WELDING PROCESSES AND TECHNOLOGY FOR STAINLESS STEELS

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INTRODUCTION

Stainless steels (SS) can be defined as alloys that contain at least 10.5%Cr, no more than 1.5%C, and more Fe than any other single element. There are five major families of SS, based on microstructure and properties:' (i) martensitic SS; (ii) ferritic SS; (iii) austenitic SS; (iv) precipitation-hardening (PH) SS; and (v) duplex ferritic-austenitic SS. Each family requires different weldability considerations, because of the varied phase transformation behaviour on cooling from solidification to room temperature (RT) or below.

All the types of SS are weldable by virtually all the welding processes. In part, process selection is often dictated by the available equipment. Perhaps the simplest and most universal welding process is manual SMAW with coated electrodes. It has been applied to material as thin as 1.2 mm, and there is no upper limit on thickness. Other very commonly used arc welding processes for SS are GTAW, GMAW, SAW and FCAW. Often, the optimal filler metal is not the one that most closely matches the base metal composition. The most successful. procedures for one family are often markedly different from those that are appropriate for another family.

Base metals of SS and, therefore, the welding filler metals used with them, are almost invariably chosen on the basis of adequate corrosion resistance for the intended application .This usually means that the welding filler metal must at least match (and sometimes over match) the contents of the base metal in terms of specific alloying elements, such as Cr, Ni and Mo.

After considering corrosion resistance, the avoidance of cracking becomes the unifying theme in filler-metal selection and procedure development for the welding of SS. Cracking can occur at temperatures that are just below the bulk solidus temperature of the alloy(s) being welded. The hot cracking, as it is called, can appear as large weld-metal cracks, usually along the weld centreline. However, it can also appear as small, short cracks (microfissures) in the weld metal or in the heat-affected zone (HAZ) at the fusion line and, usually, perpendicular to it. Hot cracking in SS welds is of most concern in austenitic weld metals, although it can occur in all types of SS weldments.

Cracking can also occur at rather low temperatures of, typically 150°C or below, because of the interaction of high welding stresses, high-strength metal and diffusible hydrogen. This cold cracking commonly occurs in martensitic weld metals, as well as HAZs, including those of PH SS. Cold cracking can occur in ferritic SS weldments that have become embrittled by grain coarsening and/ or second-phase particles.

In many instances of cold cracking, where the resulting weld has acceptable properties, the substitution of a mostly austenitic filler metal (with appropriate corrosion resistance) for a martensitic or ferritic filler metal serves as a remedy. When hot cracking occurs in an austenitic weld metal, a common remedy is to use a mostly austenitic filler metal that includes a small amount of ferrite. However, another approach toward avoiding may be necessary in situations that require low magnetic permeability, high toughness at cryogenic temperatures, resistance to media that selectively attack ferrite (such as urea), or post-weld heat treatment (PWHT) that embrittle ferrite because their requirements may severely limit the amount of ferrite that is acceptable.

MARTENSITIC STAINLESS STEELS

A number of martensitic SS base metals, and welding filler metals that have approximately matching composition as classified by AWS are listed in Table 1 Martensitic SS generally develop full hardness on air-cooling from about 1000°C. They can be softened by tempering in the range 500-750°C, unless they contain significant amount of Ni, in

Table 1 : Filler metals for nominally martensitic stainless steels

Base Metal		Matching filler metals		
Designation	**Nominal Composition, wt%**	**A5.4**	**A5.9[(a)]**	**A5.22**
XM-32	0.12C-12Cr-2.5Ni-1.75Mo-0.03N-0.3V	...	...	...
403	0.15C-12Cr	E410-xx	ER410	E410T-x
410	0.15C-12.5Cr-0.75Ni	E410-xx	ER410	E410T-x
410S	0.08C-12.5Cr-0.6Ni	E410-xx	ER410	E410T-x
XM-30	0.18C-12.5Cr-0.2Nb+Ta	...	...	...
414	0.15C-12.5Cr-1.8Ni	...	...	...
410NiMo	0.05C-13Cr-4.5Ni-0.75Mo	E410NiMo-xx	ER410NiMo	410NiMoT-x
416	0.15C-13Cr-0.6Mo	NCW	NCW	NCW
XM-6	0.15C-13Cr	NCW	NCW	NCW
416Se	0.15C-13Cr-0.15Se(min)	NCW	NCW`	NCW
615	0.18-13Cr-2Ni-0.5Mo-3W	...	...	...
420	0.15C(min)-13Cr	...	ER420	...
420F	0.35-13Cr-0.5Ni-0.6Cu	NCW	NCW	NCW
420FSe	0.3C-13Cr-0.5Ni-0.6Cu-0.15Se(min)	NCW	NCW	NCW
616	0.23C-12Cr-0.75Ni-1.1Mo-0.,25V-1.1W	...	...	...
619	0.3C-11.5Cr0.5Ni2.75Mo-0.25V	...	...	...
413	0.20C-16Cr1.9Ni	...	...	...
440A	0.68C-17Cr-0.75Mo	...	...	...
440B	0.85C-17Cr-0.75Mo	...	...	...
440C	1.1C-17Cr-0.75Mo	...	...	...
440F	1.1C-17Cr-0.5Ni-0.6Cu	NCW	NCW	NCW
440FSe	1.1C-17Cr-0.5Ni-0.6Cu-0.15 Se (min)	NCW	NCW	NCW
CA-15	0.15C-13Cr-1Ni-0.50Mo	E410-xx	ER4109	E410T-x
CA-15M	0.15C-13Cr-1Ni-0.58Mo	...	...	...
CA-40	0.3C-13Cr-1Ni-0.5Mo-0.04S	...	ER420	...
CA-40F	0.3C-13Cr-1Ni-0.5Mo-0.3S	NCW	NCW	NCW
CA-6N	0.06C-11.5Cr-7Ni	...	...	...
CA-6NM	0.06C-13Cr-4Ni-0.7Mo	E410NiMo-xx	ER410NiMo	E410NiMoT-x
CA28MWV	0.24C-12Cr-0.75Ni-1.1Mo-0.25V-1.1W	...	...	...

