, the risk of hot cracking will be reduced if a large quantity of filler metal is fed down into the weld pool. Because the weld metal is ferrite-free, its impact strength at low temperature is very good. This is important to manufacturers of, for example, welded tanks used to transport cryogenic liquids.

To avoid cracks in fully austenitic weld metals the following rules should be observed:

- when welding thick plates in possibly high restraint situations, consideration should be given at the design stage to avoiding the creation of crevices
- do not weave the electrode (less than 2 x core wire diameter)
- $\frac{\text{weld width}}{\text{weld depth}} \sim 1.5\text{-}2.5$
- never leave crater cracks before the next bead is welded.

Ferritic filler metals

Fully ferritic filler metals have previously been regarded as very difficult to weld. They also required heat treatment of the weld metal after welding. Those that are used today have very low carbon and nitrogen contents and are often stabilized with titanium. Today's filler metals therefore produce weld metals that are less sensitive to intergranular corrosion. Nor is any postweld heat treatment necessary.

Another very important phenomenon that applies to all fully ferritic filler metals is that they tend to give rise to a coarse crystalline structure in the weld metal. Ductility decreases greatly with increasing grain size. These filler metals must therefore be welded using low heat input.

Ferritic filler metals are mostly used for welding matching work metal.

Ferritic-austenitic filler metals

In order to achieve good ferrite-austenite balance in the weld metal, the filler metals are often superalloyed with regard to nickel and/or nitrogen. Welding without filler metal can therefore produce 80-100% ferrite in some steels, with a consequential reduction in the ductility and corrosion resistance of the weld metal.

The ferritic-austenitic filler metals are not susceptible to hot cracking, since they have a high ferrite content.

Weldability as a whole is considerably better than for the fully ferritic steels. There is some susceptibility to grain coarsening, but not very much. In order to keep grain size down, heat input should be limited.

The first ferritic-austenitic filler metals (type 329) were sensitive to so-called 475°C embrittlement. Subsequent stress relieving was therefore unsuitable for these filler metals. Today's ferritic-austenitic filler metals (type 22Cr9Ni3MoN and 25Cr10Ni4MoN) are relatively unsusceptible to 475°C embrittlement. The reason for this is that they have higher nickel contents and are alloyed with nitrogen.

Ferritic-austenitic filler metals are mainly used for welding matching base metals for use in environments where there is a risk of stress corrosion cracking. Some types are also used for welding ferritic chromium steels or ferritic-martensitic steels. Ferritic-austenitic filler metals have higher strength than the common austenitic filler metals. The higher ferrite content results in lower impact strength, however, especially at low temperatures.

Martensitic-Martensitic/austenitic filler metals

Welding with matching filler metal is recommended if optimal mechanical properties are desired.

FILLER METAL FORMS

Covered electrodes are available with many different types of coverings. They can be roughly classified into basic and rutile. There are a number of variants of these types, for example rutile-basic and rutile-acidic. The latter type is the most common. Rutile-acidic electrodes are often easy to weld with alternating current. These coverings are therefore sometimes designated AC/DC (= Alternating Current / Direct Current). There are also special position electrodes specially suited for position welding and for pipe welding. The position welding electrodes sometimes have the suffix -PW (= Position Welding) or -VDX (Vertical Down). There are special high-recovery electrodes for welding thick plate in the horizontal position.

Different coverings give the electrodes special properties. Basic electrodes are particularly suitable for restrained weldments, where the risk of hot cracking is high. Basic electrodes give good penetration in the parent metal. This is advantageous if the root gap is too narrow in some cases, due to shrinkage. This can then minimize the grinding work from the root side. One disadvantage of basic electrodes is that they have poorer weldability and deslagging characteristics than rutile and rutile-acidic electrodes. Basic electrodes produce a convex profile in fillet joints. Rutile-acidic electrodes produce a concave profile in fillet joints. In terms of corrosion, it is less important which type of covering is used, provided that there are no defects in the weld metal.

