WELDING OF STAINLESS STEELS AND OTHER JOINING METHODS

A DESIGNERS' HANDBOOK SERIES

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Originally, this handbook was published in 1979 by the Committee of Stainless Steel Producers, American Iron and Steel Institute.

The Nickel Institute republished the handbook in 2020. Despite the age of this publication the information herein is considered to be generally valid.

Material presented in the handbook has been prepared for the general information of the reader and should not be used or relied on for specific applications without first securing competent advice.

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Subsequent to the symposium, ASM International published a book, *Joining of Stainless Steels*. Tables and charts, which are not given references in this publication, were obtained either from the ASM International book or from other sources within the stainless steel industry in the United States.

It should be noted that the data are typical or average values. Materials specifically suggested for applications described herein are made solely for the purpose of illustration to enable the reader to make his own evaluation.

Introduction

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 weldable 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.

Contents

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.

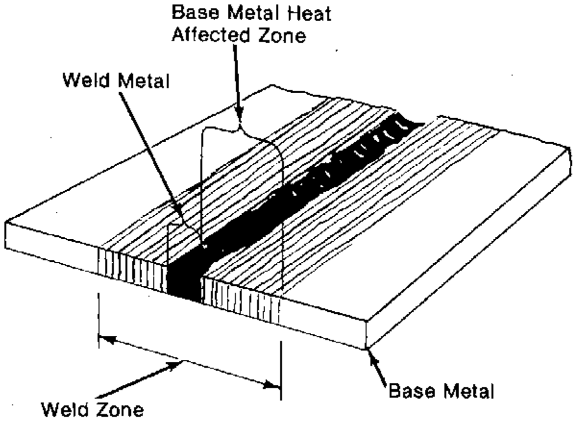


Figure 1
Thermal Affected Area of Metal Due to Welding

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.)			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.
At 68 °F	12.5	72.0	
At 1625 °F	125	126	
Rate of Heat Conductivity (Compared in Percent) At 212 °F	100%	28%	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.
Over 1200 °F	100%	66%	
	Note: Type 304 at 212 °F has a rate of 9.4 and at 932 °F a rate of 12.4 Btu/ft^2/hr/F/ft.		
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

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
AISI Type (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 (N0S330)	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.

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.

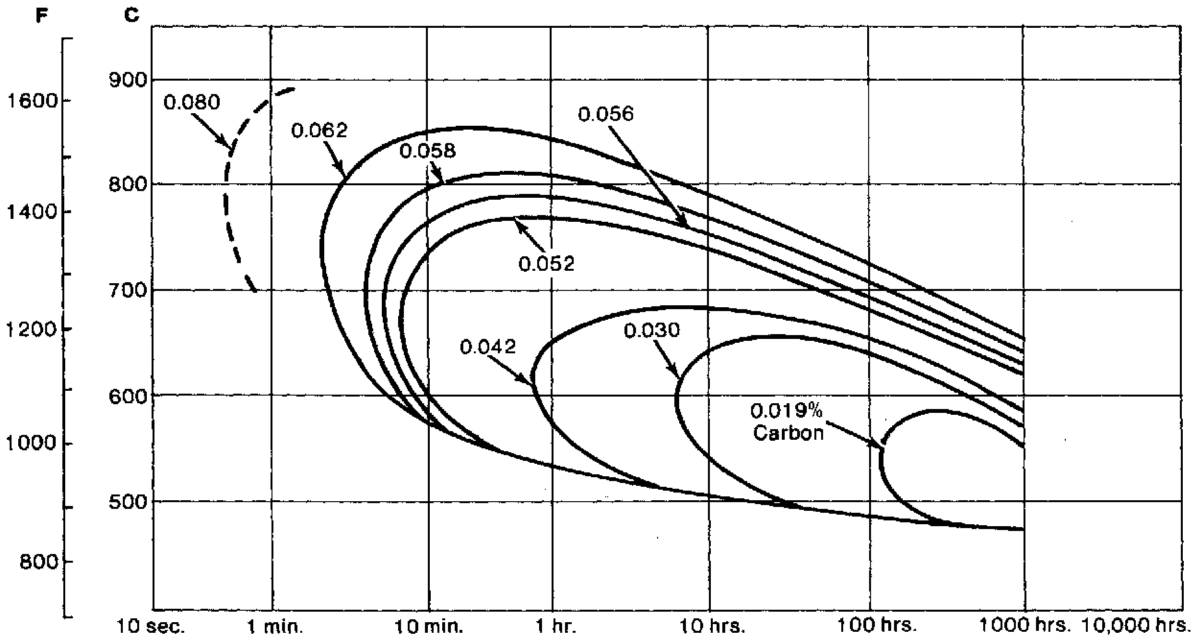
Carbide Precipitation - A characteristic of an annealed austenitic stainless steel, such as Type 304 is its susceptibility to an important microstructural change if it is exposed to temperatures within an approximate range of 800-1650ºF. Within this range, chromium and carbon form chromium carbides, 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 800-1650ºF is one factor. Chromium carbides form most rapidly at about 1200ºF, 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 2150ºF) (above the sensitizing range) followed by rapid cooling. Stress relieving a weldment at 1500-1700ºF 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	
	309S	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.

Figure 3

Schaeffler Constitution Diagram for Stainless Steel Weld Metal

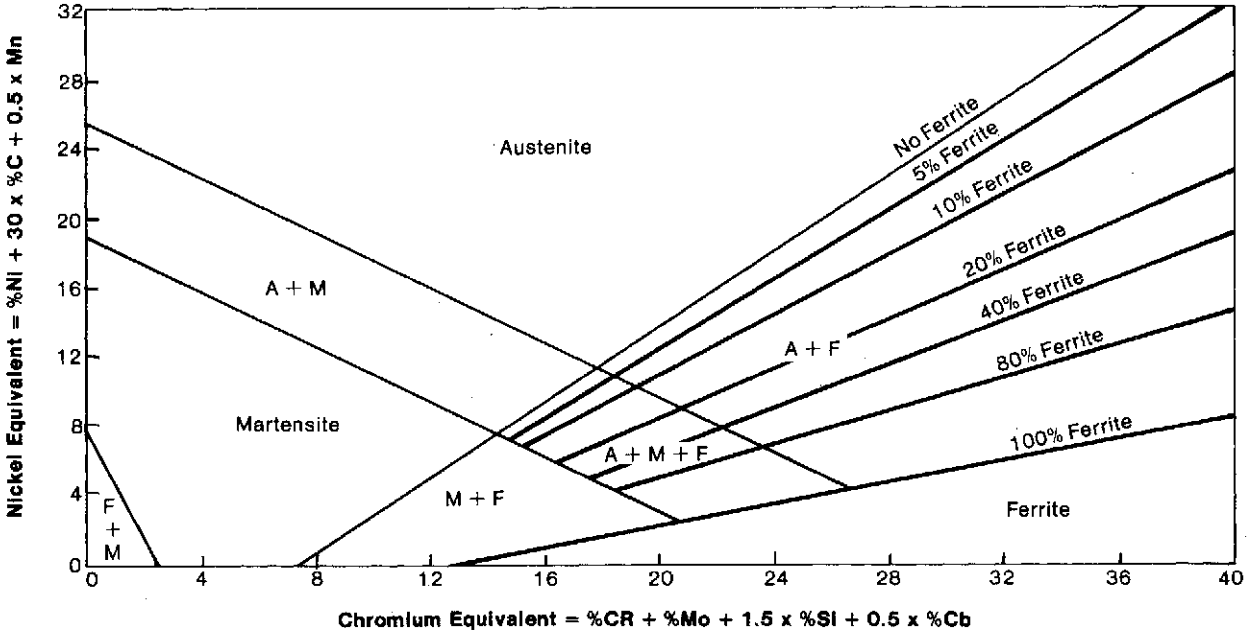
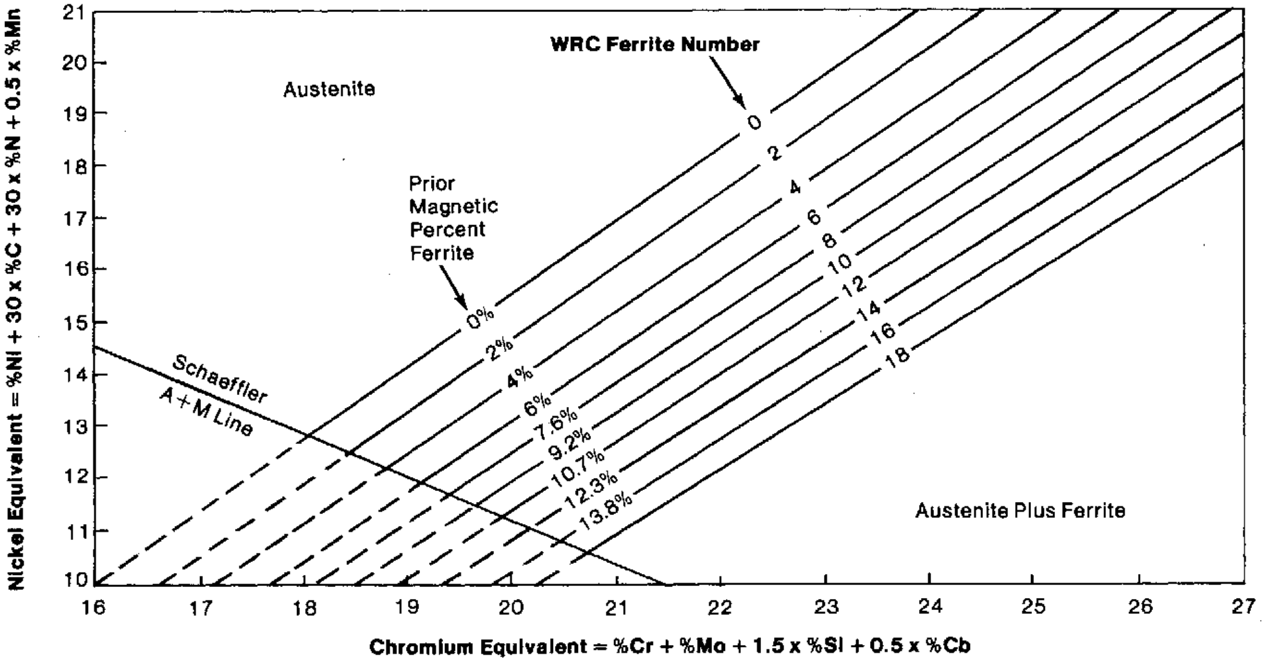


Figure 4

DeLong Constitution Diagram for Stainless Steel Weld Metal



Calculate the nickel and chromium equivalents from the weld metal analysis. If nitrogen analysis of the weld metal is not available, assume 0.06% for GTA and covered electrode, or 0.08% for GMA weld metals. If the chemistry is accurate the diagram predicts the WRC Ferrite Number within plus or minus 3 in approximately 90% of the tests for the 308, 309, 316 and 317 families.

Comparison with the Schaeffler Diagram.

1. A nickel equivalent of 30 x %N has been added.
2. Ferrite Numbers for 308, 308L and 347 covered electrodes are similar. The higher alloy 309, 316 and 317 families have about 2 to 4 higher FN on this diagram.
3. Generally this diagram correlates better with GTA and GMA weld metals because it allows for nitrogen pick up.
4. The Schaeffler austenite-martensite boundary has been included here for reference.

small amount of it in a Type 316 weld deposit can cause serious corrosion problems. So, depending on the nature of the application, ferrite can be good or bad. Corrosion is a complex subject, and if the application is not a time-tested one, experts should be consulted whether or not ferrite-bearing materials are involved.

As to how much ferrite is needed in a weld deposit to prevent cracking; according to the Welding Research Council, both ASME and NRC have adopted a policy of 5FN minimum for the welding consumables to be used in nuclear work, and 3FN minimum in any multipass weld to prevent fissuring. (Readers are referred to the following American Welding Society Specifications and appended discussions for further information: AWS 5.4-77 and AWS 5.9-77.)

Despite the preference for ferrite-containing weld deposit, it should be pointed out that millions of pounds of multipass fully austenitic, fissure-prone weld metal of Types 310, 316, 316L, and 330 have been used in production weldments over the past 40 years.

Compositions of most filler metals are adjusted by the manufacturers to produce ferrite-containing structures when deposited. This is done by maintaining the ferrite-forming elements (such as chromium and molybdenum) on the high side of the allowable ranges, while austenite-forming elements (for example, nickel) are held low. The amount of free ferrite in the weld metal structure will vary with the proportionality or balance of these elements.