(a) Metal-cored electrodes, indicated by a "C" in place of "R" in the classification, are also included which case the maximum temperature of tempering is reduced. After tempering at 650-750°C, their hardness values generally drop to about R_C 30 or lower. This can be useful if it is necessary to soften a martensitic SS before welding to allow enough ductility in the bulk material to accommodate shrinkage stresses associated with welding. However, such high-temperature tempering produces rather coarse Cr-carbides, which damage the corrosion resistance of the metal. Then, it may be necessary after welding to austenitise, air cool to RT, and temper at a low temperature (less than 450°C) to restore corrosion resistance.

For use in as-welded condition

Except for very small weldments or very low carbon base metals, martensitic SS is not used in as-welded condition. This is due to the very brittle weld area (comprising the weld metal with matching or near-matching composition and the HAZ) that normally results. However, repair situations can necessitate that one works with these circumstances:

If a weldment of martensitic SS must be used in the as-welded condition, then it is usually best to avoid autogenous welds and weld with matching filler metal. Small parts that are welded by GTAW (or LBW/EBW) processes are an exception, because residual stresses can be very low and the welding processes generate almost no diffusible hydrogen.

If possible, austenitic SS filler metal (e.g., type 309 or 309L) or duplex ferritic-austenitic SS filler metal (e.g. type 312) should be chosen, depending on the base metal. The filler-metal choice should provide for a small amount of ferrite in the weld metal, in order to avoid hot cracking. If the weld metal is austenite with a little ferrite, then the weld metal itself will have appreciable ductility, and only the HAZ will be at risk for cold cracking. This possibility can be minimised by using high preheat temperatures (200°C minimum for type 410 base metal, and 350°C minimum for type 440 base metal) and slow cooling after welding.

For Use after Post-Weld Heat Treatment

Due to the major weld-metal strength (hardness) under-match that often occurs when martensitic SS base metals are welded with austenitic filler metals, the base metals are usually welded with martensitic SS filler metals, and the weldment is subsequently welded to improve the properties of the weld area. Heat treatment after welding usually takes one of two forms. The weldment could be either tempered by heat treatment below the austenite-start (A_s) temperature, or heated above the austenite-finish (A_f) temperature to austenitise the entire' mass, and then cooled back to nearly RT to fully harden it, and heated again, but to a temperature below the A_S temperature in order to temper the metal to desired properties. Tempering heat treatments at temperature between the A_S and A_f temperatures are generally avoided, because they result in a mixture of heavily tempered martensite and fresh untempered martensite, although it is possible to follow such a temper (after cooling to near RT) with a second temper just below the A_s temperature. Such a "double temper" has been successfully used to obtain low hardness and high toughness properties in weldments of 4l0NiMo.

Tempering at temperatures up to about 450°C has little effect on the hardness of martensitic SS, compared with the hardness of the same steel in the untempered condition. Tempering above 450°C causes the hardness to fall rapidly with increasing tempering temperature, but at the same time, ductility increases. The tempering temperature upper limit is the A_S temperature, which is about 800°C for the Ni-free alloys, such as types 410, 420 and 440. The addition of Ni to a martensitic alloy reduces the As temperature appreciably, e.g. for 4lONiMo by about 640°C.

Tempering at temperatures above 450°C, but below the A_S temperature, also can be useful before welding, because the base metal is softened and made more ductile, which better accommodates the shrinkage strains that accompany cooling of the weld metal. This helps to avoid weld cracking during cooling.

With all but the lowest carbon content martensitic SS base metals, high preheat and high interpass temperatures are usually necessary to avoid cracking when the weld metal is also martensitic SS. The alloy 410NiMo only requires about 140°C (min.), whereas types 410 and 420 require about 200°C, and type 440 requires about 260°C (min.). However, for a sizeable weldment, a safer procedure is to perform all welding at temperatures above the martensite-start (M_S) temperature of the weld metal, so that no martensite forms in the weld until welding is completed. Preheat and interpass temperatures in the range 300-500°C are successfully used. In either case, the weldment must be very slowly cooled to below 100°C to complete the martensitic transformation of the weld metal and HAZ without cracking, once welding is finished.

Only when martensitic transformation is completed (when the weldment is below 100°C) should tempering of the weldment be undertaken. If untransformed austenite is still present, tempering followed by cooling will result in fresh martensite formation when the weldment reaches RT, and unexpected hardness (possibly accompanied by cracking) is likely to be encountered.

