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WELDING OF STAINLESS STEELS AND OTHER JOINING METHODS

Introduction

Stainless steels are iron-base alloys containing 10.5% or more chromium. They have been used for many industrial, architectural, chemical, and consumer applications for over a half century.

Reference is often made to stainless steel in the singular sense as if it were one material. Actually there are well over 100 stainless steel alloys. Three general classifications are used to identify stainless steels. They are: 1. Metallurgical Structure; 2. The AISI numbering system: namely 200, 300, and 400 Series numbers; 3. The Unified Numbering System, which was developed by American Society for Testing Materials (ASTM) and Society of Automotive Engineers (SAE) to apply to all commercial metals and alloys.

Stainless steels are engineering materials capable of meeting a broad range of design criteria. They exhibit excellent corrosion resistance, strength at elevated temperature, toughness at cryogenic temperature, and fabrication characteristics and they are selected for a broad range of consumer, commercial, and industrial applications. They are used for the demanding requirements of chemical processing to the delicate handling of food and pharmaceuticals. They are preferred over many other materials because of their performance in even the most aggressive environments, and they are fabricated by methods common to most manufacturers.

In the fabrication of stainless steel products, components, or equipment, manufacturers employ welding as the principal joining method. Stainless steels are welded materials, and a welded joint can provide optimum corrosion resistance, strength, and fabrication economy. However, designers should recognize that any metal, including stainless steels, may undergo certain changes during welding. It is necessary, therefore, to exercise a reasonable degree of care during welding to minimize or prevent any deleterious effects that may occur, and to preserve the same degree of corrosion resistance and strength in the weld zone that is an inherent part of the base metal.

The purpose of this booklet is to help designers and manufacturing engineers achieve a better understanding of the welding characteristics of stainless steels, so they may exercise better control over the finished products with respect to welding. In addition to welding, other ancillary joining methods are discussed, including soldering and brazing.

Stainless Steel Welding Characteristics

During the welding of stainless steels, the temperatures of the base metal adjacent to the weld reach levels at which microstructural transformations occur. The degree to which these changes occur, and their effect on the finished weldment — in terms of resistance to corrosion and mechanical properties — depends upon alloy content, thickness, filler metal, joint design, weld method, and welder skill. Regardless of the changes that take place, the principal objective in welding stainless steels is to provide a sound joint with qualities equal to or better than those of the base metal, allowing for any metallurgical changes that take place in the base metal adjacent to the weld and any differences in the weld filler metal.

For purposes of discussion, in welding there are three zones of principal concern: 1) The solidified weld metal, composed of either base metal or base metal and filler metal; 2) the heat-affected zone (HAZ) in which the base metal is heated to high temperatures but less than the melting temperature; and 3) the base metal which is only moderately warmed or not warmed at all. The three zones are illustrated by the drawing in Figure 1.

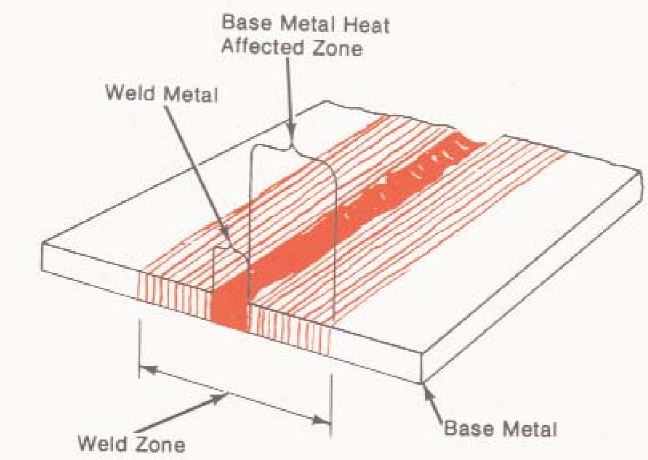


Figure 1
Thermal Affected Area of Metal Due to Welding

Although risking over-simplification, the following discussion will be helpful in understanding the metallurgical characteristics of stainless steels and how their microstructures can change during welding.

AUSTENITIC STAINLESS STEELS

Austenitic stainless steels (Table 1) containing chromium and nickel as the principal alloying elements (in addition to iron) are identified as 300 Series (UNS designated S3xxxx). Those containing chromium, nickel, and manganese (in addition to iron) are identified as 200 Series (UNS designated S2xxxx).

The stainless steels in the austenitic group have different compositions and properties but many common characteristics. They can be hardened by cold working, but not by heat treatment. In the annealed condition, all are nonmagnetic, although some may become slightly magnetic by cold working. At room temperature the 300 and 200 Series stainless steels retain an austenitic microstructure.

While resistance to corrosion is their principal attribute, they are also selected for their excellent strength properties at high or extremely low temperatures. They are considered to be the most weldable of the high-alloy steels and can be welded by all fusion and resistance welding processes. Comparatively little trouble is experienced in making satisfactory welded joints if their inherent physical characteristics and mechanical properties are given proper consideration.