Wire for MIG and plasma-arc welding is layer wound on a spool. **TIG** wire is normally supplied in one-metre lengths. Layer wound wire should lie flat if a few turns are cut off the spool and laid freely on the floor. The resultant loop should have a diameter of 400-1200 mm (cast). If the loop rises more than about 25 mm from the floor (helix), the wire may flop about during welding, disrupting the welding procedure. Too little cast will result in sluggish wire feed.

The surface finish of the MIG wire has great importance for the wire's feeding properties. The finish should be neither too rough nor too smooth. Electrolytically polished wire, which is very smooth, often runs heavily in the wire guide. Scratched wire also runs poorly. If the wire is too soft, it may bend and get stuck at the feed rolls.

It is often advantageous to use filler metal in TIG and plasma-arc welding. The quantity of trace elements in the parent material is normally higher than in the filler metal wire. Using filler metal wire dilutes the trace elements, reducing the risk of hot cracking. The melting of the wire also reduces the temperature of the molten metal, which also reduces the risk of hot cracking.

For MIG welding of common steels of type AISI 304, 316, 304L and 316L, wire with an elevated Si content is also available. Such wire produces a more stable arc and the molten metal flows out better than when a wire with a low Si content is used. Wire with a high Si content cannot be used in fully austenitic steels of type N08904 since the risk of hot cracking increases with increasing Si content in fully austenitic steels.

Wire intended **for submerged-arc welding (SAW)** should not be too large in diameter, since there is sometimes a risk of hot cracking. Wire with a maximum diameter of 3.2 mm is therefore normally used.

A **flux** is used in submerged-arc welding to protect the molten metal against oxidation, but many fluxes also add chromium to the molten metal. An elevated chromium content and thereby elevated ferrite content counteracts hot cracking.

Flux-cored wire electrodes for stainless steel welding are becoming increasingly popular. Some of the wires available today have very good welding characteristics and produce adequately corrosion-resistant weld metals. Unfortunately, their impact strength is not as good as that of MIG weld metal. Another advantage of cored-wire electrodes is that they can be welded with a wide range of currents and perform well in different positions. Welding with high current in thick sections gives very high deposition rates.

Another important point to consider is that if welding can be carried out in the horizontal position, the learning time for the welder is much shorter, compared to TIG or covered electrode welding.

There are flux-cored wire electrodes that can be welded without shielding gas. However, this type of wire does not possess as good welding properties as the wires welded with shielding gas.

WELD DEFECTS/PRACTICAL ADVICE

Some of the most common types of defects are defined below.

– Hot cracking

This is the most common type of weld defect, and is caused by, among other things, excessively large weld pools, high impurity levels, high weldment restraint, and too thin welds. Weld-crater cracks are a type of hot cracking and occur if the arc is extinguished too quickly. Ferrite in the weld metal counteracts hot cracking. Hot cracks must be ground away.

– Strike scars

Strike scars occur if the arc strays outside the joint briefly while the electrode is being struck. This type of defect has high inherent stress, often in combination with a sharp crack. It can cause stress corrosion cracking and crevice corrosion. Strike scars in duplex steels can give rise to 90-100% ferrite, resulting in embrittlement and reduced corrosion resistance. Strike scars must be ground away.

– Porosity

Porosity is caused by moisture on the work metal, moisture in the electrodes, moisture in the gas (TIG, MIG), contamination of the joint (oil, paint etc).

– Slag inclusions

These may result from the use of an electrode with too large a diameter in a narrow joint, or by careless welding.

– Incomplete penetration

This results from using the wrong type of joint, or incorrect welding parameters.

– Root defect

Incomplete penetration can cause crevice corrosion and stress corrosion cracking.

– Incomplete fusion

This is caused by an incorrect travel speed in MIG welding, an excessively narrow joint, excessively low welding current, or the wrong electrode angle.

– Hydrogen cracking in 13 Cr weld metal

Preheat temperature too low, moisture content in covering too high.

– Excessive local penetration (pipe welding)

Gap too large, heat input too high.

– Sink or concavity (pipe welding)

Incorrect joint design.

– Oxidized root side

Poor shielding can cause corrosion attacks. Remove the oxide.

– Spatter

Grinding spatter can cause pitting and must therefore be removed. Weld spatter can also cause pitting.

– Grinding scratches

Coarse grinding of the welded joint must be followed by fine grinding and possibly polishing.