The availability of matching filler metals is a problem for martensitic SS. For covered electrodes, only E410-xx and E410NiMo-xx types are commercially significant (as per ANSI/ AWS A5.4). The same compositions are also the only entries in the flux-cored electrode standard (ANSI/AWS A5.22). These compositions, as well as ER420, are given as solid wires in the ANSI/ AWS A5.9 standard. Hence, the fabricator may be forced to choose a filler metal that does not match the base metal:

FERRITIC STAINLESS STEELS

Table2 lists selected ferritic SS base metals, and some corresponding welding filler metals. The ferritic SS generally requires rapid cooling from hot working temperatures to avoid grain growth and embrittlement from the α phase. As a result, most ferritic

Table 2 : Filler metals for nominally ferritic stainless steels

Base Metal		Matching filler metals		
Designation	Nominal Composition, wt%	A5.4	A5.9[a]	A5.22
XM-34	0.08C-18.5Cr-2Mo	NCW	NCW	NCW
405	0.08C-13Cr-0.6Ni-0.2Al	...	...	E409T-x
409	0.08C-11Cr-0.5Ni-0.6Ti	...	ER409	E409T-x
429	0.12C-15Cr-0.75Ni	...	...	...
430	0.12C-17Cr-0.75Ni	E430-xx	ER430	E430T-x
430F	0.12C-17Cr-0.75Ni-0.6Mo-0.15S	NCW	NCW	NCW
430FSe	0.12C-17Cr-0.75Ni-0.06S-0.15Se(min)	NCW	NCW	NCW
439	0.07C-18Cr-0.5Ni-0.04N-0.9Ti-0.15Al	...	...	...
444	0.025C-18.5Cr-1Ni-2Mo-0.035N-0.6Ti+Nb	...	...	...
446	0.2C-25Cr-0.25N	...	...	...
XM-27	0.01C-26Cr-0.5Ni-1Mo-0.015N-.1Nb+Ta-.2Al	...	ER446LMo	...
XM-33	0.06C-26Cr-0.5Ni-1Mo-0.04N-0.5Ti-0.2Cu	...	...	...
29-4	0.01C-29Cr-4Mo-0.15Ni-0.015N	...	...	...
29-4-2	0.01C-29Cr-4Mo-2Ni-0.015N	...	...	...
CB-30	0.30C-20Cr-2Ni	...	...	...
CC-50	0.50C-28Cr-4Ni	...	...	...

(a) Metal-cored electrodes, indicated by a "C" in place of "R" in the classification,are also included.

SS is used in relatively thin gauges, especially in alloys that are high in Cr. The "super ferritics" (e.g., type 444) are limited to thin plate, sheet and tube forms. To avoid embrittlement in welding, the general rule is "weld cold"; which means to weld with either no or low preheating; a low interpass temperature; and a low level of welding heat input, commensurate with adequate fusion, to avoid cold laps and other defects.

For Use in As-Welded Condition

In contrast to martensitic SS, weldments in ferritic SS, at least in the stabilised grades (e.g. types 409 and 405) or super ferritics, are usually used in the as-welded condition. If the "weld cold" rule is followed, then embrittlement that is due to grain coarsening in the HAZ can be avoided. However it is not easy to avoid coarse grains in the fusion zone if the weld metal is fully ferritic. As a result, a considerable amount (but not all) of the filler metal used to join ferritic SS is austenitic, usually with considerable ferrite.

If an austenitic filler metal is contemplated, then consideration should be given to differences in corrosion resistance (especially localised corrosion resistance) across the joint, as well as differences in properties, such as the coefficient of thermal expansion between asustenitic filler metal and ferritic base metal. Ni-base alloy filler metals are another possible alternative, especially for the super ferritics, which have the highest corrosion resistance requirements. High Mo content Ni-base alloy filler metals of the ANSI/AWS A5.11 specification, covered-electrode classifications ENiCrMo-3, ENiCrMo-4 and ENiCrMo-10, as well as the ANSI/AWS A5.14 specification, solid-wire classifications ERNiCrMo-3, ERNiCrMo-4 and ERNiCrMo-10, have been successfully used for the most corrosion resistant ferritic SS.

Undoubtedly, the greatest quantity of ferritic SS welded at present is type 409, which is used for automobile exhaust system components. The welds are virtually all single-pass fillet or lap welds. The most common filler metal is a matching composition supplied as a l.l mm diameter metal-cored wire (EC409 or EC4O9Cb as per ANSI/AWS A5.9-92), which is used for GMA welding with $Ar\text{-}O_2$, such as the popular $98Ar\text{-}2O_2$ mixture. This filler metal is often used in robotic welding, at high travel speeds, in a vertical-down position on rotating pieces that are 18 gauge or less in thickness. Welding is done in a short-circuiting transfer mode, or nearly so.

For Use in Post-Weld Heat Treated Condition

In general, only the unstabilised grades of ferritic SS are post-weld heat treated, especially type 430. If it were welded with matching filler metal (or no filler metal), then both the weld metal and the HAZ would contain fresh martensite in the as-welded condition. In addition, some carbon would have gone into solution in the ferrite at elevated temperatures, and rapid cooling after welding would result in ferrite in both the weld metal and the HAZ being supersaturated with carbon. Thus, the joint would be quite brittle, compared with the unwelded condition. Ductility could be significantly improved by a PWHT at 760°C for 1 h, followed by rapid cooling to avoid the 475°C embrittlement phenomenon.

AUSTENITIC STAINLESS STEELS

Table 3 lists some of the common nominally austenitic SS base metals and their corresponding welding filler metals.