It must be appreciated that when a joint is arc welded without adding filler metal (autogenous weld), the weld metal structure is determined by the base metal composition. Sometimes this practice leads to unfavorable results because wrought base metals are not always manufactured to the composition limits required for good weld metal.

WELDING PROCEDURES

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 orthe heat-affected zones. In some cases, preheating could be harmful in causing increased carbide precipitation, or greater warpage.

When dealing with a crack-sensitive austenitic weld metal (usually containing little or no ferrite), it is important to minimize the amount of stress imposed on the weld metal while cooling from the temperature at which solidification begins down to about 1800°F. Somewhere in this temperature range micro-fissures form in the grain boundaries of the weld metal. If the level of stress is particularly high, the fissures will propagate to form visible cracks.

The most helpful means of controlling cracking is to minimize the restraint on the base metal during welding and to deposit or fuse relatively narrow beads. Both of these precautions work to reduce the stress imposed on the weld metal. The use of narrow welds or stringer beads is usually permissible. However, the amount of restraint is often determined by the clamping that is needed to hold the components within the dimensional tolerances.

MARTENSITIC STAINLESS STEELS

Martensitic stainless steels, which are identified by AISI 400 Series numbers (Table 4), 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

Table 4 Martensitic Stainless Steels

	Chemical Analysis % (Max. unless noted otherwise)									Nominal Mechanical Properties (Annealed sheet unless noted otherwise)						
										Tensile Strength		Yield Strength (0.2 % offset)		Elon-gation in 2" (50.80 mm)	Hard-ness (Rock-well)	Prod-uct Form
AISI Type (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)

*Maybe added at manufacturer's option. **Hardened and Tempered 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.

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 2700ºF, which compares with 2800ºF 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 Type 410 (the general-purpose grade) exhibits maximum ductility. On heating to temperatures above about 1500ºF, the metallurgical structure begins to change to austenite; at approximately 1850ºF 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 1850ºF results in maximum martensite content. Cooling from temperatures between 1500-1850ºF 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 1500-1850ºF). 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 PROCEDURES

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 600ºF. 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 500ºF, weld, and cool slowly.
0.20 to 0.50%C –	Preheat to 500ºF, weld, and heat treat after welding.
Over 0.50%C –	Preheat to 500ºF, 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 1500ºF or higher followed by controlled cooling to 1100ºF at a rate of 50 degrees per hour and then air cooling.
2) Heat to 1350-1400ºF and follow with the same cooling cycle as described in (1).

Table 5 Ferritic Stainless Steels

Chemical Analysis % (Max. unless noted otherwise)										Nominal Mechanical Properties (Annealed sheet unless noted otherwise)						
AISI Type (UN)	**C**	**Mn**	**P**	**S**	**Si**	**Cr**	**Ni**	**Mo**	**Other**	**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/0.75Ti	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)
430FSe (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	
442 (S44200)	0.20	1.00	0.040	0.030	1.00	18.00/23.00				80	552	45	310	20	B90	(Bar)
446 (S44600)	0.20	1.50	0.040	0.030	1.00	23.00/27.00			0.25N	80	552	50	345	20	B83	

*Maybe added at manufacturer's option.

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.

FERRITIC STAINLESS STEELS

Ferritic stainless steels are also straight-chromium alloys in the AISI 400 Series with a microstructure, in the annealed condition, consisting of ferrite and carbides (Table 5). 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 700ºF. may cause intergranular precipitation (similar to carbide precipitation in austenltic stainless steels) that results in reduced resistance to corrosion. Consequently, the AISI-numbered 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 AISI Type 430. In most cases these steels are stabilized by additions of either titanium or columbium, or the combination of the two. These steels are terrific 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 1450ºF. 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 1100ºF, followed by rapid cooling. Slow cooling through a temperature range of 1050ºF down to 750ºF 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 PROCEDURES

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 ¼ 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 300-450ºF 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 ¼ inch thick.

PRECIPITATION HARDENING STAINLESS STEELS

In general, the AISI-numbered precipitation hardening stainless steels (Table 6) 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

Table 6 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
AISI Type (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	

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.

INFLUENCE OF ELEMENTS IN WELD ENVIRONMENT

Chromium has a strong chemical affinity for oxygen and carbon. The consequences of having chromium combine with significant amounts of these elements from an extraneous source must be taken into consideration whenever stainless steels are welded. Other elements in the environment, on the surface of the base metal or weld filler metal, or within the metal itself can also affect the welding characteristics of stainless steels. Some of these effects are covered in the following discussion.

OXYGEN

The resistance of stainless steels to discoloration, oxidation, or corrosion is attributed to the chromium oxide film that forms on the surface. Despite the useful service it performs, however, this stable oxide-forming characteristic is an obstacle to most welding, brazing, and soldering operations. If the surface of stainless steel is exposed to air during welding, the oxygen in the air causes the formation of a heavy oxide film. As heating continues to the melting point in the presence of air, greater quantities of chromium and other oxidizable elements combine with oxygen to form a heavy, viscous slag-like covering on the molten metal.

This chromium-rich, refractory slag covering on the molten metal offers a certain amount of protection against further oxidation. However, it may represent an important loss of chromium from the metal. Of greater importance from a welding standpoint, the oxide slag is a decided handicap to successful welding. For example, if arc welding is attempted with a bare stainless steel electrode in air, the arc will be extinguished every few seconds as the refractory slag film covers the molten weld pool and interrupts the passage of current. To prevent this, precise control must be exercised over the amount of oxygen reaching the weld.

CARBON

The affinity of chromium in stainless steel for carbon will not interfere with the welding operation itself, but can lead to undesirable conditions in the finished weld joints, such as carburization. For this reason the flux coverings on stainless steel arc-welding electrodes do not contain cellulose because the carbon contained in this material would cause objectionable carburization in the weld metal during deposition and possibly lead to reduced corrosion resistance. For the same reason, oil and grease should be thoroughly removed from joint surfaces prior to welding.

NITROGEN

Nitrogen pickup or nitrification of the exposed heated surfaces has not proved as troublesome as oxidation. The steps regularly taken to shield the metal from oxygen in the air also serve to keep out nitrogen. Fusion-line porosity occasionally has been troublesome in welding Types 321 and 347, but they generally have modifications in composition to serve as counter measures.

HYDROGEN

Hydrogen can be a cause of blowholes and porosity in stainless steels. The residual hydrogen content of stainless steels is within safe limits, so the problem occurs when this residual hydrogen is supplemented by other sources – often deceptive. A few examples of deceptive sources of unwanted hydrogen are damp fluxes, including weld rod coatings, improperly compounded electrode coverings, and imperfectly sealed joints in welding torch cooling systems which bleed water vapor. The atomic-hydrogen arc welding process, seldom used today, is another source of hydrogen.

COPPER OR LEAD

Free copper or lead on the surface of the base metal can result in embrittlement and cracking of the finished weldment. The joint area (including the HAZ) should be clean and free of these and all other contaminants.

INFLUENCE OF ALLOYING ELEMENTS ON WELDABILITY

None of the alloying elements used in stainless steels affect the welding characteristics more than does chromium. Elements employed in large amounts to adjust properties, such as nickel, manganese and molybdenum, do have some effect on the oxide slag during melting, but not to the extent that they become a significant factor. Some other elements that might have a significant effect, such as aluminum, are present in relatively small percentages.

Silicon, like chromium, is a strong, oxide-former, and high silicon contents tend to cause the molten metal and slag coverings to become more fluid. This sometimes can be helpful to the welder.

Residual Elements. The effects of other residual elements in stainless steels, such as carbon, phosphorus, selenium, and sulfur are of considerable importance in welding, although the effects may be either beneficial or deleterious. The available evidence suggests that even though elements that form refractory oxides may be present, it is possible to have the final slag of a composition which is quite fluid at welding temperatures and, therefore, will not be objectionable.

The sulfur, phosphorus, or selenium added to stainless steels to achieve free-machining characteristics impairs weldability to some extent, such as causing porosity or a tendency to hot-shortness that may result in weld-metal cracking. Modifications in composition of free-machining grades can be made to enhance weldability.

INFLUENCE OF ALLOYING ELEMENTS ON WELD STRUCTURE

The metallurgy of all stainless steel weld metals is controlled by both composition and solidification rate with composition being the major factor. The structures of welds in the austenitic or 300 Series steels are either full austenite or ferrite in a matrix of austenite. The soundness of the weld or freedom from crack defects is in most cases related to the presence of ferrite in the austenitic matrix. Therefore, it is desirable to know in the case of each element its effect in forming austenite or ferrite. In addition, some elements have an effect on austenite stability which is important in maintaining toughness of the weld.

Chromium and Molybdenum perform dual roles, acting first as strong ferrite formers and second as austenite stabilizers.

Nickel, Carbon and Nitrogen also perform dual roles, acting first as strong austenite formers and second as strong austenite stabilizers.

Silicon and Columbium perform only as ferrite formers.

Manganese performs a dual role, acting first as a weak austenite former and second as a strong austenite stabilizer.

Quantification of the above influences in any given weld determines the weld structure as illustrated by the Schaeffler and DeLong diagrams.

In the 400 Series steels the influence of each element on weld structure is similar to the above comments except that the total alloy content is lowered so that most austenite formed transforms readily to martensite. Quantification of the composition on weld structure is then obtained by use of the Schaeffler diagram. Because of limited toughness and ductility associated with martensite, martensite mixed with ferrite weld structures, extra care is suggested in selecting 400 Series welds.

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. 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 (which will be discussed in this booklet beginning on page15)or by the action of chemical fluxes applied to welding rods.

The first criteria for weld rod selection is alloy content, and Table 7 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, Type 308 for example, is useful for welding Types 302 and 304 base metals and hence is standard for all the lower chromium-nickel base metals. While the same principle applies to Type 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 standard types of weld metal invariably have a fully austenitic structure, for example, Types 310, 310Cb, 310Mo, and 330. In these types, 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 Types 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 Type 347, which is a stabilized grade for preventing carbide precipitation in high-temperature service. Type 347 should *not* be used as a "general-purpose" filler metal for welding other alloys, because Type 347 can be crack sensitive.

The one principal exception in the list of austenitic stainless steels is Type 329, which is a duplex (dual-phase) alloy. If welding of Type 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 Types 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, Type 430 is frequently welded with ` Type 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., Type 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.

Table 7 Filler Metals Suggested for Welding Stainless Steels

Type	Condition (in which weldment will be placed in service)	Electrode or Filler Rod Type	Remarks
Austenitic Stainless Steels			
201 202	As-welded or fully annealed	308	Type 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. Type 310 weld metal may be used, but the pickup of silicon from the base metal may result in weld hot cracking.
301 302 304 305 308	As-welded or fully annealed	308	
302B	As-welded	309	
304L	As-welded or stress-relieved	347 308L	
303 303Se	As-welded or fully annealed	312	Free-machining base metal will increase the tendency for hot cracks to form in weld metal. Type 312 weld metal contains a large amount of ferrite to overcome this cracking tendency.
309 309S	As-welded	309	
310 310S	As-welded	309 310 316	
316	As-welded or fully annealed	310	Welds made with Types 316, 316L, 317, 317-Cb and 318 electrodes may occasionally display poor corrosion resistance in the "as-welded" condition. In such cases, corrosion resistance of the weld metal may be restored by the following heat treatments: (1) For Types 316 and 317 base metal, full anneal at 1950-2050ºF. (2) For Types 316L and (317L) base metal, 1600ºF stress-relief. (3) For 316-Cb base metal, 1600-1650ºF stabilizing treatment. Where postweld heat treatment is not possible, other filler metals may be specially selected to meet the requirements of the application for corrosion resistance.
316L	As welded or stress-relieved	316-Cb 316L	
(316-Cb)	As-welded or after stabilizing and stress-relieving heat treatment	316-Cb	
317	As-welded or fully annealed	317	
317L	As-welded or stress-relieved	317-Cb	
321	As-welded or after stablizing and stress-relieving heat treatment	321 347	Type 321 covered electrodes are not regularly manufactured because titanium is not readily recovered during deposition.
347	As welded or after stabilizing and stress-relieving heat treatment	347	Caution needed in welding thick sections because of cracking problems in base metal heat-affected zones.
348	As-welded or after stabilizing and stress-relieving heat treatment	347	Ta restricted to 0.10 max, and Co restricted to 0.20 max for nuclear service.
Ferritic Stainless Steels			
405	Annealed	405-Cb 430	Annealing improves ductility of base metal heat-affected zones and weld metal. Type 405 weld metal contains columbium rather than aluminum to reduce hardening.
	As-welded	309 310 410-NiMo	These austenitic weld metals are soft and ductile. However, base metal heat-affected zone has limited ductility.
430	Annealed	430	Annealing employed to improve weld joint ductility.
	As-welded	308 309 310	Weld metal is soft and ductile, but base metal heat-affected zones have limited ductility.
430F	Annealed	430	Remarks on Type 430 base metal apply.
430F Se	As-welded	308 309 312	Remarks on Type 430 base metal apply.
446	Annealed	446	Type 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.
	As-welded	308 309 310	
Martensitic Stainless Steels			
403 410	Annealed or hardened and stress-relieved	410	Annealing softens and imparts ductility to heat-affected zones and weld. Weld metal responds to heat treatment in a manner similar to the base metal.
	As-welded	309 310 410-NiMo	These austenitic weld metals are soft and ductile in as-welded condition. However, base metal heat-affected zone will have limited ductility.
416 416 Se	Annealed or hardened and stress-relieved	410	Remarks on Type 410 base metal apply.
	As-welded	308 309 312	Remarks on Type 410 base metal apply.
420	Annealed or hardened and stress-relieved	420	Requires careful preheating and postweld heat treatment to avoid cracking.
431	Annealed or hardened and stress-relieved	410	Requires careful preheating and postweld heat treatment to avoid cracking.
	As-welded	308 309 310	Requires careful preheating. Service in as-welded condition requires consideration of hardened weld heat-affected zones.

