A DESIGNERS' HANDBOOK SERIES

WELDING OF STAINLESS STEELS AND OTHER JOINING METHODS

Committee of Stainless Steel Producers
American Iron and Steel Institute
Washington, D.C.

Stainless Steel Welding Characteristics

By definition, stainless steels are iron-base alloys containing 10% or more chromium, which imparts to the metal the corrosion-resistant properties for which stainless steels are so highly regarded. The chromium content may be increased and other alloying elements added or adjusted to meet specific end-use or manufacturing requirements. Currently available are 57 AISI-numbered stainless steels, which are identified in Tables 1, 4, 5 and 6, plus numerous proprietary or special-analysis grades.

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.

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.

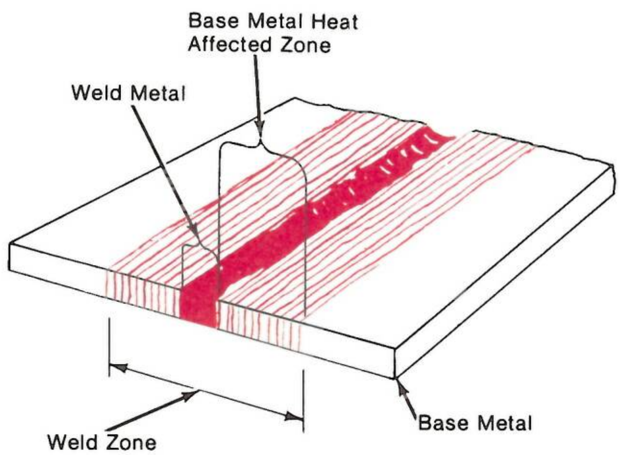


Figure 1
Thermal Affected Area of Metal Due to Welding

AUSTENITIC STAINLESS STEELS

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

The 31 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

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

	Carbon Steel	Type 304	Remarks
Melting Point °F Approx.	2800	2550-2650	Type 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 Type 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 Type 304.
Rate of Heat Conductivity (Compared in Percent) At 212 F Over 1200 F	100% 100% Note: Type 304 at 212 F has a rate of 9.4 and at 932 F a rate of 12.4 Btu/ft²/hr/F/ft.	28% 66%	Type 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.
Coefficient of expansion per °F Over range indicated	.0000065 (68-1162 F)	.0000098 (68-932 F)	Type 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.

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

Table 1 Austenitic 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
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 max) 0.20 Co	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.

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.

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.

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. Selection of filler rod material is discussed beginning on Page 13, while the following discussion will be devoted to preserving corrosion resistance in the base metal heat affected zone.

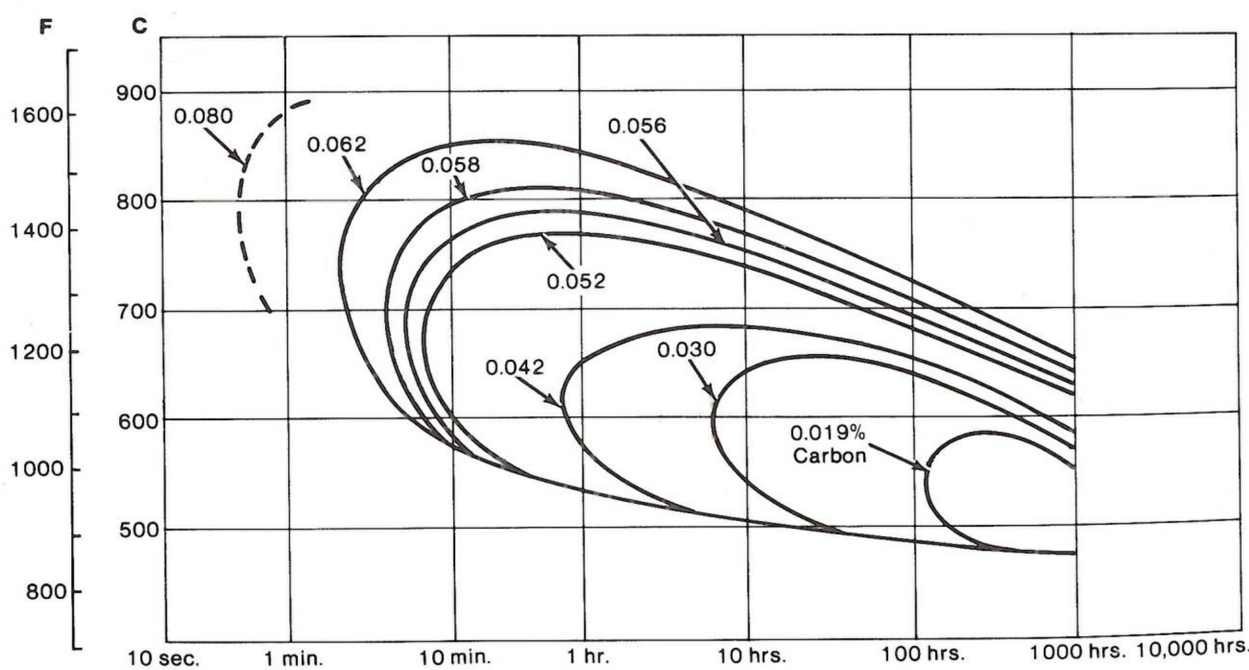
Carbide Precipitation — A characteristic of an annealed austenitic stainless steel,such as Type 304,is its susceptibility to an important microstructural change if it is exposed to temperatures within an approximate range of 800-1650F. Within this range,chromium and carbon form chromium carbides, and these precipitate out of the solid solution at the boundaries between the grains. The rapidity of carbide development depends on a number of factors, which can be illustrated by the chart in Figure 2. 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. However, the behavior of a weld-sensitized stainless steel weldment when exposed to a corrosive environment is difficult to predict. Intergranular corrosion does not always occur and there are many environments in which sensitized austenitic stainless steel are providing satisfactory service.