In comparison with mild steel, for example, the austenitic stainless steels have several characteristics that require some revision of welding procedures that are considered standard for mild steel. As illustrated in Table 2, the melting point of the austenitic grades is lower, so less heat is required to produce fusion. Their electrical resistance is higher than that of mild steel so less electrical current (lower heat settings) is required for welding. These stainless steels also have a lower coefficient of thermal conductivity, which causes a tendency for heat to concentrate in a small zone adjacent to the weld. The austenitic stainless steels also have coefficients of thermal expansion approximately 50% greater than mild steel, which calls for more attention to the control of warpage and distortion.

Table 2
Comparison of Welding Characteristics of 304 Stainless Steel with Carbon Steel

	Carbon Steel	304	Remarks
Melting Point °F Approx.	2800	2550-2650	304 requires less heat to produce fusion, which means faster welding for the same heat or less heat input for the same speed.
Electrical Resistance (Annealed) (Michrohm-cm, approx.) At 68 F At 1625 F	12.5 125	72.0 126	This is of importance in electric fusion methods. The higher electrical resistance of 304 results in the generation of more heat for the same current or the same heat with lower current, as compared with carbon steel. This, together with its low rate of heat conductivity, accounts for the effectiveness of resistance welding methods on 304.
Rate of Heat Conductivity (Compared in Percent) At 212 F Over 1200 F	100% 100%	28% 66%	304 conducts heat much more slowly than carbon steel thus promoting sharper heat gradients. This accelerates warping, especially in combination with higher expansion rates. Slower diffusion of heat through the base metal means that weld zones remain hot longer, one result of which may be longer dwell in the carbide precipitation range unless excess heat is artificially removed by chill bars, etc.
	Note: 304 at 212 F has a rate of 9.4 and at 932 F a rate of 12.4 Btu/ft²/hr/F/ft.		
Coefficient of expansion per °F Over range indicated	.0000065 (68-1162 F)	.0000098 (68-932 F)	304 expands and contracts at a faster rate than carbon steel, which means that increased expansion and contraction must be allowed for in order to control warping and the development of thermal stresses upon cooling.

An important part of successful welding of the austenitic grades, therefore, requires proper selection of alloy (for both the base metal and filler rod), and correct welding procedures. For the stainless steels more complex in composition, heavier in sections or the end-use conditions more demanding (which narrows the choice of a base metal), a greater knowledge of stainless steel metallurgy is desirable.

Two important objectives in making weld joints in austenitic stainless steels are: (1) preservation of corrosion resistance, and (2) prevention or cracking.