Additional information on weld rod selection is provided in the next section on welding processes used for stainless steels. Also, 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.

Welding Processes For Stainless Steels

The two basic methods for welding stainless steels are fusion welding and resistance welding. In fusion welding, heat is provided by an electric arc struck between a carbon or metal electrode (connected to one terminal of a power supply) and the metal to be welded (which is connected to the other terminal). In resistance welding, bonding is the result of heat and pressure. Heat is produced by the resistance to the flow of electric current through the parts to be welded, and pressure is applied by the electrodes. Both methods are widely used for stainless steels.

FUSION WELDING

There are four principal processes for fusion welding stainless steels. They are:

1. Shielded Metal Arc Welding (SMAW)
2. Gas Tungsten Arc Welding (GTAW)
3. Gas Metal Arc Welding (GMAW)
4. Submerged Arc Welding (SAW)

Other fusion welding methods for stainless steels include plasma arc, electron beam, and laser. In all cases, the weld zone is protected from the atmosphere by a gas, slag, or vacuum, which is absolutely necessary to achieve and preserve optimum corrosion resistance and mechanical properties in the joint.

SHIELDED METAL ARC WELDING

SMAW is a fast, versatile process that is very popular for welding stainless steels, especially for joining shapes that cannot be easily set up for automatic welding methods. It is characterized by the use of a solid electrode wire with an extruded baked-on coating material. Because the electrode is coated, SMAW is commonly called "covered" or "stick" electrode welding. The electrode is bare at one end and is held in a spring-loaded jaw-type electrode holder.

The welding is performed manually with the operator holding the electrode at an angle, with the end just far enough away from the base metal to maintain an arc. As the metal melts off the end of the rod, the operator moves the electrode closer to the work as well as moving it along the joint.

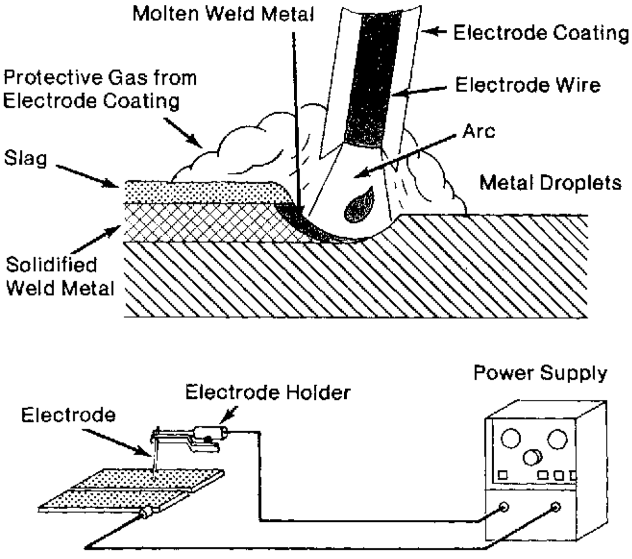


Figure 5
Arc Zone in Shielded Metal Arc Welding

The coating functions in several ways, as shown in Figure 5: (1) Electrode material burns off faster than the outer flux, forming a "crucible" that partially shields the arc from the atmophere. (2) Impurities are removed from the molten metal by the flux. (3) A gaseous envelope is formed by the decomposition of the ingredients in the covering. This excludes the oxygen and nitrogen in the air from contact with the molten weld pool. (4) The slag formed on top of the weld metal acts as a protective covering against contamination by the atmosphere as the weld cools, and serves to control the shape of the weld pool. (5) It provides alloy additions to the weld metal.

SMAW Electrodes

Electrodes for SMAW are selected first on the basis of alloy composition, as shown in Table 7, and then according to the coating. The electrode coatings are generally lime base or titania base materials, depending on the type of welding to be done and the type of power supply used. For example, Table 8 shows AWS classifications for 17 stainless steel SMAW electrodes. The suffix -15 indicates that the coating is primarily of the "lime-type," and these electrodes are used with direct current (DC) reverse polarity (RP). For alternating current (AC), electrodes with the suffix -16 are used. These electrodes are

Table 8
AWS Stainless Steel Shielded Metal Arc Welding Electrode Classification

DC Reverse Polarity		AC or DC Reverse Polarity	
E308-15	E312-15	E308-16	E312-16
E308L-15	E16-8-2-15	E308L-16	E16-8-2-16
E309-15	E316-15	E309-16	E316-16
E309Cb-15	E316L-15	E309Cb-16	E316L-16
E309Mo-15	E317-15	E309Mo-16	E317-16
E310-15	E318-15	E310-16	E318-16
E310Cb-15	E330-15	E310Cb-16	E330-16
E310Mo-15	E347-15	E310Mo-16	E347-16
	E349-15		E349-16

Table 9
Suggested Welding Conditions for Austenitic Chromium-Nickel Steels

			Current, amp			
	Passes	**Electrode Size, in.**	**Flat Horizontal Overhead**	**Vertical**	**Voltage (max.)**	**Type Weld**
24 gage	1	3/64	15-25	15-25	23	B, L, F
20-24 gage	1	1/16	20-40	25-40	24	B, L, F
16-22 gage	1	5/64	30-60	35-55	24	B, L, F
12-18 gage	1	3/32	45-90	45-65	24	B, L, F
12 3/16in.	1	1/8	70-120	70-95	25	B, L, F
3/16-½ in.	1	5/32	100-160	100-125	26	B, L, F
¼ in.	1	5/32	125	110	26	B
	1	3/16	160	125	26	B, L, F
	2	3/16	160	125	26	B
3/8 in.	2	3/16	160	125	26	F
	3	3/16	160	125	26	B
½-¾ in.	Multi-pass	3/16	130-190	130-145	27	B, L, F
3/8 in. and more	Multi-pass	¼	210-300	-	28	B, L, F
½ in. and more	Multi-pass	5/16	250-400	-	29	B, L, F

B–Butt L–Lap F–Fillet

also useable with DC and may have either a "lime-type" or a "titania-type" coating.

The -15 type electrodes are useable in all welding positions, but result in a relatively rough appearing weld bead. The type -16 electrodes are useable in the flat position only and are preferred because they result in a smoother weld bead. Experienced welders generally know which coating to use, but designers generally specify the alloy composition.

The handling and storage of coated stainless steel SMAW electrodes is very important because coatings tend to absorb moisture, and moisture in the weld zone during welding can lead to porosity, which weakens the weld and becomes focal points for corrosion. For this reason, stainless steel electrodes *must* be stored in a warm, dry environment (preferably in the original sealed container).

Other sources of moisture in the weld area should also be avoided, such as damp rags, condensation, or moisture in air lines used to blow dirt away from the area to be welded.

AC versus DC. Either alternating or direct current can be •• ••••••••••É•¼••••tive, work negative) produces deeper weld penetration and more consistent fusion when welding stainless steel plates.

Table 9 suggests various welding conditions for austenitic stainless steels.

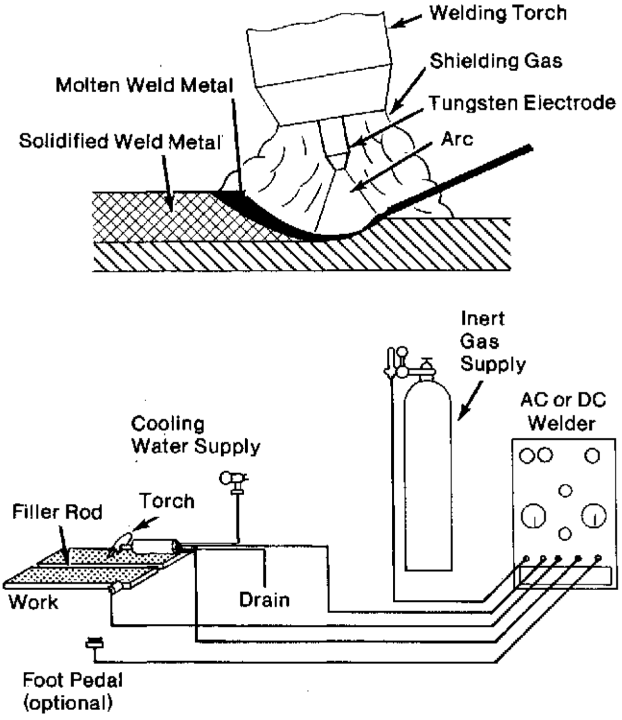


Figure 6
General Representation of GTAW

GAS TUNGSTEN ARC WELDING

GTAW, or TIG welding as it is sometimes called, is a fusion welding process that uses an inert gas (such as argon) to protect the weld zone from the atmosphere. The heat for welding is provided by an intense electric arc between a nonconsumable tungsten electrode and the workpiece (Figure 6). When filler metal is required, a bare welding wire (or rod) is either manually or automatically fed into the weld zone and melted with the base metal.

GTAW easily welds all stainless steels and is particularly suited for welding stainless steel pipe, with or without an insert or backing ring. It is also used extensively in joining tubes to tube sheets in shell-and-tube heat exchangers.

Generally, filler metal is fed manually by the welder, but this method is slow, especially for thick components. To achieve higher deposition rates, the process can be automated and the filler wire heated by resistance heating. This process is called hot-wire GTAW, and it can result in a 100% increase in welding speed (Figure 7).

Another variation of GTAW is pulsed-arc. In this process, the pulsing arc provides control of the molten weld puddle to increase penetration and to minimize porosity.

Figure 8 shows typical joint preparation for GTAW welding, and Table 10 shows general requirements for GTAW welding of stainless steels according to the thickness of the base metal, the joint configuration, and the welding position. As in all welding of stainless steels, cleanliness of the joint area is imperative for optimum results. Table 11 shows some typical conditions for automatic hot-wire GTAW.