For Jse in As-Welded Condition

Most Weldments in nominally austenitic SS base metals are put into service in the as welded condition. In contrast to the situations with martensitic and ferritic SS base metals, many of the nominally austenitic SS base metals have matching, or near-matching, welding filler metals (see Table 3). In many cases, a nearly matching filler metal is a good choice.

Filler-metal selection and welding procedure development for austenitic SS base metals primarily depend on whether or not ferrite is possible and acceptable in the weld metal. In general, if ferrite is both

Table 3 : Filler metals for some common nominally austenitic stainless steels

Base Metal		Matching filler metals		
Designation	**Nominal Composition, wt%**	**A5.4**	**A5.9[a]**	**A5.22**
304	0.08C-19Cr-9.5Ni	E308-xx	ER308	E308T-x
304L	0.03C-19Cr-10Ni	E308L-xx	ER308L	E308LT-x
304N	0.08C-19Cr-9.5Ni-0.13N	...	...	...
304LN	0.035C-19Cr-9.5NI-0.13N	...	...	...
308	0.08C-20Cr-11Ni	E308-xx	ER308	E308T-x
309S	0.08C-23Cr-13.5Ni	E309-xx	ER309	E309T-x
309Cb	0.08C-23Cr-14Ni-1Nb+Ta	E309Cb-xx	...	...
310S	0.08C-25Cr-20.5Ni	E310-xx	ER310	E310T-x
310Cb	0.08C-25Cr-20.5Ni-1Nb+Ta	E310Cb-xx	...	...
316	0.08C-17Cr-12.5Ni-2.5Mo	E316-xx	ER316	E316T-x
316L	0.03C-17Cr-12Ni-2.5Mo	E316L-xx	ER316L	E316LT-x
316N	0.08C-17Cr-12.5Ni-2.5Mo-0.13N	...	...	...
316LN	0.035C-17Cr-12.5Ni-2.5Mo-0.13N	...	...	...
317	0.08C-19Cr-13Ni-3.5Mo-0.1N	E317-xx	ER317	E317Tx
317L	0.03C-19Cr-13Ni-3.5Mo-0.1N	E317L-xx	ER317L	E317LT-x
321	0.08C-18.5Cr-11Ni-0.5Ti	E347-xx	ER321	E347T-x
347	0.08C-18.5Cr-11Ni-0.9Nb+Ta	E347-xx	ER347	E347T-x
16-8-2H	0.075C-16Cr-8Ni-2Mo	E16-8-2xx	ER16-8-2	...

(a) Metal-cored electrodes, indicated by a "C" in place of "R" in the classification,are also included.

possible and acceptable, then the suitable choices of filler metals and procedures are broad. If the weld metal solidifies as primary ferrite, then the range of acceptable welding procedures can be as broad as it would be for ordinary mild steel. However, if ferrite in the weld metal is neither possible nor acceptable, then the filler metal and procedure choices are much more restricted, because of hot-cracking considerations.

Most filler-metal compositions are available in a variety of forms. When the presence of ferrite is possible, filler-metals are tailored to meet specific needs, at least in filler metals that are composites (for SMAW, FCAW, and metal-cored wires for GMAW or SAW processes). For example, in type 308 or 308L filler metals, which are typically selected for joining base-metal types 304, 304L etc. the filler metal can be designed for zero ferrite, more than 20 FN, or any FN value between these extremes, and still be within the composition limits for the classification in the relevant AWS filler-metal specification. In solid wires of type 308 or 308L, which are used for GMAW, GTAW; or SAW processes, the potential ferrite content of all-weld metal is often designed to provide maximum yield from the heat of steel which is maximized when the ferrite content ranges from 3-8 FN, based on the WRC-1988 diagram. Weld rod demand is usually for a minimum of 8 FN, and poor yields make the production of metal with more than 10 FN uneconomical and, thus, limit its availability.

With composite filler metals, both composition and ferrite content can be adjusted via alloying in either the electrode coating of SMAW electrodes or the core of flux-cored and metalcored wires. Tailoring composition and ferrite for special applications is much more easily accomplished than it is for solid wires. For most off-the-shelf composite filler metals, the target all weld metal FN is considered when designing the filler metal. For a given alloy type, such as 308L, the target FN is likely to depend on the economics of filler-metal design, the appropriate FN for the specific type of filler metal to avoid hot cracking, and market requirements.

For example, the ANSI/AWS A5.4 classification system recognizes three all-position coating types. In general, E308L-15 electrodes provide better hot-cracking resistance at low or no levels of ferrite than do E308L-16 electrodes, which, in turn, provide better hot-cracking resistance than do E308L-17 electrodes when little or no fernte is present in the deposit. This difference in cracking resistance without ferrite primarily stems from bead shape. The E308L-15 electrodes tend to produce a convex bead shape. Convexity provides something of a riser, as in a casting, which tends to resist hot cracking.. The E308L-16 electrodes tend to produce a nearly flat profile, which provides little or no riser. The E308L-17 electrodes tend to produce a concave profile (as well as a high Si deposit), which makes this the least crack resistant coating type when there is little or no ferrite in the deposit. Further, the sensitivity to N-pickup with a long arc (and consequent loss of ferrite) is least with E308L-15 and greatest with E308L-17 electrodes.