Table 1 Austenitic Stainless Steels

	Chemical Analysis % (Max. unless noted otherwise)									Nominal Mechanical Properties (Annealed sheet unless noted otherwise)						
										Tensile Strength		Yield Strength (0.2% offset)		Elongation in 2″ (50.80 mm)	Hardness (Rockwell)	Product Form
(UNS)	C	Mn	P	S	Si	Cr	Ni	Mo	Other	ksi	MPa	ksi	MPa	%		
201 (S20100)	0.15	5.50/7.50	0.060	0.030	1.00	16.00/18.00	3.50/5.50		0.25N	95	655	45	310	40	B90	
202 (S20200)	0.15	7.50/10.00	0.060	0.030	1.00	17.00/19.00	4.00/6.00		0.25N	90	612	45	310	40	B90	
205 (S20500)	0.12/0.25	14.00/15.50	0.030	0.030	0.50	16.50/18.00	1.00/1.75		0.32/0.40N	120.5	831	69	476	58	B98	(Plate)
301 (S30100)	0.15	2.00	0.045	0.030	1.00	16.00/18.00	6.00/8.00			110	758	40	276	60	B85	
302 (S30200)	0.15	2.00	0.045	0.030	1.00	17.00/19.00	8.00/10.00			90	612	40	276	50	B85	
302B (S30215)	0.15	2.00	0.045	0.030	2.00/3.00	17.00/19.00	8.00/10.00			95	655	40	276	55	B85	
303 (S30300)	0.15	2.00	0.20	0.15 (min)	1.00	17.00/19.00	8.00/10.00	0.60*		90	621	35	241	50		(Bar)
303Se (S30323)	0.15	2.00	0.20	0.060	1.00	17.00/19.00	8.00/10.00		0.15Se (min)	90	621	35	241	50		(Bar)
304 (S30400)	0.08	2.00	0.045	0.030	1.00	18.00/20.00	8.00/10.50			84	579	42	290	55	B80	
304L (S30403)	0.030	2.00	0.045	0.030	1.00	18.00/20.00	8.00/12.00			81	558	39	269	55	B79	
S30430	0.08	2.00	0.045	0.030	1.00	17.00/19.00	8.00/10.00		3.00/4.00Cu	73	503	31	214	70	B70	(Wire)
304N (S30451)	0.08	2.00	0.045	0.030	1.00	18.00/20.00	8.00/10.50		0.10/0.16N	90	621	48	331	50	B85	
305 (S30500)	0.12	2.00	0.045	0.030	1.00	17.00/19.00	10.50/13.00			85	586	38	262	50	B80	
308 (S30800)	0.08	2.00	0.045	0.030	1.00	19.00/21.00	10.00/12.00			115	793	80	552	40		(Wire)
309 (S30900)	0.20	2.00	0.045	0.030	1.00	22.00/24.00	12.00/15.00			90	621	45	310	45	B85	
309S (S30908)	0.08	2.00	0.045	0.030	1.00	22.00/24.00	12.00/15.00			90	621	45	310	45	B85	
310 (S31000)	0.25	2.00	0.045	0.030	1.50	24.00/26.00	19.00/22.00			95	655	45	310	45	B85	
310S (S31008)	0.08	2.00	0.045	0.030	1.50	24.00/26.00	19.00/22.00			95	655	45	310	45	B85	
314 (S31400)	0.25	2.00	0.045	0.030	1.50/3.00	23.00/26.00	19.00/22.00			100	689	50	345	40	B85	
316 (S31600)	0.08	2.00	0.045	0.030	1.00	16.00/18.00	10.00/14.00	2.00/3.00		84	579	42	290	50	B79	
316F (S31620)	0.08	2.00	0.20	0.10 (min)	1.00	16.00/18.00	10.00/14.00	1.75/2.50		85	586	38	262	60	B85	
316L (S31603)	0.030	2.00	0.045	0.030	1.00	16.00/18.00	10.00/14.00	2.00/3.00		81	558	42	290	50	B79	
316N (S31651)	0.08	2.00	0.045	0.030	1.00	16.00/18.00	10.00/14.00	2.00/3.00	0.10/0.16N	90	621	48	331	48	B85	
317 (S31700)	0.08	2.00	0.045	0.030	1.00	18.00/20.00	11.00/15.00	3.00/4.00		90	621	40	276	45	B85	
317L (S31703)	0.030	2.00	0.045	0.030	1.00	18.00/20.00	11.00/15.00	3.00/4.00		86	593	38	262	55	B85	
321 (S32100)	0.08	2.00	0.045	0.030	1.00	17.00/19.00	9.00/12.00		5xC Ti (min)	90	621	35	241	45	B80	
329** (S32900)	0.10	2.00	0.040	0.030	1.00	25.00/30.00	3.00/6.00	1.00/2.00		105	724	80	552	25	230 (Brinell)	(Strip)
330 (N08330)	0.08	2.00	0.040	0.030	0.75/1.50	17.00/20.00	34.00/37.00		0.10Ta 0.20Cb	80	552	38	262	40	B80	
347 (S34700)	0.08	2.00	0.045	0.030	1.00	17.00/19.00	9.00/13.00		10xC Cb+Ta (min)	95	655	40	276	45	B85	
348 (S34800)	0.08	2.00	0.045	0.030	1.00	17.00/19.00	9.00/13.00		10xC Cb+Ta (min) (Ta 0.10 – 0.20 Co max)	95	655	40	276	45	B85	
384 (S38400)	0.08	2.00	0.045	0.030	1.00	15.00/17.00	17.00/19.00			75	517	35	241	55	B70	(Wire)

*May be added at manufacturer's option.
**Duplex alloy– austenite + ferrite.

PRESERVATION OF CORROSION RESISTANCE

The principal criteria for selecting a stainless steel usually is resistance to corrosion, and while most consideration is given to the corrosion resistance of the base metal, additional consideration should be given to the weld metal and to the base metal immediately adjacent to the weld zone. Welding naturally produces a temperature gradient in the metal being welded, ranging from the melting temperature of the fused weld metal to ambient temperature at some distance from the weld. The following discussion will be devoted to preserving corrosion resistance in the base metal heat affected zone.

Carbide Precipitation — A characteristic of an annealed austenitic stainless steels such as 304, is its susceptibility to an important microstructural change if it is exposed to temperatures within an approximate range of 800-1650F. Within this range, chromium and carbon form chromium carbides, and these precipitate out of the solid solution at the boundaries between the grains. The rapidity of carbide development depends on a number of factors. The actual metal temperature between the range of 800-1650F is one factor. Chromium carbides form most rapidly at about 1200F, and the formation falls off to nil at the upper and lower limits. Another factor is the amount of carbon originally present in the material — the higher the carbon content the more pronounced the action. Time at temperature is a third factor.

The effect of carbide precipitation on corrosion resistance is to reduce the chromium available to provide corrosion resistance. Because low-carbon content reduces the extent to which carbide precipitation occurs, the low-carbon austenitic grades may be preferred for weldments to be used in highly corrosive service. 304 with a maximum carbon content of 0.08% is widely used. Also available are low-carbon 304L, 316L, and 317L with 0.03% carbon.

321 and 347 contain titanium and columbium-tantalum, respectively, alloying elements which have a greater affinity for carbon than does chromium, thus reducing the possibility of chromium carbide precipitation. These stabilized types are intended for long-time service at elevated temperatures in a corrosive environment or when the low-carbon grades are not adequate.

The removal of precipitated carbides from 304 in order to restore maximum corrosion resistance can be accomplished by annealing (at 1800 to 2150F) (above the sensitizing range) followed by rapid cooling. Stress relieving a weldment at 1500-1700F will not restore corrosion resistance, and, in fact, may foster carbide precipitation in stainless steels that do not have a low-carbon content or are not stabilized.