Table 10
General Requirements for GTAW Welding of Stainless Steel

Thickness, in.	Type of Weld (see Fig. 8)	Welding Current: Characteristics	Welding Current: amp. Flat	Welding Current: amp. Vertical	Welding Current: amp. Overhead	Electrode Diameter, in.	Welding Speed, ipm	Welding Rod Size, in.	Argon Gas Flow, cfh	Remarks
1/16	1, 2 Butt	Straight polarity—direct current	80-100	70- 90 up	70- 90	1/16	12	1/16	10	
	5, 6 Lap		100-120	80-100 up	80-100	1/16	10	1/16	10	
	7 Corner		80-100	70- 90 up	70- 90	1/16	12	1/16	10	
	8, 9 Fillet		90-100	80-100 up	80-100	1/16	10	1/16	10	
3/32	1, 2 Butt		100-120	90-110 up	90-110	1/16	12	1/16 or 3/32	10	
	5, 6 Lap		110-130	100-120 up	100-120	1/16	10	1/16 or 3/32	10	
	7 Corner		100-120	90-110 up	90-110	1/16	12	1/16 or 3/32	10	
	8, 9 Fillet		110-130	100-120 up	100-120	1/16	10	1/16 or 3/32	10	
1/8	1, 2 Butt		120-140	110-130 up	105-125	1/16	12	3/32	10	
	5, 6 Lap		130-150	120-140 up	120-140	1/16	10	3/32	10	
	7 Corner		120-140	110-130 up	115-135	1/16	12	3/32	10	
	8,9 Fillet		130-150	115-135 up	120-140	1/16	10	3/32	10	
3/16	1, 2 Butt		200-250	150-200 up	150-200	3/32	10	1/8	15	
	6 Lap		225-275	175-225 up	175-225	3/32 , 1/8	8	1/8	15	
	7 Corner		200-250	150-200 up	150-200	3/32	10	1/8	15	
	8, 9 Fillet		225-275	175-225 up	175-225	3/32 , 1/8	8	1/8	15	
¼	2, 3 Butt		275-350	200-250 up	200-250	1/8	-	3/16	15	1 or 2 passes
	6 Lap		300-375	225-275 up	225-275	1/8	-	3/16	15	1 or 2 passes
	7 Corner		275-350	200-250 up	200-250	1/8	-	3/16	15	1 pass
	8, 10 Fillet		300-375	225-275 up	225-275	1/8	-	3/16	15	
½	3, 4 Butt		350-450	225-275 up	225-275	1/8, 3/16	-	¼	15	2 or 3 passes
	6 Lap		375-475	230-280 up	230-280	1/8, 3/16	-	¼	15	3 passes
	8, 10 Fillet		375-475	230-280 up	230-280	1/8, 3/16	-		15	3 passes

Table 11
Typical Conditions for GTAW Hot-Wire Automatic Welding

Wire Size: 0.045 in.
Shielding Gas: 75% He, 25% Ar
Electrode: 5/32 - 3/16in. diam, 2% Th

Arc Current, amp	Voltage	Speed, in./min	Wire, in./min	Disposition Rate, lb/hr
300	10-12	4-10	110-370	3-10
400	11-13	6-14	185-445	5-12
500	12-15	8-20	295-665	8-18

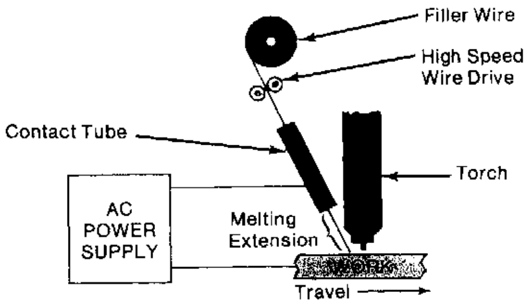


Figure 7
Schematic Diagram of GTAW Hot-Wire Welding System

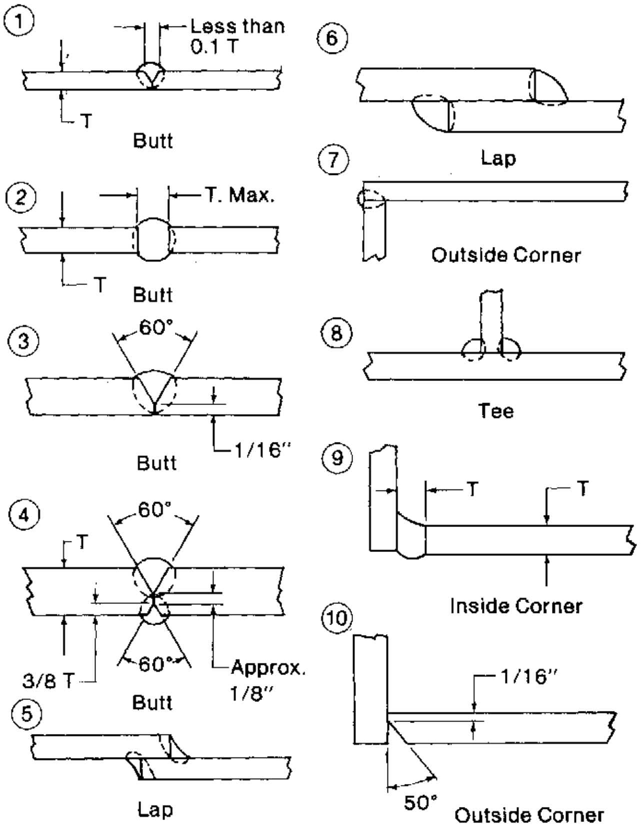


Figure 8
Typical Joint Designs for GTAW

Filler Rod Selection

Bare, uncoated wire is used with GTAW. Selection of the correct alloy composition, however, is generally the same as for SMAW in that the filler metal should match the base metal, as suggested in Table 7. Filler rods must be kept clean to prevent the introduction of any contaminants into the weld zone.

GTAW Equipment

The electrode holder is the heart of the GTAW process. It holds the tungsten electrode and controls the flow of shielding gas to the weld zone. Some holders, or torches, are equipped with a "gas lens" to focus the gas to improve shielding. (The gas lens causes laminar gas flow much like the screen in a water faucet.) For welding stainless steels, thoriated tungsten electrodes are preferred, and the shielding inert gas is usually argon. Thoriated tungsten has excellent emissive qualities and allows higher current with excellent arc stability. Argon has good density, as compared to helium, which cuts down the rate of diffusion with air.

Welding torches are usually water cooled, and direct current is preferred – although alternating current is used with the "hot wire" method of GTAW.

GAS METAL ARC WELDING

GMAW, or MIG welding, is a gas-shielded arc welding process in which the welding heat is obtained from an arc between a consumable electrode and the work-piece. The bare filler wire (electrode) is melted in a gas atmosphere and is efficiently transferred to the joint where the are provides sufficient heat for fusion. The molten weld puddle is protected from the atmosphere during the welding operation and prevents atmospheric oxygen and nitrogen from combining with the molten weld metal.

The filler metal (electrode wire), which is in coiled form, is mechanically driven into the welding zone. The type of filler metal used is generally of the same composition as the metal being welded. As metal transfer is very efficient, chemical analysis of the electrode wire and deposited undiluted weld metal are relatively close for all the common stainless steel alloys. Even very active elements, such as titanium, may be recovered in the weld when they are present as alloy elements, such as in Type 321 electrode wire. Good gas shielding is required for relatively high efficiency.

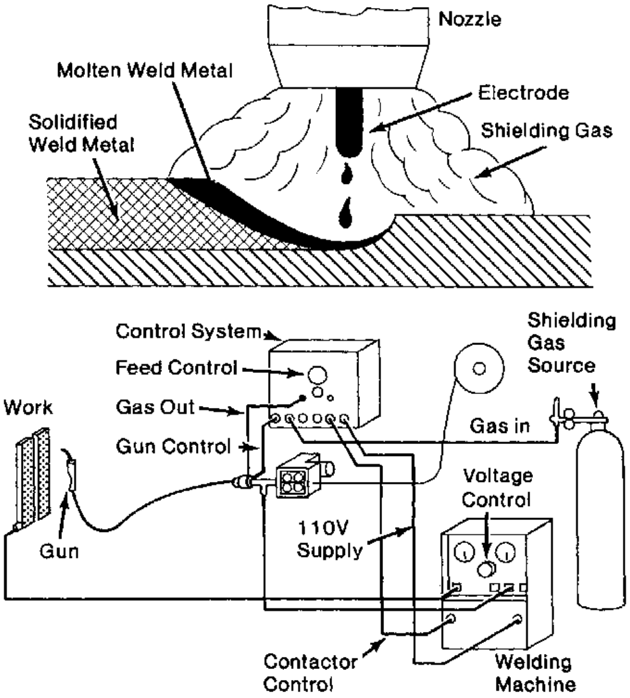


Figure 9
Schematic Diagram of Basic Components of GMAW Process

There are three basic variations of the GMAW process, dependent on the method of transfer of metal. These are: spray or free-flight transfer, short-circuiting transfer; and pulsed-type transfer. The spray type of transfer was the first developed and is characterized by a relatively hot arc and fluid puddle. Short-circuiting transfer utilizes small diameter wire (usually under 0.045 in.) and is particularly effective for welding thin material. This development has increased the utility of basic GMAW, particularly in industries where thin gauge stainless steels are fabricated.

The most recent variation of the gas metal-arc process is pulsed-arc welding. This process is characterized by a controlled free-flight metal drop rate of 60 drops per second at a lower current density than conventional spray-arc welding. Generally speaking, GMAW is about four times faster than GTAW.

GMAW is accomplished by means of a gas-shielded arc maintained between the workpiece and a consumable (bare wire) electrode from which metal is transferred to the workpiece. The basic equipment used is shown schematically in Figure 9. The essential components are: A torch through which the electrode is fed; a supply of shielding gas (usually argon); a control for governing the wire feed speed through the torch; and a constant potential DC power supply.

The type of welding current used for GMAW depends primarily on the type of penetration desired. Whereas GTAW obtains its greatest penetration on straight polarity, GMAW obtains its greatest penetration on reverse polarity (electrode positive). To understand this, it must be remembered that in GMAW welding there is metal drop transfer. This means that regardless of whether the electrons impinge upon the wire as in DCRP or on the work as in DCSP, the heat all ends up on the base plate via these metal drops. Furthermore, these metal drops are subjected to considerable force during reverse polarity by the positive gas ions. This results in deep penetration. Conversely when straight polarity is used for GMAW welding, the force on the metal drops by the gas ions tend to support them, resulting in shallow penetration. Although there are other complex reasons to account for the penetration characteristics of GMAW, it will suffice to say that over 95% of GMAW welding of stainless steel is done using DCRP. DCSP is used occasionally for weld surfacing of Stainless Steels.

Spray Arc Welding

High electrode current density is the principal requirement for the spray transfer of metal from the electrode to the metal workpiece. At a certain minimum current density, which varies with electrode size and material, metal transfer through the arc changes from very large globular drops, which fall off the end of the electrode, to a spray of extremely fine droplets axially projected from the end of the electrode. The metal transfer changes from a fluttering, erratic discharge with a wandering cathode spot, to a steady, quiet arc column. This arc column is a well-defined, narrow, incandescent, cone-shaped core within which the metal transfers (Figure 10). This type of metal transfer is sometimes referred to as “free-flight” metal transfer.

Because this method of metal transfer uses high currents and voltages, the weld pool is quite fluid. Deposition rates are high, penetration is deep on reverse polarity, and the arc is exceptionally stable. However, the large fluid puddle limits the use of spray arc welding to the downhand position.

The joint designs shown in Figure 11 are typical of those used for GMAW welding of stainless steel. Minimum thickness with the spray type of transfer is about 1/8 in. The general welding procedure outlined for shielded metal-arc welding should be used.

The usual wire size for spray transfer is 1/16-in. Approximately 250-300 amps are required for the 1/16-in. electrode to obtain good spray metal transfer, depending upon the type of stainless steel wire used. DCRP is used for practically all stainless steel welding, and argon plus 2% oxygen is the recommended gas.

On all butt welds, a backup strip should be used to prevent weld drop-through. When fitup is poor or copper backing cannot be used, drop-through may be minimized by using short-circuiting transfer for the root pass. Gas backup with argon will prevent weld underbead contamination.

During manual welding, forehand techniques are beneficial. Although the operator's hand is exposed to more radiated heat, better visibility is obtained.

For welding plate ¼ in. and over, the torch should be moved back and forth in the direction of the joint and, at the same time, moved slightly from side to side. General welding conditions are shown in Table 12.

Short Circuiting Type Transfer

Welding with a short-circuiting arc employs low currents generally ranging from 50 to 225 amp, low potentials of 17 to 24 V, and small-diameter wires – 0.030, 0.035, and 0.045 inch. The outstanding characteristic of the short-circuiting arc is the frequent shorting of the wire to the work. All metal transfer takes place at arc outages which occur at a steady rate and which can vary from 20 to over 200 times a second. The net result is a very stable arc of low energy and heat input ideally suited for welding thin materials in all positions and heavier materials in the vertical and overhead positions and welding large gaps where encountered. The low heat input minimizes distortion and metallurgical effects.

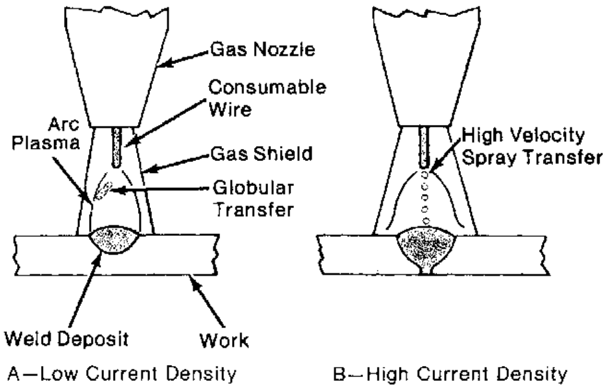


Figure 10
Effect of Current Density on Metal Transfer in GMAW

Table 12
Typical Welding Conditions for GMA (spray) Welding of Stainless Steel

Wire Diameter	1/16 inch
Welding Current (DCRP) amps	250/300
Wire Feed Speed (ipm)	150/200
Shielding Gas	A +2% 0_2
Flow Rate	35 CFH
Weld Travel Speed	15 in./min. (20 in./ min. on square butt joint)

Note: See Figure 11 for joint design and the number of passes for different base-metal thickness.