As a result, the off-the-shelf E308L-15 electrodes are generally aimed towards a lower FN than the E308L-16 electrodes, which, in turn, are aimed towards lower FN values than are the E308L-17 electrodes. Of course, the same tendencies apply to other alloy compositions with the same coating types, which can be generalized as Exxx-15, Exxx-16, or Exxx-17; where "xxx" stands for 308, 308L, 309, 309L, 316, 316L, and so on.

Until 1992, the Fxxx-17 coating type was not recognized by the ANSI/AWS A5.4 specification as being a distinct type, although the electrodes that are properly classified as Exxx-17 generally weld satisfactorily on both DC and AC, they had to be classified as Exxx-16 electrodes until the publication of ANSI/AWS A5.4-92 introduced the Exxx-17 classifications. Using these electrodes and meeting the vertical-up fillet weld size and convexity requirements of the Exxx-16 classifications were diffcult to achieve, at best.

Although the Exxx-17 classifications have relaxed vertical-up fillet size and convexity requirements, some electrode manufacturers have been reluctant to change the classification of certain brand names (originally classified as Exxx-16) in order to more correctly reflect the true vertical-up capabilities of the electrodes. The knowledgeable fabricator can detect an electrode that is classified by its manufacturer as Exxx-16, when it properly ought to be classified as Exxx17, either by attempting to meet the vertical-up fillet requirements of the Exxx-16 classification or by examining the all-weld metal composition that the electrode produces. The Exxx-17 electrodes all produce deposits of low Mn and high Si. In general, a nominally austenitic electrode with an all-weld metal Si content that is nearly as high as, or higher than, its Mn content (i.e., Si content approaches the 0.9% maximum of the specification) is in all probability properly classified as an Exxx-17 electrode.

Flux-cored and metal-cored electrodes do not have the clear distinctions that exist among the three main coating types. In general, both off-the-shelf flux-cored and metal-cored electrodes tend to have higher FN, more like those of Exxx-17 e,ectrodes, because the higher heat input that normally accompanies the use of these products tends to make the weld metal less crack resistant when little or no ferrite is present.

If a fully austenitic stainless steel as-welded deposit, or one with almost no ferrite is necessary; and solidification as primary austenite, or fully austenitic solidification, is expected, then the choices of both filler metals and procedures are more restricted. When designing filler metals with low or no ferrite, one tries to obtain raw materials with minimal S and P contents. Generally, high-Si compositions are avoided, because of their hot-cracking tendencies. Concave beads and high heat input are best avoided in procedure development. As a result, little or no filler metals are even offered commercially as Exxx-17 SMAW electrodes without ferrite. SAW joining with fully austenitic filler metals is usually avoided, because of cracking problems, although SAW cladding is more successful. The GMAW process is often restricted to a short-circuiting transfer mode.

A general rule to follow in procedure development for fully austenitic weld metals, in order to avoid or minimize cracking problems, is to "weld ugly". In particular, this means that if cracking is encountered, then welding procedures that produce markedly convex beads can overcome it. For compositions that are very crack sensitive steels, crack-free welding with matching filler metal may be possible only with either small-diameter (1.6-2.4 mm) Exxx-15 electrodes that are welded on the low side of the recommended current range or small-diameter (< 0.9 mm) GMAW wire in the short-circuiting transfer mode. Nb, P and S in such alloys generally tend to make hot-cracking problems more severe. As a result, both SMAW electrodes (Exxx-15) and GMAW wires (ERxxx) are available with reduced residual elements, as well as low C, so that Nb can be minimized without loss of the stabilization of carbides.

Additional welding procedure approaches to eliminating hot cracking for weld metals that solidify either fully austenitic or as primary austenite include those that reduce heat build-up in the steel. Low welding heat input and low pre-heat and interpass temperatures are all beneficial.

Weld puddle shape has a strong influence on hot-cracking tendencies. Narrow, deep puddles crack more readily than wide, shallow puddles. In particular, it is helpful to adjust welding conditions to obtain a weld pool that is elliptical in surface shape and to avoid tear-drop-shaped weld pools, the sharp tail of which tends to promote hot cracking. Low current and slow travel speed favour an elliptical pool shape. Copper chill blocks also can help to extract heat and speed cooling.

With fully austenitic or primary austenite solidification, it is essential to backfill weld craters to avoid crater cracks, which are a form of localized hot cracking. This means stopping the travel of the arc while continuing to add filler metal, with a down-sloping current, if possible, before breaking the arc, so that the crater becomes convex, rather than concave.

It was noted earlier that the usual choice for a filler metal for austenitic SS is a matching or near-matching composition to that of the base metal. However, one situation generally requires an exception. This situation occurs when a high-Mo base metal is chosen for pitting or crevice corrosion resistance in a chloride-containing aqueous solution. Although the high Mo content of the weld metal provides resistance to localized corrosion, it invariably has segregation of Mo on a microscopic scale. The centre of each dendrite is leaner in Mo than are the inter-dendritic spaces. The centre of a dendrite then becomes a preferential site for localized corrosion.