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. Type 304 with a maximum carbon content of 0.08% is widely used. Also available are low-carbon Types 304L, 316L, and 317L with 0.03% carbon.

Types 321 and 347 contain titanium and columbium-

Figure 2
Effect of Carbon Content on Carbide Precipitation



Time-Temperature-Sensitization Curves

Time required for formation of carbide precipitation in stainless steels with various carbon contents. Carbide precipitation forms in the areas to the right of the various carbon-content curves. Within time-periods applicable to welding, chromium-nickel stainless steels with 0.05% carbon would be quite free from grain boundary precipitation.

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 Type 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.

The relative susceptibility of several austenitic stainless steels to sensitization during welding is shown in Table 3.

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.

PREVENTION OF CRACKING

Two general forms of cracking have been observed to occur in welded austenitic stainless steels. They are:

1) In the weld metal during or immediately after welding.
2) In the base metal near a weld joint.

Microfissures can develop in the as-deposited weld metal shortly after solidification, or they can occur in the heat-affected zones of previously deposited (sound) beads of weld metal. Hot cracks or microfissuring gave much difficulty some years ago, but today enough is known about these cracking problems to avoid their occurrence in weldments.

The microstructure of the weld metal strongly affects susceptibility to microfissuring. Weld metal having a wholly austenitic microstructure is considerably more sensitive to conditions that promote microfissuring than weld metal containing some delta or free ferrite in an austenitic matrix. Consequently, whenever possible a ferrite-containing austenitic weld structure is employed. Selection of filler metal and the planning of a welding procedure must be done carefully to secure the small, but important amount of delta ferrite.

Much use has been made of the Schaeffler Diagram (Figure 3) for determining whether a specified weld metal composition will contain delta ferrite, and the approximate percentage. The Schaeffler Diagram, published in the mid-1940's, shows calculated ferrite content as a percentage. In 1956 the DeLong Diagram (revised 1973) (Figure 4) was published that shows ferrite content as a "Ferrite Number" (FN) rather than percent ferrite, and most welding rod suppliers now certify austenitic stainless steels by FN. The DeLong Diagram places greater emphasis on the role of nitrogen, thereby allowing more accurate calculations.

A little ferrite in a weld deposit of predominantly austenitic stainless steel, such as Type 308, for example, tends to eliminate hot cracking, a phenomenon that can destroy an otherwise well designed product. The chemical processing industry, on the other hand, sees ferrite in a different light. A

Table 3
Relative Susceptibility of the Various Grades to Sensitization During Welding

	Grade	Commercial Analysis Range			Susceptibility to Intergranular Carbide Formation Compared To Type 304 (SEE NOTE 3)			Cause of Difference			
								Carbon Content Being		Ratio of Cr & Ni to C Being	
		% Chromium	% Nickel	% Carbon	Greater	Less	None	Higher	Lower	Higher	Lower
Normal Compositions	304	18.0/20.0	8.0/10.5	0.08 max							
	302	17.0/19.0	8.0/10.0	0.15 max	X			X			X
	301	16.0/18.0	6.0/ 8.0	0.15 max	X			X			X
	305	17.0/19.0	10.5/13.0	0.12 max		Note 1			Usually X	X	
	308	19.0/21.0	10.0/12.0	0.08 max		X		Same		X	
	316	16.0/18.0	10.0/14.0	0.08 max		Approximately the same as Type 304					
	317	18.0/20.0	11.0/15.0	0.08 max		Approximately the same as Type 304					
	309	22.0/24.0	12.0/15.0	0.20 max				X		Note 1	
	309 S	22.0/24.0	12.0/15.0	0.08 max		X		Same		X	
	310	24.0/26.0	19.0/22.0	0.25 max	X			X		Note 1	
	314	23.0/26.0	19.0/22.0	0.25 max	X			X		Note 1	
Extra Low Carbon Compositions	304 L	18.0/20.0	8.0/12.0	0.03 max			Note 4		X	X	
	316 L	16.0/18.0	10.0/14.0	0.03 max			Note 4		X	X	
Stabilized Compositions	347	17.0/19.0	9.0/13.0	0.08 max			Note 2				
	321	17.0/19.0	9.0/12.0	0.08 max			Note 2				
	309 C	22.0/24.0	12.0/15.0	0.08 max			Note 2				
	318	17.0/19.0	13.0/15.0	0.08 max			Note 2				

Note 1. Depends upon exact analysis within its broad range. Carbon of Types 309, 310, and 314 is usually above 0.08% maximum.
Note 2. Formation of intergranular carbides prevented by content of stabilizing agents.
Note 3. Temperature and time at temperature constant.
Note 4. Carbide formation greatly minimized for welding but not for long-term service at elevated temperature.