Stress-Corrosion Cracking — The chance of stress-corrosion cracking is another reason for post-weld heat treatment. In the as-welded condition, areas close to the weld contain residual stresses approaching the yield point of the material. It is difficult to predict when an environment will produce stress-corrosion cracking and to decide how much reduction must be made in the magnitude of residual stress to avoid its occurrence. To ensure against this stress-corrosion cracking in welded austenitic stainless steels is to anneal the types which contain regular carbon content, and to stress relieve the stabilized and extra-low-carbon types.

WELDING PREHEATING

The question often arises whether an austenitic stainless steel should be preheated for welding. In general, preheating is not helpful because no structural changes, such as martensite formation, occur in the weld or the heat-affected zones. In some cases, preheating could be harmful in causing increased carbide precipitation, or greater warpage.

MARTENSITIC STAINLESS STEELS

Martensitic stainless steels, which are identified by 400 Series numbers (UNS desiignated S4xxxx) (Table 3), contain chromium as the principal alloying element. In the annealed condition these stainless steels have basically a ferritic microstructure and are magnetic. On heating beyond the critical temperature, the ferrite transforms into austenite. If then rapidly cooled to below the critical temperature, the austenite transforms into martensite. In many respects, the martensitic stainless steels are similar to the quenched and tempered carbon or alloy steels whose mechanical properties can be varied through heat treatment. Whether or not the transformations take place depends upon alloy content, especially the chromium and carbon contents. Other alloying additions may also affect transformation.

Table 3 **Martensitic Stainless Steels**

	Chemical Analysis % (Max. unless noted otherwise)									Nominal Mechanical Properties (Annealed sheet unless noted otherwise)						
										Tensile Strength		Yield Strength (0.2% offset)		Elongation in 2″ (50.80 mm)	Hardness (Rockwell)	Product Form
(UNS)	C	Mn	P	S	Si	Cr	Ni	Mo	Other	ksi	MPa	ksi	MPa	%		
403 (S40300)	0.15	1.00	0.040	0.030	0.50	11.50/13.00				70	483	45	310	25	B80	
410 (S41000)	0.15	1.00	0.040	0.030	1.00	11.50/13.50				70	483	45	310	25	B80	
414 (S41400)	0.15	1.00	0.040	0.030	1.00	11.50/13.50	1.25/2.50			120	827	105	724	15	B98	
416 (S41600)	0.15	1.25	0.060	0.15 (min)	1.00	12.00/14.00		0.60*		75	517	40	276	30	B82	(Bar)
416 Se (S41623)	0.15	1.25	0.060	0.060	1.00	12.00/14.00			0.15 Se (min)	75	517	40	276	30	B82	(Bar)
420 (S42000)	0.15 (min)	1.00	0.040	0.030	1.00	12.00/14.00				95	655	50	345	25	B92	(Bar)
420 F (S42020)	0.15 (min)	1.25	0.060	0.15 (min)	1.00	12.00/14.00		0.60*		95	655	55	379	22	220 (Brinell)	(Bar)
422** (S42200)	0.20/0.25	1.00	0.025	0.025	0.75	11.00/13.00	0.50/1.00	0.75/1.25	0.15/0.30 V 0.75/1.25 W	145	1000	125	862	18	320 (Brinell)	(Bar)
431 (S43100)	0.20	1.00	0.040	0.030	1.00	15.00/17.00	1.25/2.50			125	862	95	655	20	C24	(Bar)
440 A (S44002)	0.60/0.75	1.00	0.040	0.030	1.00	16.00/18.00		0.75		105	724	60	414	20	B95	(Bar)
440 B (S44003)	0.75/0.95	1.00	0.040	0.030	1.00	16.00/18.00		0.75		107	738	62	427	18	B96	(Bar)
440 C (S44004)	0.95/1.20	1.00	0.040	0.030	1.00	16.00/18.00		0.75		110	758	65	448	14	B97	(Bar)

*May be added at manufacturer's option. **Hardened and Tempered

As a group, the martensitic stainless steels (hardenable by heat treatment) have certain characteristics in common which influence their behavior when subjected to the temperatures encountered in welding. These characteristics are as follows:

1) Their melting points are approximately 2700F, which compares with 2800F for mild steel. This means that they require less heat for their melting or that they melt faster than mild steel for the same rate of heat input.
2) Their coefficients of expansion and contraction are about the same as or slightly less than the corresponding value for carbon steel. This is in contrast to the chromium-nickel grades whose coefficients are about 45-50% higher than that of mild steel.
3) The heat conductivity ratings are less than half that of mild steel depending upon temperature. In this respect, they are similar to the chromium-nickel grades.
4) Their resistance to the flow of electrical current is higher than that of mild steel. For that reason, less amperage is required for their welding.

In the soft annealed condition, a martensitic stainless steel such as 410 (the general-purpose grade) exhibits maximum ductility. On heating to temperatures above about 1500F, the metallurgical structure begins to change to austenite; at approximately 1850F the structure is completely austenititic. Cooling from these temperatures results in the transformation of austenite to martensite, a hard, strong, nonductile structure. Rapid cooling from 1850F results in maximum martensite content. Cooling from temperatures between 1500-1850F results in less martensite. These characteristic reactions to heating and cooling determine the welding behavior of the martensitic stainless steels.