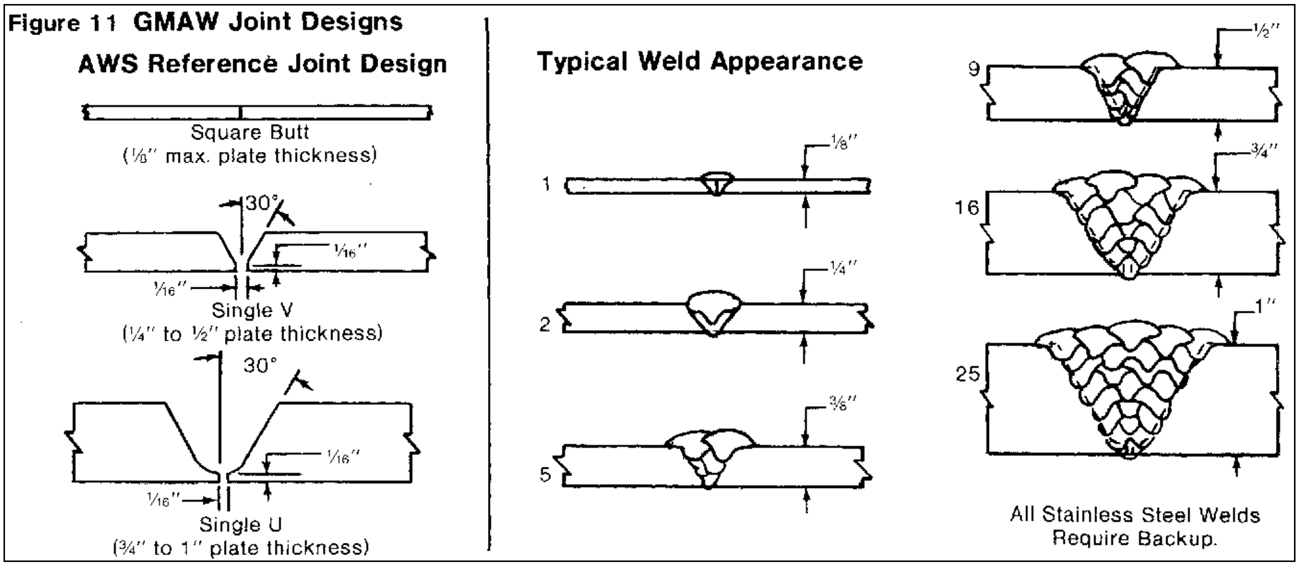


Figure 11 GMAW Joint Designs

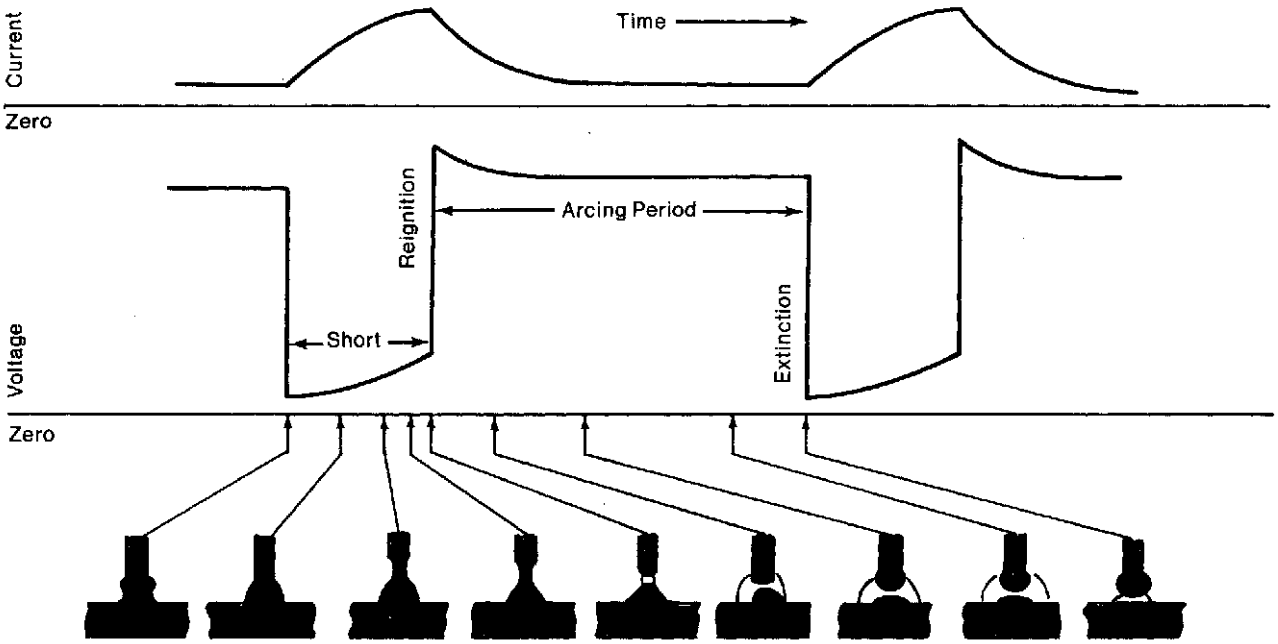


Figure 12

Relationship Between Metal Transfer and Arc Voltage and Arc Current During a Full GMAW Cycle

Figure 12 illustrates, by means of a typical oscillograph trace, arc voltage and arc current during a typical welding cycle. Each outage should produce a predictable and controlled current surge sufficient to recreate the arc without an undesirable high surge or blast. The bottom portion of the figure also illustrates a complete cycle showing short circuit and metal transfer followed by re-establishment of the arc. One cycle is completed as the wire touches the puddle again. General welding conditions for short circuiting GMAW are shown in Table 13.

Pulsed Arc Welding

The pulsed spray process is, by definition, a spray transfer process wherein spray transfer occurs in pulses at regularly spaced intervals rather than at random intervals. In the time-interval between pulses, the welding current is reduced and no metal transfer occurs.

The pulsing operation is obtained by combining the output of two power sources working at two current levels. One source acts as a "background" current to preheat and precondition the advancing continuously fed electrode, the other power source supplies a "peak" current for forcing the drop from the electrode to the workpiece. The peaking current is half-wave DC; because it is tied into line frequency, drops will be transferred 60 time/sec. (Figure 13)

Wire diameters of 0.045 and 1/16 in. are most common with this process. Gases for pulsed arc transfer are the same as for spray arc welding, namely argon plus 1 % oxygen.

Pulsed arc welding is a rather recent innovation and appears to have some application for the welding of stainless steel.

Welding Wires

The wire diameters for GMAW are generally between 0.030 and 3/32-in. It is well known that for each wire diameter there is a certain minimum welding current that must be exceeded to achieve spray transfer. For example, when welding stainless steel in an argon-oxygen atmosphere with 1/16-inch diameter stainless steel wire, spray transfer will be obtained at a welding current of about 275 amp DCRP It must be kept in mind that along with the minimum current a minimum arc voltage must also be obtained. This is generally between 25 and 30 V.

GMAW wires come on spools varying in weight between 2-60 lb. Recently, a new series of austenitic stainless steel wires has been introduced that contain more than the usual amount of

Table 13
General Welding Conditions for Short-Circuiting Welding of Stainless Steel

Plate Thickness, in.	Joint and Edge Preparation	Wire diam, in.	Current (DCRP), amp	Voltage*	Wire Feed Speed, ipm	Welding Speed, ipm	Passes
0.063	Nonpositioned fillet or lap	0.030	85	21	184	18	1
0.063	Butt (square edge)	0.030	85	22	184	20	1
0.078	Nonpositioned fillet or lap	0.030	90	22	192	14	1
0.078	Butt (square edge)	0.030	90	22	192	12	1
0.093	Nonpositioned fillet or lap	0.030	105	23	232	15	1
0.125	Nonpositioned fillet or lap	0.030	125	23	280	16	1

*Voltage values are for helium-argon-$C0_2$ gas silicon. These higher silicon welding wires have particularly good wetting characteristics when they are used with the short-circuiting transfer process.

Minimizing Hot Cracking

Some stainless steels during welding have a tendency toward hot shortness or tearing – Type 347, for example – so more welding passes than listed in the tables may be needed. Stringer bead techniques are also recommended rather than weaving or oscillating from side to side. Hot cracking may be eliminated by stringer bead techniques since there is a reduction in contraction stresses, hence cooling is more rapid through the hot-short temperature range.

Weld metal hot cracking can be reduced by short-circuiting welding because of the lower dilution of the base metal. Excessive dilution sometimes produces a completely austenitic weld metal having strong cracking characteristics. Preheating to about 500ºF also helps to improve bead contour and reduce hot cracking when using the stringer-bead technique on sections 1 inch or thicker.

Summary

The gas metal-arc welding of stainless steel has found wide acceptance as a fabrication tool in industry. Because no flux is required and the gas is very dry, it is essentially a low-hydrogen process. Most welders can be made proficient in the use of the process in a short period of time.

Spray arc welding is essentially a downhand welding process. Short-circuiting and pulsed-spray transfer are for all-position welding.

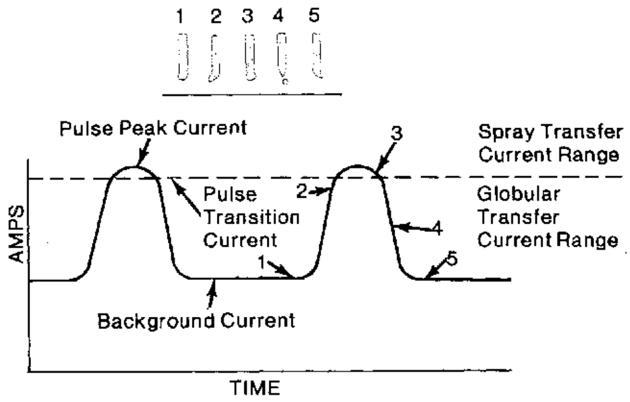


Figure 13
Output Current Waveform of the Pulsed-Current Power Supply

SUBMERGED ARC WELDING

Submerged arc welding (SAW) is a method in which the heat required to fuse the metal is generated by an electric current passing between the welding wire and the workpiece. The tip of the welding wire, the arc and the workpiece weld area are covered by a layer of granulated mineral flux composition. There is no visible arc and no sparks, spatter or smoke. The welding flux composition feeds through a hopper tube and continuously distributes itself over the seam a short distance ahead of the welding zone, some of which melts to form a slag covering. A representation of this welding method is shown in Figure 14, and typical joint designs are shown in Figure 15.

The extreme heat evolved by the passage of the electric current through the welding zone melts the end of the wire and the adjacent edges of the workpieces, creating a puddle of molten metal. This puddle is in a highly liquid state and is

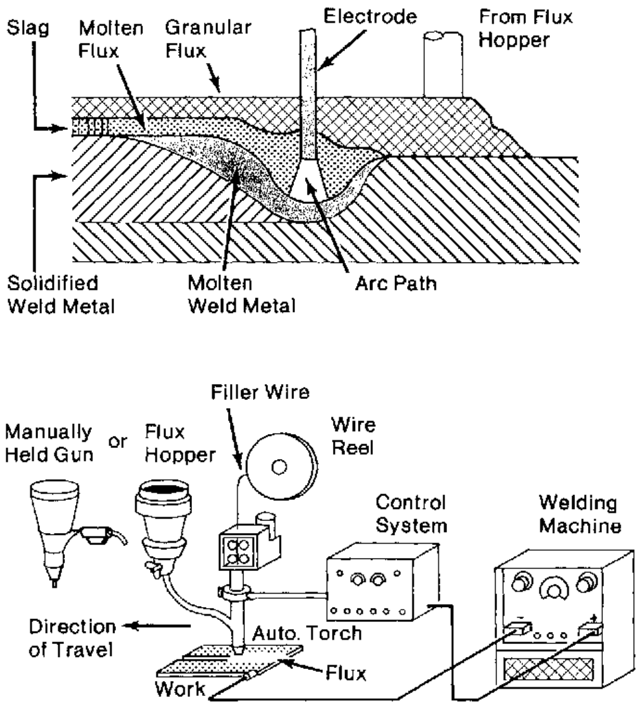


Figure 14
Principle of Submerged Arc Welding.