It has been found that this preferential localized corrosion in the weld metal can be overcome by using a filler metal that is higher in Mo than is the base metal. Thus, a 3%Mo base metal requires a filler metal of at least 4%Mo. A 4%Mo base metal requires a filler metal of at least 6%Mo. A 6%Mo base metal requires a filler metal of at least 8%Mo. However, SS weld metal that contains more than 5%Mo often has poor mechanical properties. Therefore, a Ni-base alloy of at least 8%Mo is usually chosen for filler metal when joining SS with contents of 4%Mo and higher. The most common filler metals selected are the ERNiCrMo-3 or ERNiCrMo-10 covered electrode classifications in the ANSI/AWS A5.11 and the ERNiCrMo-3 or ERNiCrMo-10 bare-wire classifications in the ANSI/AWS A5.14 specification.

For Use in Post -weld Heat Treated Condition

Austenitic SS weldments are usually put into service in the as-welded condition, except in the situations described below. When non-low-C grades are welded and sensitisation that is due to Cr-carbide precipitation cannot be tolerated, then annealing at 1050-1150 °C, followed by a water quench, can be used to dissolve all carbides (and any inter-metallic compounds, such as σ phase) and to maintain a solid solution. This annealing heat treatment also causes much of the ferrite that is present to transform to austenite.

Autogenous welds in high-Mo SS, such as longitudinal seams in pipe, represent another exception. Annealing is used to cause the diffusion of Mo to erase the micro-segregation of the as-welded condition, thus allowing the weld to match the pitting and crevice corrosion resistance of the base metal. Because these welds generally contain no fernte in the as-welded condition, no ferrite is lost.

A third exception is the joints between austenitic SS and carbon or low-alloy steel or the weld overlay of carbon or low-alloy steel with austenitic SS filler metal. Type 309 filler metal often has been used for such a joint or overlay, so that the weld metal (especially in a multi-pass weld where type 309 is used throughout) contains an appreciable amount of ferrite. The HAZ of the carbon or low-alloy steel may require a PWHT at various temperatures from 600-700 °C, depending on the specific alloy. These temperatures produce both carbide precipitation in the austenitic base metal and weld metal and transformation of ferrite to σ phase in the weld metal.

In the weld metal, carbide precipitation works against σ phase formation because the carbides tend to precipitate where Cr is highest: at the ferrite-austenite interface. Because carbide precipitation reduces the Cr in the adjacent ferrite, some of it becomes unstable and transforms to austenite. This reduces the amount of ferrite available for σ formation. In a joint, but not in an overlay, corrosion resistance of the weld metal is seldom of concern because of the proximity of carbon or low-alloy steel. At the same ferrite content in the as-welded condition, less ferrite will be available for σ formation in type 309 than in type 309L weld-metal. Therefore, the higher-C filler metal is often preferred for such applications.

At the same time, C from the mild steel or low-alloy steel immediately adjacent to the fusion line migrates to the higher-Cr weld metal, producing a layer of carbides along the fusion line in the weld metal and a C-depleted layer in the HAZ off the base metal. This C-depleted layer is weak at elevated temperatures. If the weldment is in service at suitable temperatures, then creep failure can occur there. There is also a serious mismatch in the coefficient of thermal expansion (CTE) between austenitic SS filler metal and carbon steel or low-alloy steel base metal. Therefore, thermal cycling produces strain accumulations along the interface and can lead to premature failure in creep, as has occurred in joints of Cr-Mo low-alloy steels to SS. As a result, such dissimilar joints intended for elevated-temperature service are often welded with Ni-base alloy filler metals.

Although PWHT can be used for stress relief in austenitic SS weldments, the yield strength (YS) of austenitic SS falls much more slowly with rising temperature than does the YS of carbon or low-alloy steel. In addition, carbide precipitation and σ phase embrittlement occur in the temperature range 600-700^{o}C where carbon steels and low-alloy steels are normally stress relieved. Significant improvement in relieving residual stresses without damaging corrosion resistance is only accomplished with a full anneal at temperatures in the range 1050-1150 ^{o}C, followed by rapid cooling to avoid carbide precipitation in unstabilised grades.

In stabilized grades, heat treatment at these temperatures causes Nb or Ti carbides to precipitate in part, which accomplishes much of the stabilisation. However, rapid cooling is still necessary to obtain full

Table 4 : Filler metals for precipitation - hardening stainless steels

Base Metal		Matching filler metals		
Designation	**Nominal Composition, wt%**	**A5.4**	**A5.9[(a)]**	**A5.22**
630 (17-4PH)	0.07C-17Cr-4Ni-4Cu	E630-xx	ER630	...
631	0.09C-17Cr-7Ni-1Al	...	...	...
632	0.09C-15Cr-7Ni-2.5Mo-1Al	...	...	...
633	0.09C-16.5Cr-4.5Ni-3Mo-0.1N	...	...	...
634	0.13C-15.5Cr-4.5Ni-3Mo-0.1N	...	...	...
635	0.08C-17Cr-7Ni-0.8Ti	...	...	...
XM-9	0.05C-14Cr-6.5Ni-0.3Mo-0.75Ti-0.1Al	...	...	...
XM-12	0.07C-15Cr-4.5Ni-3.5Cu-0.3Nb+Ta	...	...	...
XM-13	0.05C-13Cr-8Ni-2Mo-0.01N-1.1Al	...	...	...
XM-16	0.03C-12Cr-8.5Ni-0.5Mo-2Cu-1Al-0.3Nb+Ta	...	...	...
XM-25	0.05C-15Cr-6Ni-0.75Mo-1.5Cu-0.4Nb+Ta	...	...	...
660(A286)	0.08C-15Cr-26Ni-1Mo-0.35Al-0.5Cu-2Ti-0.01B	...	...	...
662	0.08C-14Cr-26Ni-3Mo-0.35Al-0.3V-2Ti-0.01B	...	...	...