Martensitic stainless steels can be welded in any one of several conditions: annealed, semihardened, hardened, stress relieved, or tempered. Regardless of prior condition, welding will produce a hardened martensitic zone adjacent to the weld (where the temperature reaches 1500-1850F). The hardness of the zone will be dependent primarily upon the carbon content and can be controlled to a degree by the welding procedure. It should be recognized that the sharp temperature gradients, which are accentuated by the low rate of heat conductivity, cause intense stresses to be developed due both to thermal expansion and to volumetric changes caused by the changes in the crystal structure. Their severity may be sufficient to produce fractures.

WELDING PREHEATING

Preheating and interpass temperature control are the best means of avoiding cracking in the welding of martensitic stainless steels. The preheating temperatures employed are usually in the order of 400 to 600F. Carbon content is the most important factor in establishing whether preheating will be necessary.

The following guide can be useful to coordinate welding procedures with carbon content and to accommodate the welding characteristics of the martensitic grades:

Below 0.10%C — Generally no preheating or heat treating after welding required.
0.10 to 0.20%C — Preheat to 500F, weld, and cool slowly.
0.20 to 0.50%C — Preheat to 500F, weld, and heat treat after welding.
Over 0.50%C — Preheat to 500F, weld with high heat input, and heat treat after welding.

Post-heating, which should always be regarded as an integral part of a welding operation on the martensitic types, may be accomplished by either of two methods:

1) Anneal at 1500F or higher followed by controlled cooling to 1100F at a rate of 50 degrees per hour and then air cooling.
2) Heat to 1350-1400F and follow with the same cooling cycle as described in (1).

If hardening and tempering immediately follow welding, the post-anneal may be eliminated. Otherwise, anneal promptly after welding without allowing the part to cool to room temperature.

Where permissible, the use of austenitic stainless steel filler metal will help in preventing brittle welds. A ductile weld bead is deposited, but, of course, the hardening of the metal in the HAZ will not be eliminated.

Table 4

Table 5 Ferritic Stainless Steels

AISI Type (UNS)	Chemical Analysis % (Max. unless noted otherwise) C	Mn	P	S	Si	Cr	Ni	Mo	Other	Nominal Mechanical Properties (Annealed sheet unless noted otherwise) Tensile Strength ksi	Tensile Strength MPa	Yield Strength (0.2% offset) ksi	Yield Strength (0.2% offset) MPa	Elongation in 2″ (50.80 mm) %	Hardness (Rockwell)	Product Form
405 (S40500)	0.08	1.00	0.040	0.030	1.00	11.50/14.50			0.10/0.30 Al	65	448	40	276	25	B75	
409 (S40900)	0.08	1.00	0.045	0.045	1.00	10.50/11.75			6xC/0.75 Ti	65	448	35	241	25	B75	
429 (S42900)	0.12	1.00	0.040	0.030	1.00	14.00/16.00				70	483	40	276	30	B80	(Plate)
430 (S43000)	0.12	1.00	0.040	0.030	1.00	16.00/18.00				75	517	50	345	25	B85	
430F (S43020)	0.12	1.25	0.060	0.15 (min)	1.00	16.00/18.00		0.60*		95	655	85	586	10	B92	(Wire)
430F Se (S43023)	0.12	1.25	0.060	0.060	1.00	16.00/18.00			0.15 Se (min)	95	655	85	586	10	B92	(Wire)
434 (S43400)	0.12	1.00	0.040	0.030	1.00	16.00/18.00		0.75/1.25		77	531	53	365	23	B83	
436 (S43600)	0.12	1.00	0.040	0.030	1.00	16.00/18.00		0.75/1.25	5xC/0.70 Cb + Ta	77	531	53	365	23	B83	

FERRITIC STAINLESS STEELS

Ferritic stainless steels are also straight chromium alloys in the 400 Series with a microstructure, in the annealed condition, consisting of ferrite and carbides (Table 4). They are also magnetic. On heating most ferritic types above a critical temperature, the structure becomes austenitic which on cooling may partially transform into martensite (but not sufficiently to impart high strength). Consequently, ferritic stainless steels are considered not to be hardenable by heat treatment. Also, there will be a tendency for the ferrite grains to increase in size.

These two structural features, (a) martensite formation and (b) grain growth, result in a reduction of ductility and toughness. Also, rapid cooling from temperatures above 700F may cause intergranular precipitation (similar to carbide precipitation in austenitic stainless steels) that results in reduced resistance to corrosion. Consequently, the ferritic stainless steels are not considered attractive from the standpoint of weldability.

In the last few years several new ferritic stainless steels have been introduced. These steels are characterized by levels of carbon and nitrogen substantially below those typically produced in 430. In most cases these steels are stabilized by additions of either titanium or columbium, or the combination of the two. These steels are ferritic at all temperatures below the melting point showing no transformations to austenite or martensite. As is typical of ferritic grades they are susceptible to grain growth, but at the lowered carbon levels the toughness of these grades is significantly higher than the standard grades.