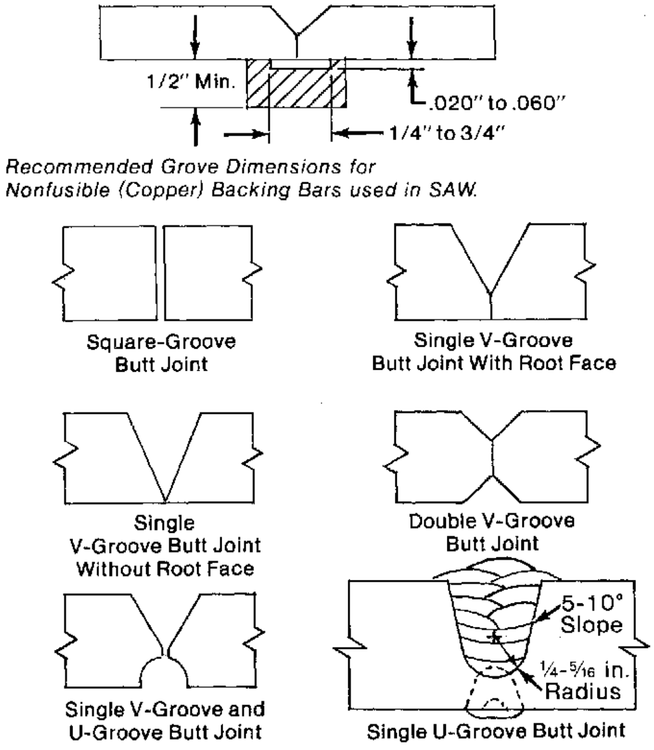


Figure 15
Butt Joint Designs for SAW

turbulent. For these reasons, any slag or gas bubbles are quickly swept to the surface. The flux composition completely shields the welding zone from contact with the atmosphere. A small amount of the flux composition fuses. This fused portion serves several functions: it completely blankets the top surface of the weld, preventing atmospheric gases from contaminating the metal; it dissolves impurities that separate themselves from the molten steel and float to the surface and this also can be the vehicle for adding certain alloying elements to the weld.

The difference between submerged arc welding and other processes used to weld stainless steel is one of degree. Submerged arc can use much higher heat input than other processes and has slower solidification and cooling characteristics. Also, the silicon content will be much higher in submerged arc welding than with other methods, if care is not exercised in selecting the flux material.

Submerged arc is not recommended where a weld deposit is needed that is fully austenitic or is controlled to a low ferrite content (below 4%). However, high quality welds may be produced for applications in which more than 4% ferrite in weld deposits is allowable.

Description of Equipment

In submerged arc welding, the welding heads are used to perform the triple function of progressively depositing metal along the welding groove, feeding the wire into the weld zone and transmitting the welding current to the welding wire. The flux is supplied from a hopper either mounted directly on the head or connected to the head by tubing. The bare wire is fed into the welding head in straight lengths or from a coil or rod mounted on a rod reel, or from a pay-off pack.

Strip Electrodes

A variation of the submerged-arc welding process is primarily applicable to overlaying stainless steel surfacing on mild steel or low alloy steels. With this method, the wire electrode is replaced by a strip electrode. What would otherwise be achieved by oscillating the arc mechanically when wire is used, happens when a strip is used allowing a welding bead 2 inches wide to be laid down at one time, without oscillation and with 20% less dilution. Strips up to 4 inches wide have been successfully welded with one pass of the arc. Special fluxes are required for making welds with strip electrodes. The flux must provide a slag with a melting point, viscosity and wetting action that leaves a flat bead along with a smooth defect-free bond between beads. With two strips feeding into the arc zone with one electrode or "hot" strip and one not carrying current known as a "cold" strip, even greater rates of deposition are possible.

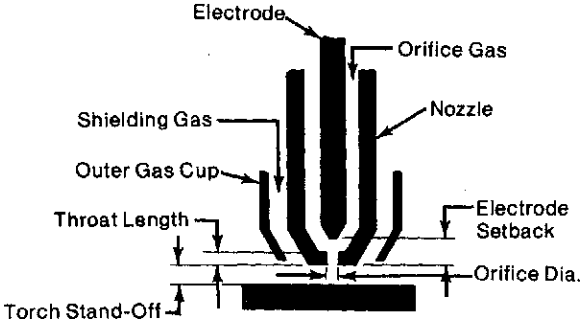


Figure 16
Terms Used With the PAW Torch

PLASMA-ARC WELDING

Plasma-arc welding (PAW) is an inert gas, nonconsumable electrode welding method utilizing a transferred, constricted arc, Figure 16. As the orifice gas passes through the torch to the work, it is heated by the arc, ionized, and passes through the arc-constricting nozzle at an accelerated rate. Since too powerful a jet would cause turbulence in the molten puddle, the jet effect on the work is softened by limiting the gas flow rates through the nozzle. Typical orifice gas flow rates are in the range of 3-30 cubic feet per hour (cfh). Since this flow alone is not adequate to protect the molten puddle from atmospheric contamination, auxiliary shielding gas is provided through an outer gas cup on the torch. A typical shielding gas flow is 40 cfh.

One of the chief differences between the plasma arc and GTAW processes is the "keyhole" effect (Figure 17) obtained with the plasma arc when welding square butt joints in the thickness range of $^{3}/_{32}$ to ¼ inch. A keyhole is formed at the leading edge of the weld puddle where the forces of the plasma jet displace the molten metal to permit the arc to pass completely through the workpiece. As the torch progresses, the molten metal, supported by surface tension, flows in behind the keyhole to form the weld bead. The keyhole is a positive indication of complete penetration and weld uniformity.

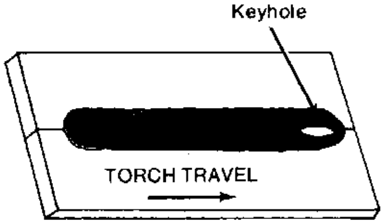


Figure 17
Representative of Keyhole Effect Associated with PAW

Since the puddle of a keyhole plasma-arc weld is supported by the surface tension of the molten metal, it is not necessary to employ close-fitting backing bars. (Underbead gas shielding, however, is generally required to protect the molten underbead from atmospheric contamination.) The snugly fitting backing bars, with their attendant problems of varying chill and mechanical tolerances, often needed with melt-through welding with the GTAW processes, can be replaced in plasma-arc-keyhole welding by a backing bar with a simple rectangular groove (Figure 18).

A multipass plasma-arc weld involves a keyhole root pass followed by one or more non-keyhole weld passes with filler metal addition. In making the fill and cover passes, the force of the plasma jet is adjusted to obtain suitable penetration by regulating the type and amount of gas flowing through the constricting orifice. The characteristic keyhole, however, is not present. This ability to control arc force also provides greater control over penetration than is available with GTAW.

Typical plasma arc conditions for welding stainless steel are shown in Table 14. In each case, the electrode setback distance is $^{1}/_{8}$ in. The conditions for square butt joints presented in Table 14 are for undercut-free welds made without filler metal addition. The addition of small amounts of filler metal will produce undercut-free welds at somewhat higher speeds.

Table 14
PAW Conditions for Stainless Steel

Thickness in.	**Travel Speed, ipm**	**Current (DCSP), amp**	**Arc Voltage***	**Nozzle Type†**	**Gas Flow‡ Orifice, cfh**	**Shield, cfh**	**Remarks**
0.093	24	115	30	111M	6¶	35¶	Keyhole; square butt
0.125	30	145	32	111M	10¶	35¶	Keyhole; square butt
0.187	16	165	36	136M	13¶	45¶	Keyhole; square butt
0.250	14	240	38	136M	18¶	50¶	Keyhole; square butt
0.375							
Root pass	9	230	36	136M	12¶	45¶	Keyhole; "V" joint; $^3/_{16}$ in. nose, 60° included angle
Cap pass	7	220	40	136M	25§	175§	60 ipm of 0.045 in. filler wire

*Torch standoff: $^3/_{16}$ in.
†Nozzle type: number designates orifice diameter in thousandths of an inch; "M" designates multiport design.
‡Gas backup required for all welds.
¶Gas used: 95% Ar + 5% He.
§Gas used: He.

Plasma-arc welding shows the greatest advantages on plate thicknesses appropriate for keyholing. Generally speaking, this range includes square butt joints from 0.090 to 0.25 in. thick on most metals. Keyholing has been used on sections as thin as 0.062 in., but the keyhole welding speed was lower than the normal GTAW speed.

On plates thicker than 0.250 in., a prepared joint can be used to obtain keyholing. Obviously the penetration power of the plasma jet diminishes as the thickness of the plate increases; thus, even with a prepared joint, the thickest plate that can be plasma-arc welded is about 1 in.

Continuously formed stainless steel tubing is generally welded without filler metal addition to conform to ASTM Specification A312-62T. Use of the plasma-arc process for this purpose has resulted in increased welding speed over GTAW. A comparison of average tube-mill welding speeds for GTAW on various wall thicknesses is shown in Table 15. Note that the plasma arc process shows the greatest speed advantage on the heavier wall thicknesses. In addition, the uniform penetrating power of the plasma jet makes the rejection or repair rate experienced with plasma-arc welding of heavier wall tubing much lower than that resulting for GTAW.

Circumferential Pipe Welding

Plasma-arc welding has been used in the horizontal and vertical rolled positions to make circumferential joints in stainless steel. This application would normally be handled with multipass GTAW using a weld backing ring and filler wire on a prepared joint. By contrast, use of the plasma arc permits keyhole welding of square butt joints in one pass on pipe with wall thicknesses of from 0.090 to 0.250 in. On pipe, with wall thicknesses from 0.250 to 0.375 in., a joint preparation consisting of a root face with half the thickness of the wall and a 60 degree included angle is used. The prepared joint requires two passes: A root pass using the keyholing technique and a second pass with filler metal addition to complete the joint.

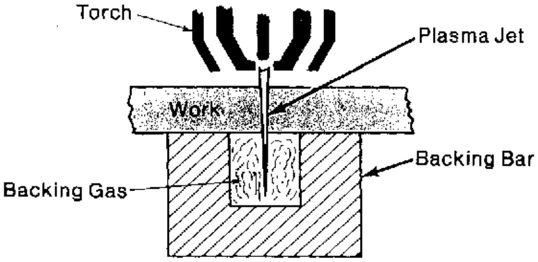


Figure 18
Typical Backing Bar for PAW

Table 15
Comparison of Average GTAW and PAW Speeds for Welding Stainless Steel Tubing

Wall Thickness, in.	GTAW Welding Speed, ipm	PAW Welding Speed, ipm	Speed Increase with PAW %
0.109	26	36	38
0.125	22	36	64
0.154	20	36	80
0.216	8	15	88
0.237	6	14	134

Plasma-Arc Welding Equipment

Mechanized equipment must be used to achieve the welding ••••••••••••••••••••••••••• ••••••••••É•¹⁄₄••••\••••••••••••••••••••••••••••• ••••••••••••••••••••••••• ••••••••••É•¹⁄₄•••• of a torch, control unit, high-frequency generator, power supply and cooling water pump. The torch may be mounted on a stand or a carriage; accessory units such as an arc voltage control or filler wire feed system may be used in conjunction with it.

Gases

Argon is suitable as the orifice and shielding gas for welding all metals, but it doesn't necessarily produce optimum welding results. Additions of hydrogen produce a hotter arc and more efficient heat transfer to the workpiece. In this way, higher welding speeds are obtained with a given arc current.

The amount of hydrogen that can be used in the mixture is limited by the fact that excessive hydrogen additions tend to cause porosity in the weld bead. Since, however, a given material thickness can be welded with higher percentages of hydrogen using the plasma-arc process than with the gas tungsten-arc process, a greater advantage can be realized over the former technique.

The ability to use greater percentages of hydrogen without inducing porosity may be associated with the keyhole effect and the different solidification pattern it produces. In all but a few cases, the shielding gas is the same as the orifice gas. This is done to avoid the variations in the consistency of the arc effluent that would be inevitable if two different types of gases were used.

Permissible hydrogen percentages vary from the 5% used on 0.250-in. thick stainless steel to the 15% used for highest welding speeds on 0.050 in. and thinner wall stainless steel tubing in tube mills. In general, the permissible percentage of hydrogen in the gas mixture increases as thickness of the base metal decreases. (Argon-hydrogen gas mixtures cannot be used when welding Type 321 stainless steel.)

LOW-CURRENT PLASMA ARC WELDING

The welding of very thin metals requires the use of low arc currents. The GTAW process, widely used for joining thin sections, is generally satisfactory for welding at currents down to about 10 amp. Below this level considerably more skill is required for manual welding. Even a small change in torch standoff, which in turn produces a change in arc voltage, causes a fairly large change in current. Arc starting has also been a problem when welding with extremely low currents – the high frequency used for starting may leave undesirable etching marks on the work. Also, surge currents sometimes associated with arc starting have resulted in "blasting" through the workpiece.