(a) Metal-cored electrodes, indicated by a "C" in place of "R" in the classification,are also included.

corrosion resistance. In either case, the rapid cooling often reintroduces residual stresses; which means that this approach has to be used carefully. At the annealing. temperatures, significant surface oxidation occurs in air. This oxide is tenacious on SS and must be removed by pickling, followed by a water rinse and then passivation, in order to restore full corrosion resistance.

PRECIPITATION-HARDENING STAINLESS STEELS

Table 4 lists several PH SS. Most of their applications are in aerospace and other high technology industries. Only one composition; the martensitic type 630 (17-4 PH), is made as a welding filler metal in sufficient volume to warrant AWS classification of a matching filler metal, as can be seen in Table 4.

For Use in As-Welded Condition

As PH SS achieve high strength by heat treatment, it is not reasonable to expect the weld metal to match the properties of the base metal in the as-welded condition. Therefore, the design of a weldment to be used in the as-welded condition generally must assume that the weld metal will under-match the strength of the base metal. If that is acceptable, then austenitic filler metals, such as types 308 and 309, can be suitable filler metals for the martensitic and semi-austenitic PH SS. As with many other filler metal selections, consideration should be given to obtaining some ferrite in the weld metal to avoid hot cracking.

For Use in Post-Weld Heat Treated Condition

Normally, PWHT is one on a weldment of PH SS because a weld metal strength comparable to the base metal is desired. This generally means that the weld metal must also be a PH SS. Many PH SS weldments are light-gage materials that are readily welded by autogenous GTAW (or LBW) process. Then, the weld metal matches the base metal and responds similarly to heat treatment.

Except for 17-4 PH SS (type 630), matching filler metals for PH SS are not easy to locate and do not have AWS classification. Some are covered by Aerospace Material Specifications (AMS as bare wires only, which match base metal compositions. These wires, used for GTAW and GMAW processes, are most likely to be available from suppliers to the aerospace industry. Alternatively, the shearing of base metal into narrow strips can provide filler metal for the GTAW process:

Table 5 : Filler metals for duplex ferritic-austenitic stainless steels

Base Metal		Matching filler metals		
Designation	Nominal Composition, wt%	A5.4	A5.9[a]	A5.22
XM-26	0.06C-26Cr-6.5Ni-0.25Ti	...	...	...
2205	0.03C-22Cr-5.5Ni-3Mo-0.14N	E2209-xx	ER2209	...
2304	0.03C-23Cr-4.25Ni-0.3Mo-0.13N-0.55Cu	...	...	...
255	0.04C-26Cr-5.5Ni-3.4Mo-0.2N-2Cu	E22553-xx	ER2553	...
2507	0.03C-25Cr-7Ni-4Mo-0.28N-0.5Cu	...	...	...
329	0.08C-26Cr-3.75 Ni-1.5Mo	...	...	...
CD-4Mcu	0.04C-26Cr-5.4 Ni-2Mo-3Cu	E22553-xx	ER2553	...

(a) Metal-cored electrodes, indicated by a "C" in place of "R" in the classification,are also included.

It is common practice to use type 630 (17-4 PH) as the filler metal with several martensitic and semi-austenitic PH SS base metals. The best weldment properties can then be obtained by a full-solution heat treatment, rapid cooling to RT, reheating to age harden at about 480^{o}C (900^{o}F), and cooling to RT. As type 630 filler metal transforms to martensite on cooling from solidification, it is also possible to obtain nearly full-strength weld metal, when using this filler metal, by simply cooling to RT and then ageing at 480^{o}C to harden the weld metal. This presupposes that the weld metal does not pick up enough alloying elements by dilution to stabilise austenite and therefore does transform to martensite. When the weldment is simply aged after welding, without first using a solution heat treatment, some portion of the HAZ will have been overaged by the heat of welding and will become the weak link in the weldment. Then, 100% joint efficiency cannot be expected. A procedure qualification test becomes necessary to determine if the weldment strength will be adequate.

DUPLEX FERRITIC-AUSTENITIC STAINLESS STEELS

Table 5 lists selected duplex ferritic-austenitic SS base metals and a limited number of "matching" filler metals. In a duplex ferritic-austenitic SS, the optimum phase balance is usually approximately equal amounts of fernte and austenite. Base metal compositions are usually adjusted to obtain this phase balance as the equilibrium structure at about 1040 °C after hot working and/or annealing. Of the alloying elements, C is generally undesirable for reasons of corrosion resistance. All the other elements are slow to diffuse substitutional alloy elements, except for N. The other alloy elements contribute to determine the equilibrium phase balance, but N is most important in determining the relative ease of a near-equilibrium phase balance. The earlier duplex SS (such as types 329 and CD-4Mcu), N was not a deliberate alloying element. Therefore, under normal weld cooling conditions, the weld HAZs and matching weld metals reached RT with very little austenite, and had poor mechanical properties and corrosion resistance. To obtain useful properties, the welds required an annealing heat treatment, followed by quenching to avoid embrittlement of the ferrite by σ and other phases.