PRESERVATION OF CORROSION RESISTANCE

Although fabricators would much prefer to avoid post-weld heat treatment, this operation may be vital under some circumstances to assure adequate corrosion resistance or mechanical properties. The customary annealing temperature is 1450F. The time at temperature depends upon the mass involved and may vary from only a few minutes for thin-gauge sheet to several hours for heavy plate.

Cooling ferritic stainless steels from the annealing temperature can be done by air or water quenching. Often the parts are allowed to furnace cool to about 1100F, followed by rapid cooling. Slow cooling through a temperature range of 1050F down to 750F should be avoided since it induces room-temperature brittleness. Heavy sections usually require at least a spray quench to bring them through this range of embrittlement.

Also, modifications to the steel in the form of titanium or columbium additions help to reduce the amount of intergranular precipitation.

WELDING PREHEATING

Although little danger exists from excessive hardening in the HAZ during welding of ferritic stainless steels, there is a consideration to use preheating. Heavier sections (about 1/4 inch thick and heavier) are in greater danger of cracking during welding. However, the design of the weldment, the restraint afforded by clamping or jigging, the type of joint, the ambient temperature, the weld process to be used, and sequence of welding may have almost as much influence as the material thickness. In actual practice, a preheat temperature range of 300-450F is used for heavier sections. This point should be explored in the prudent development of any welding procedure.

For the low carbon or stabilized ferritic grades, the use of preheat is usually undesirable for lighter sections, less than 1/4 inch thick.

PRECIPITATION HARDENING STAINLESS STEELS

In general, the precipitation hardening stainless steels (Table 5) can be readily welded and good mechanical properties can be developed in weldments. However, differences in welding properties can be expected. Those grades containing only additions of copper or molybdenum produce a molten pool similar to the austenitic stainless steels, while those grades containing aluminum or unusually high titanium content may appear noticeably different and possibly will require a greater degree of protection from the atmosphere during welding.

Changes in structure can occur in the precipitation hardening grades when they are subjected to the localized heat of welding. It will be important to note the condition of the base metal prior to welding; that is, whether it is annealed, solution treated, or hardened. The heat of welding will invariably produce a solution treated or annealed base metal zone, and the post-weld heat treatments required to harden this zone may involve either single or double treatments.

Because of the many combinations of welding and heat treatment that can be used with the precipitation hardening stainless steels, more-detailed information should be obtained from producers.

WELD ROD SELECTION

Proper weld or filler rod selection is important to achieve a weld metal with the desired corrosion-resistant and strength characteristics. A well designed product, for example, can fail in the weld zone if the weld rod selected results in the weld zone having a lower alloy content than that of the parent metal.

Table 5 **Precipitation Hardening Stainless Steels**

Chemical Analysis % (Max. unless noted otherwise)										Nominal Mechanical Properties (Solution Treated Bar)						
										Tensile Strength		Yield Strength (0.2% offset)		Elongation in 2″ (50.80 mm)	Hardness (Rockwell)	Product Form
(UNS)	C	Mn	P	S	Si	Cr	Ni	Mo	Other	ksi	MPa	ksi	MPa	%		
S13800	0.05	0.10	0.010	0.008	0.10	12.25/13.25	7.50/8.50	2.00/2.50	0.90/1.35 Al 0.010 N	160	1103	120	827	17	C33	
S15500	0.07	1.00	0.04	0.03	1.00	14.00/15.50	3.50/5.50		2.50/4.50 Cu 0.15/0.45 Cb+Ta	160	1103	145	1000	15	C35	
S17400	0.07	1.00	0.040	0.030	1.00	15.50/17.50	3.00/5.00		3.00/5.00 Cu 0.15/0.45 Cb+Ta	160	1103	145	1000	15	C35	
S17700	0.09	1.00	0.040	0.040	0.040	16.00/18.00	6.50/7.75		0.75/1.50 Al	130	896	40	276	10	B90	

The characteristics of the weld metal are primarily dependent on the alloy content of the filler rod and to a lesser extent on the degree to which the molten weld metal is protected from the environment. This protection is provided by the shielding gases used in certain welding processes or by the action of chemical fluxes applied to welding rods.

The first criteria for weld rod selection is alloy content, and Table 6 lists the filler metals suggested for stainless steels. The following discussion will further help in the understanding of what filler material to use.

AUSTENITIC STAINLESS STEELS

The long list of stainless steel filler metals frequently causes concern as to how to select the filler metal appropriate for a given application. The general rule most often followed is to use the alloy most similar to the base metal being welded. The greater amount of chromium and nickel in certain alloys, 308 for example, is useful for welding 302 and 304 base metals and hence is standard for all the lower chromium-nickel base metals. While the same principle applies to 316, in that the minimum chromium is higher in the weld metal than the base metal, the designation of the filler metal is the same.

Certain standards of weld metal invariably have a fully austenitic structure, for example, 310, 310Cb, 310Mo, and 330. In these, the ratio of ferrite-formers to austenite-formers cannot be raised high enough within permissible limits to produce any free ferrite in the austenite. Consequently, these weld metals must be used carefully in highly restrained joints and on base metals containing additions of alloying elements like phosphorus, sulfur, selenium or silicon — such as base metal 302B, 303, and 314.