Low-current plasma arc welding was developed to obtain a more stable, controllable arc for welding thin-gauge metal. This process combines a continuously operating pilot arc within the torch and arc constriction to produce an arc that is stable at currents as low as 0.15 amp. The shielding gas provided through the gas cup should be an argon-hydrogen mixture for welding stainless steel. Shielding gas flow rates are usually in the range of 20 to 30 cfh. Since this is a higher voltage process than GTAW, a 1-2 volt change in are length is less serious.

Filler metal can be added during manual or mechanized low-current plasma arc welding in the same manner as during GTAW welding. Filler wire diameters, of course, must be small in keeping with the low currents used with this process. Table 16 lists typical conditions for making butt welds in thin-gauge stainless steel with the plasma-arc process. Such welds can be made either manually or with mechanized equipment. All the welds were made using 0.5 cfh argon as the orifice gas and a 0.030-in. diameter orifice.

Although low-current plasma arc is easier to manage than GTAW as a heat source, the melting behavior is the same for both processes. Therefore, joint fixturing requirements are much the same for the two processes. For example, joint edges must be in contact or sufficiently close to assure melt bridging. In general, gaps between adjacent edges should not be more than about 10% of the metal thickness. Where maintenance of this tolerance becomes too difficult, filler metal must be added. Alternatively, butt joints made with the edges turned up (flanged butt joints) can be substituted for preplaced filler metal. Generally this is done on butt joints of less than 0.005 in. thickness.

Table 16
Low-Current PAW Conditions for Making Butt Joints in Stainless Steel

Thickness, in.	Current (DCSP), amp	Shielding Gas	Welding Speed, ipm
0.001	0.3	99% Ar-1 % H_2	5
0.003	1.6	99% Ar-1 % H_2	6
0.005	2.0	99% Ar-1 % H_2	5
0.010	6.0	99% Ar-1 % H_2	8
0.030	10.0	99% Ar-1 % H_2	5

The successful welding of foil thickness assemblies is greatly simplified whenever it is possible to convert the joint into some form of edge joint. The edge joint is the easiest joint to weld since it permits the widest latitude in fixturing tolerance and in welding conditions.

Low-current plasma-arc welding has been used on several products in thin-gauge stainless steel. A few of these are bellows, relay cases and filters, and fine wire mesh.

ELECTRON BEAM WELDING

Electron beam (EB) welding is a fusion-joining process in which the workpiece is bombarded with a dense stream of high-velocity electrons and virtually all of the kinetic energy (energy of motion) of the electrons is transformed into heat upon impact. The process derives its name from these basic particles of matter (electrons) which are characterized by a negative charge and very small mass.

In the discussion of GTAW welding, it was shown that when the circuit is connected for DC straight polarity, the electrons will leave the electrode and result in a deeply penetrated weld. Electron beam welding carries this principle further.

In many ways an EB welder is similar to a television set. Electrons in a picture tube are emitted by a heated filament, concentrated by an optic system to a fine-diameter beam, and moved rapidly by a deflection system to produce a picture. The EB welding system may have several thousand times the beam intensity of a picture tube. Welding usually takes place within an evacuated chamber although recent technology enables the workpiece to be in a partial or non-vacuum.

The heart of this process is the electron beam gun. There are many designs but all have the same basic purpose, emitting electrons and focusing to the final spot size. This focusing is accomplished with electromagnetic coils. Also, oscillation and deflection of the beam have proved useful.

Conventional welding techniques tend to melt only the surface of stainless steel so that penetration essentially comes by heat conduction. EB welding, by contrast, is capable of such intense local heating that it instantaneously vaporizes the metal so that a hole is formed through the entire thickness, e.g., a 1/15-in. wide butt weld may be made in ½in. plate. The walls of the pierced hole are molten and as the beam advances, the molten metal flows from in front to the rear of the hole where it solidifies. This is similar to the keyhole in PAW.

Equipment.

The two basic types of equipment used for electron beam welding are: low voltage, and high voltage.

Low voltage refers to systems that operate below 60,000 v. In this system the welding chamber is usually adequate to shield against x-ray emission, thereby allowing the equipment to be mounted inside the chamber.

The low-voltage type has the unique advantages of requiring only one control parameter for controlling electron beam current; and, once maximum voltage and current have been established, the gun can be made to operate at other values simply by increasing the distance between anode and cathode.

High voltage equipment (above 60 kv) is available up to 25 kv maximum output. The gun is attached to the chamber and welding is accomplished by an invisible beam in a sealed chamber. This poses problems of viewing the weld, making it

Table 17
Electron Beam Weld Settings for Several Types of Stainless Steels

Material	Thickness, in.	Weld Type	Accelerating Voltage, kv	Beam Current, ma	Welding Speed, ipm	Energy, Kilojoules/ in.
302	0.125	Sq butt	31.4	32	56	1.08
302	0.250	Sq butt	30.0	100	60	3.00
304	0.500	Sq butt	29.0	330	63	9.10
309	0.750	Sq butt	29.0	470	56	14.60
321	1.00	Sq butt	30.0	500	40	22.50
316	1.50	Sq butt	57.5	360	29	42.80

necessary to employ an optical system permitting magnified viewing of the weldment. Maximum utilization of the chamber, however, is afforded because the gun does not take up any chamber space. (Shielding should be provided to protect workers from harmful x-ray.)

The advantages of high-voltage EB welding are deeper penetration, and its excellent suitability for delicate work. In general, welds on stainless steel have proven to be both sound and ductile. Typical welding conditions are given in Table 17.

For the most part, the EB welding process is restricted to a chamber, although both intermediate and out-of-vacuum welding is finding some acceptance. Intermediate vacuum welding (100 to 400 microns) uses higher pressures (less vacuum) than ordinarily associated with the EB process – as the pressure goes up, penetration decreases and the width of the bead increases. Although the ultimate capability of the process cannot be realized at these higher pressures, weld characteristics are usually satisfactory. The advantages, of course, are faster pump-down, less costly vacuum systems and easier automation.

More recently, work has been done out of vacuum. This permits an electron beam to escape into a gas atmosphere, thus the work can be positioned outside the chamber. The major disadvantage to this system is that the work must be positioned in close proximity to the gun and, hence, restricts the contour of the workpiece, because the electron beam does not carry very far.

Electron beam welding presents significant advantages over other joining techniques. It is a rapid, precise, controllable process which produces exceptionally high quality welds while minimizing distortion and other adverse effects on the workpiece. Usually, the most precise, highest quality welds can be obtained with the workpiece in a vacuum of about 0.1 micron. At this pressure the deepest, narrowest fusion zones are produced; chemical purity is extremely high; and large working distances can be used. However, for many applications an intermediate vacuum level of 100 to 300 microns is satisfactory.

Out-of-vacuum welding, while producing wider fusion zones and restricting working distances, does have the advantage that the workpiece need not be enclosed in a vacuum chamber. Thus, it is more readily adapted to large structures and to high-speed continuous processing.

Electron beam welding is finding wide acceptance in industry. It no longer is restricted to laboratory and relatively exotic uses, but is proving to be an economic joining process for many everyday applications. However, as with any other process, equipment must be carefully selected and tooled in order to realize its full potential.

LASER WELDING

A laser beam is an intense, highly coherent beam of monochromatic light which has been amplified hundreds of times. The word laser is an acronym derived from "light amplification by stimulated emission of radiation."

Some atoms will emit radiant energy after they have first absorbed radiant energy of some particular wave length. This phenomenon is called "fluorescence" and is evident in such common devices as fluorescent lights and television tubes. The emitted radiation is usually of a longer wave-length than the absorbed radiation and may lie in any region of the spectrum. In the laser welder, the chromium atoms in a man-made ruby rod are excited to produce the laser beam.

The burst of light of a laser beam is exceptionally intense, extremely narrow in line width and highly coherent. It is the coherent property which is important in laser welding, as it allows one to focus the laser beam to an image that is brighter than the original source (this is not possible with a conventional, incoherent light source). Thus, it is possible to obtain a light source so intense it can melt a hole in any opaque material, but because the laser beam passes through transparent substances without affecting them, it can melt metals sealed in glass or plastic containers.

Since the actual welding is done by a light beam, only a clear line of sight is required and direct contact with the workpiece is not necessary. Welds can be made where the joint is normally inaccessible to conventional electrodes or soldering tips.

The laser welding of stainless steel does not present any particular problems. A good physical contact between the pieces to be joined is desirable. If the thickness or the diameter of the stainless steel material is above 0.005 in., argon shielding at a flow rate of about 3 cfh across the weld area will improve the quality and appearance of the weld, but it will also slightly increase (5 to 7%) the energy requirements.

For the laser welding of stainless steel in general, the same metallurgical considerations hold as for other fusion welding processes, with the exception that the heat-affected zone is either very small or, for all practical purposes, nonexistent. Carbide precipitation, for instance, will not occur during laser welding because of the high speed and low heat input.

The advance of laser technology has reached a point where the laser welder has several unique features which make it the ideal joining tool for many specific applications.

Wire sizes from 0.005 to 0.025 in. diameter have been successfully welded in butt, lap and "T" cross joints using a laser welder. Dissimilar metals may also be welded, for example, stainless steel and tantalum. For lap spot welding of stainless steel, the maximum thickness for the upper sheet is 0.020 in. There is no thickness limitation to the lower material.

RESISTANCE WELDING

Electrical resistance welding continues to be one of the most popular and economical methods of joining stainless steel. Generally, the process is applicable to all types of stainless steel if the proper procedures and precautions are observed.

Electrical resistance welding is best suited for mass volume repetitive production work where one machine can be keyed to making many thousands of joints on different areas but on the same metal of the same thickness.

Stainless steel can be in most instances readily welded by all resistance welding methods. The higher resistance to flow of electricity will require less current than for carbon steel for the same thickness, and the squeeze pressure for stainless steel should be approximately 50% greater than for carbon steel, because of its higher strength levels.

SPOT WELDING

In spot welding, coalescence is produced by the heat obtained from resistance to the flow of electric current through the work parts held together under pressure by electrodes. The size and shape of the welds are limited primarily by the size and contour of the electrodes.

The process,as shown in Figures 19 and 20,uses two electrodes, or wheels, made of copper alloys, and they are generally water cooled. Water cooling of spot welding tips is usually internal, which allows the use of high heat-producing currents without deforming the electrodes under clamping pressure. The electrodes are brought together with the work parts held between by a mechanical force which is supplied by foot, air, hydraulic, or a motor operated cam. The welding force is the force exerted between the electrodes which squeeze the work part material interfaces into a weld nugget when the material melts from the application of the heat. The welding cycle is squeeze time, weld heat time, hold time, and off time.

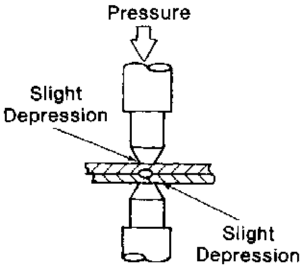


Figure 19
Principle of Electrical Resistance Spot Welding

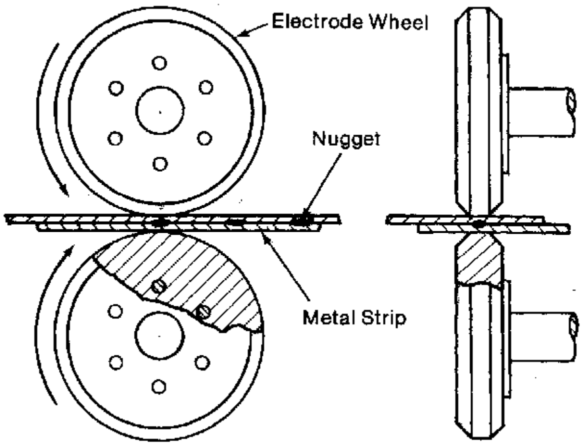


Figure 20
Roller Spot Welding

All the stainless steels that are nonhardenable by heat treatment are readily spot welded. With special precautions and procedures, all of the stainless steels can be spot welded. Preheat is used on some applications, such as the martensitic materials, to bring the workpieces into more intimate contact, and this also provides better electrode contact with the sheets. A postheat or a quench and temper may be used to prevent cracks and hardness in the cast-like structure.

Equipment for spot welding in the simplest form is called a rocker-arm spot welder, shown in Figure 21. The upper arm is movable and supplies the clamping force. The common spot welder throat depth varies from 12 to 48 in. and the current capacity from 10 to 50 kva. Special-purpose rocker arm type welders have been produced up to 250 kva and higher. Timing on simple rocker arm welders is manually operated.