Over-alloying of the weld metal with Ni causes the transformation to begin at a higher temperature, where diffusion is very rapid. Using this approach, a better phase balance can be obtained in the as-welded condition in the weld metal. However, this approach does nothing for the HAZ. Alloying with N, in the newer duplex SS, usually solves the HAZ problem. With normal welding heat input and about 0.15%Ni, a reasonable phase balance is achieved in the HAZ. In addition, the N, when it diffuses to the austenite, imparts improved pitting resistance. On the other hand, if the cooling rate is too rapid and N is trapped in the ferrite, then Cr-nitride precipitates, damaging the corrosion resistance.

Therefore, low welding heat inputs should be avoided with duplex SS.

For Use in As-Welded Condition

A weld metal with a matching composition to that of the duplex SS often has inferior ductility and toughness; because of high ferrite content. This problem is less critical with inert gas shielded weld metals (GTAW or GMAW process), when compared with flux-shielded weld metals (SMAW, SAW or FCAW process), but it is still significant. The safest procedure for the as-welded condition is to use a filler metal that matches the base metal in all respects, except that it has a higher Ni content. It is usually better to avoid autogenous welds. With the GTAW process, especially for the root pass, it is important to design the welding procedure to limit dilution of the weld metal by the base metal. This often means using a wider than normal root opening and more filler metal in the root than one would use for an austenitic SS joint.

The AWS specifications classify two filler metal compositions for the duplex SS. The 2209 filler metal composition, used as a covered electrode for the SMAW process or as a bare wire for the SAW, GTAW, GMAW. PAW and other welding processes, is a match for type 2205 base metal, except !hat it has a higher Ni content, which is necessary for proper ferrite control, ductility and toughness. It can also be used for any lower alloyed duplex SS. The 2553 filler metal composition, used as a covered electrode or as a bare wire, is a match for alloy 255 base metal. In general, it can also be used for all lower-alloyed base metals. This leaves only the super duplex alloys, such as 2507 without an acceptable matching or over-matching filler metal in the AWS specifications.

For SAW of the duplex SS, high-basicity fluxes generally provide the best results, especially if weld-metal toughness is a concern. The toughness of duplex SS weld metal is strongly sensitive to O_2 content, and basic fluxes provide the lowest weld-metal O_2 content with a given wire.

In the past, Ar-H_2 gas mixtures have been utilised to some extent in the GTAW process to achieve better wetting and bead shape. However, instances of significant hydrogen embrittlement of GTAW weldments made with Ar-H_2 gas mixtures have occurred, and this practice is best avoided for weldments used in the as-welded condition. Covered electrodes for use in the SMAW process should be treated as low-hydrogen electrodes for low alloy steels.

In contrast to the situation with low-alloy steels, preheat and interpass temperature control is not practised with duplex SS weldments for the purpose of hydrogen cracking protection, but for HAZ microstructure control. A minimum preheat of 100^{o}C and a maximum interpass temperature of 200^{o}C can be recommended for most duplex SS weldments. This modest preheat/ interpass temperature helps to slow the cooling rate to promote more extensive austenite formation in the HAZ, without posing potential problems with α' embrittlement.

A limitation on welding heat input also serves to promote austenite formation in the HAZ, as well as in the weld metal. Heat input below 1.2 kJ/mm tends to result in undesirably high ferrite content in the HAZ and sometimes in the weld metal. Further, heat input levels above about 4 kJ/mm tend to produce excessive grain growth in the HAZ and sometimes in the weld metal, which reduces toughness and may also promote Cr-nitride precipitation.

For Use in Post-Weld Heat Treated Condition

Longitudinal seams in pipe lengths, weld in forgings, and repair welds in castings are often annealed after welding. This involves heating to 1040^{o}C or higher, followed by rapid cooling, usually a water quench, to avoid σ phase. Annealing permits the use of either an exactly matched filler metal or no filler metal at all, because proper annealing adjusts the phase balance to near equilibrium. Slow heating to annealing temperature permits σ and other phases to precipitate during heating; because the precipitation of σ phase occurs in only a few minutes at 800°C. The production of pipe lengths often includes very rapid induction heating of the pipe, so that the σ phase is completely avoided during heating, and only a brief hold near 1040°C is necessary to accomplish phase balance control.

Furnace annealing can produce slow heating. Therefore, σ phase can be expected to form during heating. It is necessary to hold at the annealing temperature for longer times (an hour or more) to ensure that all σ is dissolved. However, properly run continuous furnaces can provide high heating rates, especially for light wall tubes and other thin sections. If the precipitation of σ phase during heating can be avoided, long anneals are not necessary. The extremely low creep strength of duplex SS at the annealing temperature can result in severe distortion during annealing. Rapid cooling to avoid σ phase also can contribute to distortion that is due to annealing.

High-Ni filler metals can present a special problem when the weldment is to be annealed. A high Ni content raises the minimum temperature needed to dissolve the σ phase; temperatures as high as 1100°C may be needed at levels of 9-10%Ni, especially when the Mo content exceeds about 3%.

A very significant loss in weld metal YS occurs during the annealing of duplex SS weld metals. In the as-welded condition, the YS of duplex SS weld metal, whether matching Ni (about 5-6%Ni in the weld, as in the base metal) or high Ni (about 8-10%Ni in the weld), far exceeds base metal minimum requirements. But after annealing, especially a furnace anneal, the YS of the weld metal falls to near (or even below) base metal minimum requirements. Higher N contents (over 0.2%) in the weld metal may be necessary to maintain weld-metal YS after annealing.