In selecting welding materials, there is a misconception that the higher the AISI number, the higher the alloy content. This is not always true, as in the case of 347, which is a stabilized grade for preventing carbide precipitation in high-temperature service. 347 should not be used as a “general-purpose” filler metal for welding other alloys, because 347 can be crack sensitive.

The one principal exception in the list of austenitic stainless steels is 329, which is a duplex (dual-phase) alloy. If welding of 329 is expected, it is suggested that a stainless steel producer be contacted for assistance.

MARTENSITIC STAINLESS STEELS

The only standard martensitic stainless steels available as either covered electrodes or bare welding wire are 410 and 420. This sometimes presents a problem in procurement when attempting to secure similar properties in the weld metal as in the base metal. Except for 410 NiMo, martensitic stainless steel weld metals in the as-deposited condition are low in toughness and are seldom placed in service without being heat treated.

Austenitic stainless steel weld deposits are often used to weld the martensitic grades. These electrodes provide an as-welded deposit of somewhat lower strength, but of great toughness. For as-welded applications in which thermal compatibility is desired, the 410 NiMo filler metal is a good choice.

FERRITIC STAINLESS STEELS

The weld metal of ferritic stainless steels usually is lower in toughness, ductility, and corrosion resistance than the HAZ of the base metal. For this reason, it has been the custom to heat treat after welding to improve toughness. However, a goodly amount of welded ferritic stainless steel is placed in service, as-welded where the toughness is adequate for the service.

As shown in Table 7, an austenitic stainless steel filler metal is used frequently to join ferritic base metal to secure a ductile weld. For example, 430 is frequently welded with 308 filler metal. Of course, the use of austenitic filler metals does not prevent grain growth or martensite formation in the HAZ.

For the low carbon or stabilized ferritic grades, the use of austenitic filler metal can provide a weld of good mechanical properties. The austenitic weld metal should also be selected as a low carbon grade, e.g., 316L weld wire. The filler metal should always be selected so that the chromium and molybdenum content of the filler metal will be at least equal to that of the base metal. This insures the weld will have adequate corrosion resistance in severe environments. It is generally unnecessary to post-anneal the weld of a low carbon or stabilized ferritic grade when the low carbon austenitic wire is used.

However, the use of austenitic filler metal for ferritic stainless steels should not be supplied indiscriminately, because applications may arise where the difference in color, physical characteristics — such as thermal expansion — or mechanical properties may cause difficulty. Also, if the welded part is annealed after welding, the post-anneal is liable to cause carbide precipitation that may result in intergranular corrosion of the weld.

PRECIPITATION HARDENING STAINLESS STEELS

The selection of a filler metal to weld precipitation hardening stainless steels will depend upon the properties required of the weld. If high strength is not needed at the weld joint, the filler metal may be a tough austenitic stainless steel. When mechanical properties comparable to those of the hardened base metal are desired in the weld, the weld metal must also be a precipitation hardening composition. The weld analysis may be the same as the base metal, or it may be modified slightly to gain optimum weld metal properties.

A great deal of information on weld rod selection is available from the American Welding Society (AWS), weld rod manufacturers, and stainless steel producers. Designers are encouraged to consult with these sources for help in specifying weld materials, particularly for corrosive applications or when difficult weld problems are encountered.

Table 6

Electrode or Filler Rod

308 weld metal is also referred to as 18-8 and 19-9 composition. Actual weld analysis requirements are 0.08% max C, 19.0% min Cr and 9.0 min Ni. 310 weld metal may be used, but the pickup of silicon from the base metal may result in weld hot cracking.

cracks to form in weld metal. 312 weld metal contains a large amount of ferrite to overcome this cracking tenndency.

316, 316L, 317, 317-Cbb and 318 electrodes

316 and 317 base metal, full anneal at 1950-2050F.
316 and (317L) base metal, 1600F stress-relief.

321 covered electrodes are not regularly manufactured because titanium is not readily recovered during deposition.

405 weld metal contains columbium rather than

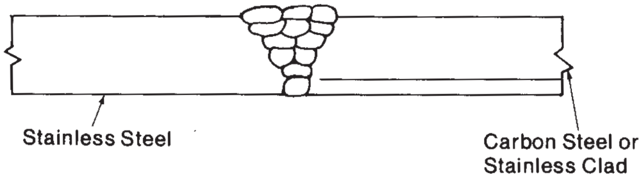
Remarks on 430 base metal apply.
Remarks on 430 base metal apply.

308 weld metal can be used, but will not display scaling resistance equal to the base metal. Consideration must be given to difference in coefficient of expansions of base and weld metal.

Remarks on 410 base metal apply.

Remarks on 410 base metal apply.

Figure 3
Clad Metal Joint Design



Design for stainless steel to carbon steel transition joints.
Step 1. Bevel both members and fit up leaving a root gap.
Step 2. Deposit the weld using stainless steel filler metal of sufficiently high alloy content to avoid problems from carbon steel dilution.
Step 3. Welding procedure employed should hold penetration into the carbon steel to the minimum value possible.