Practical advice

- Use standardized joint types. A single-U butt joint is recommended for pipe welding with TIG. The single-U butt joint is particularly advantageous in the overhead position. A tip is to machine single-V butt joints but grind up the single-V butt joint to a single-U butt joint in the overhead position. Tack with a gap of about 1.0-2.5 mm.
- Never leave grinding burr.
- Clean the joint before welding.
- When tacking with TIG, use shielding gas and grind off or thin out the tacks.
- When welding pipe with TIG, use pure argon and gas hoses of good quality.

- Spread out the gas on the root side.
  Gas flow (2)-20 l/min.
- Purge the pipe with 7-10 x the enclosed volume.
- Keep the shielding gas on until the weld has cooled to below about 200°C.
- Using a gas lens is recommended–it provides a better gas shield. Good in deep joint types, for example weldolets.
- MIG welding can be carried out with pure argon or a gas mix of argon + 30% helium + 1% oxygen.
- Heat input 0.5-1.5 kJ/mm (normal).
- If welding with covered electrodes, do not exceed the maximum recommended current.
- Extinguish the arc carefully at the end of the weld.
- Do not exceed the recommended welding current.
- Interpass temperature <100°C (150°C).
- The joint must be completely free of low-melting phases such as metallic copper, zinc or lead. Such phases can otherwise cause metal penetration during welding.
- Submerged-arc welding and resistance welding can be used, but require special welding parameters. Information can be obtained from our technical customer service.

POST-WELD TREATMENT

To ensure satisfactory corrosion resistance for the welded joint, slag, spatter and oxides must be removed. Welding oxide is rich in chromium, which means that the material underneath the oxide has been depleted of chromium, thereby reducing its resistance to pitting corrosion. Post-weld treatment is therefore very important if the weld is to be exposed to acidic or neutral, chloride containing solutions such as seawater and pulp bleach plant liquids.

In these cases, pickling should be carried out to remove this oxide and enable the formation of a new protective and passivating oxide layer.

Note that failure to use sufficient shielding gas during pipe welding may result in oxidation of the root side. In such cases the root side has to be cleaned by mechanical or chemical means.

Annealing

Stress-relief annealing of a non-stabilized stainless steel at temperatures within the range 550-650°C involves a risk of chromium carbide precipitation and might reduce the resistance to wet corrosion. Stabilized material however can undergo stress-relief annealing within the temperature range 550-650°C without any problems.

The safest method is to carry out stress-relief annealing at temperatures in excess of 1,000°C. The temperature levels can be provided by the manufacturer.

Brushing/grinding

Spatter and strike scars should be ground off, while oxide and other discoloration should be removed by brushing.

Grinding should be carried out in several stages and finished using an emery cloth with a 120 mesh or finer.

If steel brushing is preferred, stainless steel brushes must be used.

Surfaces which have undergone a process of grinding should preferably be pickled or washed with dilute nitric acid to ensure full protection against corrosion.

Blasting

If blasting is used, the blasting medium must be clean and free of iron particles, iron oxides, zink, or other similar materials.

Pickling or washing with dilute nitric acid is recommended after blasting.

Pickling

From a corrosion point of view, pickling is considered to be the best method for cleaning a welded joint. In addition to the actual cleaning process which occurs during pickling, the welded area also undergoes a new process of passivation.

This method restores the welded joint's resistance to corrosion, partly by removing the chromium depleted layer and partly by forming a new layer of the protective oxide film.

Pickling can be performed at the location of the joint using either pickling paste or pickling fluid. All residue caused by the pickling process should be thoroughly rinsed away using clean water and dealt with in accordance with the recommendations provided by the relevant authorities.

AvestaPolarit Welding offers a comprehensive range of pickling products for effective pickling and can also provide advice on how the pickling process can best be carried out in different environments.

AvestaPolarit Welding AB
P.O. Box 501
SE-774 27 Avesta, Sweden
Tel.: +46 (0)226 815 00
Fax: +46 (0)226 815 75
www.avestapolarit.com/welding

Information 270502GB; reprint of inf. 9473:2 Teknisk information/Edita Västra Aros 2002