FERRITIC AND MARTENSITIC STAINLESS STEELS TO CARBON OR LOW-ALLOY STEELS

When welding ferritic or martensitic stainless steels to carbon or low-alloy steels for general purposes (not high-temperature service), austenitic stainless steel or modified ErNiCrFe-6 filler metal will produce welds of suitable quality provided that the correct welding procedures are followed. For the low carbon or ferritic grades, the low carbon austenitic filler metals will produce welds of good mechanical quality while maintaining corrosion resistance.

There are two methods of making such a joint. The first would involve overlaying each member of the joint, utilizing suitable preheat and postheat treatments as required, and then making a weld without preheat or postheat between the overlayed surfaces. Austenitic stainless steel electrodes such as 309, which are sufficiently high in alloy content to minimize the problems from dilution by the carbon steel or straight chromium stainless steels, are widely used for this application. The welding procedure used should hold penetration into the base metal to a minimum. The second method would involve depositing the weld directly between the two members of the joint. In this case, dilution of the weld metal by both of the base metals must be kept under control while depositing the restrained weld.

Use of Chill Bars

Successful welding of stainless steel by various welding methods depends to a large extent on the type of back-up bar or plate used. Experience has indicated that pure copper is the most satisfactory material for backing up a weld.

The high heat conductivity of such a back-up bar or plate will prevent its sticking to the weld metal, while its chill-mold effect will assure a clean smooth weld metal surface. Copper back-up bars can be made by cutting pieces from copper plate or sheet. Chill bars serve the best purpose by controlling distortion on light gauge material, and also help to prevent excessive burn-through or melting of the base metal.

Joint Design

Probably the most frequently used joint in stainless steel is the butt joint. On thin sheet metal, a square butt joint may be used, as shown in Figures 4 and 5. If the members being joined are thicker than about 1/8 or 3/16 inch, it is necessary to bevel the edges in order to assure full penetration welds, Figure 6. If the base metal is thicker than about 1/2 inch, the V-joint requires a large volume of weld metal, so U-groove (Figure 7) double V- and double U- grooves (Figure 8) are used, although they are more costly to prepare.

Normally, full penetration welds are essential and therefore conventional backing rings are not used. However, consumable backing rings or inserts (Figure 9), which are melted during the first weld pass and become an integral part of the weld, are used successfully.

PREPARATION

Stainless steels cannot be cut with the ordinary oxy-acetylene torch. Powder cutting, in which iron powder is injected into the cutting stream of an oxy-acetylene torch, is used as are arc processes such as plasma arc. Stainless steels can be severed by using cutting electrodes or even mild steel coated electrodes, although these produce a great deal of spatter and rough cuts.

The edges of a thermally cut weld joint should be cleaned by machining or grinding to remove surface contamination, particularly iron. Parts to be joined must also be free of oil, grease, paint, dirt, and other contaminants.

Because of the relatively high coefficient of thermal expansion of the austenitic grades, adequate clamping or jigging devices should be employed to align the work. If it is

Figure 4 **Figure 5** **Figure 6**

Table 7
Soft Solders for Stainless Steel Industrial Sheet Metal Work

Common Name	Nominal Composition (Percent) Tin (Sn)	Lead (Pb)	Antimony (Sb)	Silver (Ag)	Short-Time Bulk Solder Strength Tensile (psi)	Shear (psi)	Density (lb/cu in)	Melting Range Melts (°F)	Flows (°F)	Max. Service Temp. (°F)	Color Match To Stainless Steel	Use	Comments
Fifty-Fifty	50	50	—	—	6,000	5,200	0.321	361	421	200	Poor	Duct work, roofing, etc. where appearance or special joint properties are not important.	Satisfactory general purpose solder. Not for color matching.
Sixty-Forty	60	40	—	—	7,600	5,600	0.308	361	374	200	Fair	Signs, ornamental trim, flashing, etc. where appearance is more important. Used for tinning.	Best all-around tin-lead solder. May discolor with time. Has better wetting and flowing properties than 50-50 solder.
Pure Tin	100	—	—	—	1,700	1,800	0.263	450	450	200	Good	Distilled water equipment or special chemical use where lead cannot be tolerated.	Low joint strength. Good corrosion resistance. Non-toxic. Good color match.
Tin-Antimony	95	—	5	—	5,900	6,000	0.260	452	464	350	Good	Food handling equipment where lead must be avoided. Refrigeration equipment to minus 160° F.	Wide service temperature range. Good food contact solder. Non-toxic. Good non-staining properties. Good joint strength. Higher cost.
Tin-Silver	96	—	—	4	(Note 1)	(Note 1)	0.266	430	430	350	Very Good	Food handling equipment, fine ornamental work, high strength and other uses requiring special joint properties.	Best color-match and blending properties. Very good joint strength. Non-toxic. Good corrosion resistance. Highest cost.

(NOTE 1) The short-time bulk solder strength of tin-silver solder is similar to tin-antimony solder. Soldered joints made with either tin-antimony or tin-silver solder have a much higher long-time tensile-shear strength than joints made with tin-lead or pure tin solder.