Elaborate spot welders are also available with air or hydraulic cylinders to provide the welding force and electronic timing controls. If high production is needed of an item that has many spot welds, machines are available with multiple heads and transformers to complete many spot welds in one operation.

In joining stainless steel, certain characteristics may influence the welding procedures, such as electrical resistance, thermal conductivity, strength at elevated temperatures and coefficient of expansion. The austenitic stainless steels, which are the most popular type used in resistance welding, have a higher electrical resistance to the flow of current than do low-carbon and low-alloy steels. Conversely, the conductivity of heat in stainless steel is lower than in low-carbon and low-alloy steels. This means that once heat is applied, it is retained longer. Both of these factors result in economy of electrical current inputs and thus, an advantage in resistance welding.

The strength at elevated temperatures of stainless steel is greater than that of low-carbon and low-alloy steels, therefore, greater pressures are required to upset the heated weld area. Because the austenitic stainless steels generally have a higher expansion rate when heated, some precautions may be necessary in the design of fixtures and parts to compensate for this condition. Additional water cooling of fixtures and parts will minimize expansion and help control distortion. The chart

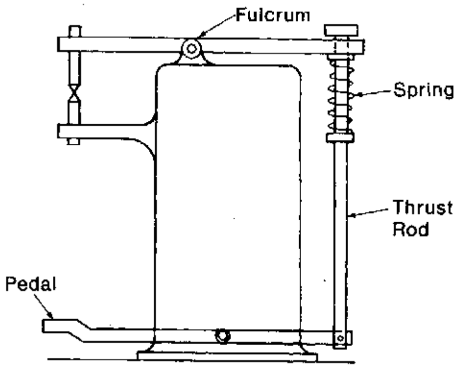


Figure 21
Manually Operated Rocker Arm Spot Welder

shown in Table 18 or spot welding stainless steel is intended as a guide; careful judgment is required in selecting specific welding conditions.

Changes in resistance of electrodes or parts to be welded will affect weld quality; therefore, for consistently good welds, electrodes and work parts must be kept clean.

Spot welding nuggets should be examined for any malfunctions of equipment as well as operator failure. Excessive expulsion at the interface of the joint, excessive indentation, unequal penetration, or cracks in nugget can be causes for weld failures.

Testing of spot welds can be done by a peel test. This test takes a minimum of equipment and is generally used for simple quality control. A sample of the two pieces is joined by a single spot using the same procedure as in the production of the finished part. The pieces should be offset as shown in Figure 22 and welded. After welding, one end is clamped in a vise and the piece that is spot welded is peeled off from the member held in the vise. Examination of the weld button, which should have pulled out, is then made. Measurement of the button (fused zone), its shape and how it peeled out will determine

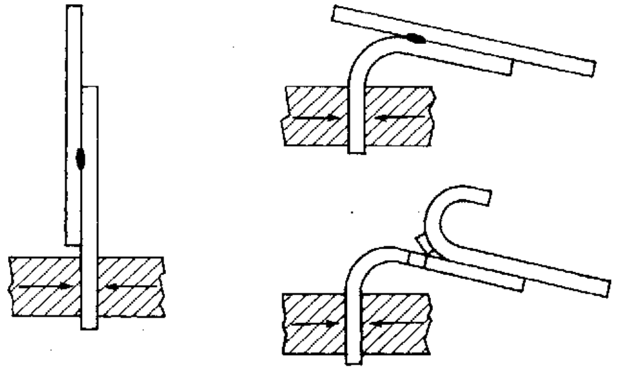
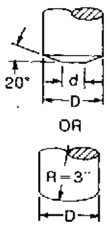
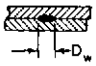
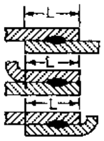


Figure 22
Peel Test

Table 18
Suggested Practices for Spot Welding Stainless Steels

Thickness "T" of Thinnest Outside Piece, in. (a), (b), (c), (d)	Electrode Diameter and Shape (e) 		Net Electrode Force, lb	Weld Time (Single Impulse), Cycles (60 per sec)	Minimum Shear Strength, lb			Welding Current, amp (approx)		Diameter of Fused Zone, in. (approx) 	Minimum Weld Spacing, (f) in. ℄ To ℄	Minimum Contacting Overlap, in. 
					Ultimate Tensile, Strength of Metal							
	D, in. min	d, in. max			70,000 up to 90,000 psi	90,000 up to 150,000 psi	150,000 psi and Higher	Tensile Strength Below 150,000 psi	Tensile Strength 150,000 psi and Higher			
0.006	3/16	3/32	180	2	60	70	85	2000	2000	0.045	3/16	3/16
0.008	3/16	3/32	200	3	100	130	145	2000	2000	0.055	3/16	3/16
0.010	3/16	1/8	230	3	150	170	210	2000	2000	0.065	3/16	3/16
0.012	¼	1/8	260	3	185	210	250	2100	2000	0.076	¼	¼
0.014	¼	1/8	300	4	240	250	320	2500	2200	0.082	¼	¼
0.016	¼	1/8	330	4	280	300	380	3000	2500	0.088	5/16	¼
0.018	¼	1/8	380	4	320	360	470	3500	2800	0.093	5/16	¼
0.021	¼	5/32	400	4	370	470	500	4000	3200	0.100	5/16	5/16
0.025	3/8	5/32	520	5	500	600	680	5000	4100	0.120	7/16	3/8
0.031	3/8	3/16	650	5	680	800	930	6000	4800	0.130	½	3/8
0.034	3/8	3/16	750	6	800	920	1100	7000	5500	0.150	9/16	7/16
0.040	3/8	3/16	900	6	1000	1270	1400	7800	6300	0.160	5/8	7/16
0.044	3/8	3/16	1000	8	1200	1450	1700	8700	7000	0.180	11/16	7/16
0.050	½	¼	1200	8	1450	1700	2000	9500	7500	0.190	¾	½
0.056	½	¼	1350	10	1700	2000	2450	10,300	8300	0.210	7/8	9/16
0.062	½	¼	1500	10	1950	2400	2900	11,000	9000	0.220	1	5/8
0.070	5/8	¼	1700	12	2400	2800	3550	12,300	10,000	0.250	1 1/8	5/8
0.078	5/8	5/16	1900	14	2700	3400	4000	14,000	11,000	0.275	1¼	11/16
0.094	5/8	5/16	2400	16	3550	4200	5300	15,700	12,700	0.285	1 3/8	¾
0.109	¾	3/8	2800	18	4200	5000	6400	17,700	14,000	0.290	1½	13/16
0.125	¾	3/8	3300	20	5000	6000	7600	18,000	15,500	0.300	2	7/8

(a) Types of steel-301, 302, 303, 304, 308, 309, 310, 316, 317, 321 and 347.
(b) Material should be free from scale, oxides, paint, grease and oil.
(c) Welding conditions determined by thickness of thinnest outside piece "T".
(d) Data for total thickness of pile-up not exceeding 4 "T". Maximum ratio between two thicknesses 3 to 1.

(e) Electrode material,	Class 2,	Class 3 or	Class 11
Minimum conductivity–	75%	45%	30% of copper
Minimum hardness –	75	95	98 Rockwell 6

(f) Minimum weld spacing is that spacing for two pieces for which no special precautions need be taken to compensate for shunted current effect of adjacent welds. For three pieces increase spacing 30%.

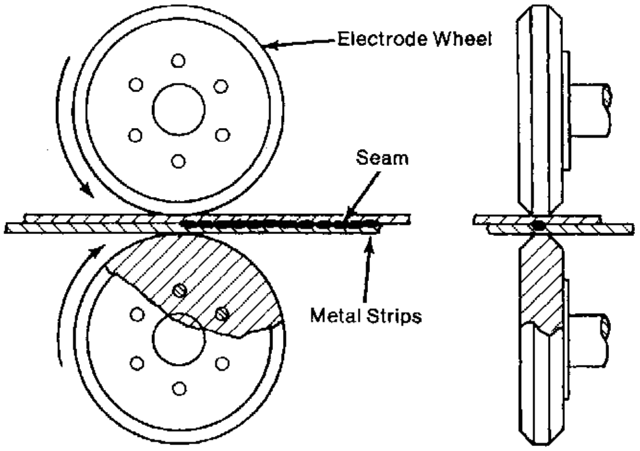


Figure 23
Roller Seam Welding

if conditions are correct. Other methods of testing spot welds are tension, impact, fatigue, macroetch, radiographic, torsion and hardness.

Electrodes

One of the most important components of resistance welding equipment is the electrode material. Resistance welding electrodes function in the form of tips, wheels and dies that have both electrical and mechanical requirements. Special alloys have been developed for electrodes, electrode holders and other current-carrying members because copper has insufficient strength, and it softens at too low a temperature. The minimum standard requirements of the alloys for electrodes are available from welding equipment suppliers.

Precautions

A certain amount of technique is required in the operation of the welding machines; i.e., tip cleaning, proper alignment of the work with respect to the tip, proper placement of the electrodes, etc. The operator must be able to detect trouble. If the operator is not familiar with control equipment and alert to key details such as appearance of the surface, heat affected area and depth of spots, it is possible that he will continue making welds with faulty current discharge, faulty timing, etc.

SEAM WELDING

Seam welding is a resistance welding process wherein coalescence is produced by the heat developed from resistance to the flow of electric current through the work parts, which are held together under pressure by circular electrodes. The resultant weld is a seam formed by a series of overlapping spot welds made progressively along a joint by the rotating electrodes.

Circular electrode wheels from Class III copper-base alloy are used to supply the current and also to supply the pressure to hold the work parts. As the wheels rotate, the weld spacing is obtained by proper adjustment of electrode speed and current off-time, Figure 23. The same materials that are welded by the resistant spot process can be welded by the seam process.

Air operated cylinders are used for applying the pressure to forge the materials together. Either or both of the wheels can be driven, usually by a variable speed reducing drive. There are three general types of seam welding machines: 1) circular, in which the face of the electrode wheels are 90 degrees to the throat of the machine; 2) longitudinal, in which the face of the electrode wheels are parallel to the throat of the machine; and 3) universal, in which the wheels may be set in either the circular or longitudinal position.

The driving force to the electrode wheels is accomplished by knurled or friction rolls or by a gear drive. Advantages of knurled friction drive are: 1) the speed remains constant regardless of electrode wear; 2) the knurling helps clean the electrode wheels of surface pickup; and 3) the knurling drive helps maintain the desired shape or edge of the electrode. When using knurled friction drive, both wheels should be driven to prevent skidding. The main advantage of a gear-driven electrode wheel is that the wheel can be small and, therefore, can be used in containers.

To prevent skidding, the smaller wheel should be driven and the larger idling wheel fitted with a knurling device for electrode dressing. There are some seam welding machines in which the circular electrode wheel travels over the joint to be welded

using a stationary copper alloy backup or platen as the other electrode. Machines of special design can be made to do seam welding, depending on the complexity of the design and cost in relation to production requirements.

In seam welding, the distortion will be greater than in spot welding because of higher heat input unless water cooling is utilized. Flooding the parts to be welded with water will help minimize the distortion and increase the electrode life greatly. Table 19 gives general requirements for seam welding of stainless steel.

Testing of seam welds can be done by several methods: macroetch, pillow, tension, radiographic, hardness and eddy current. The macroetch and the pillow test will be discussed, as these are the most frequently used today. Making a macroetch is simply cutting a sample weld through the center and etching the material so the weld nugget, grain size, heat-affected area and penetration can be visually examined. The cutting of the sample should be just off-center so the remaining section to be etched and examined will be exactly in the middle where the greatest heat concentration occurs.

The pillow test is usually used where tightness is required. The test conditions should simulate the operation conditions as closely as possible. Two flat plates of the same thickness as used in production are used. A pipe connection is welded over a small hole in the center of one plate, and then the plates are welded around the outside edge sealing the space between. Pressure is then applied until failure, which should occur in the base plate and to a predetermined testing pressure.

PROJECTION WELDING

Projection welding, as generally practiced on heavy-gauge pieces, is a resistance welding process wherein bonding is produced by heat obtained from resistance to the flow of electric current through the work parts held together under pressure by electrodes. The resultant welds are localized at predetermined points by the design of the parts to be welded. The localization is usually accomplished by projections, embossments or intersections, as shown in Figure 24.

Projections which will concentrate the heat at those points are punch-press formed or machined and can be any height up to 1/8 in. or more depending on the job. The projections can be on one or both pieces of work as shown in Figure 24. Generally, the major portion of heat is developed in the part bearing the projection, and for that reason, the projection is usually produced on the heavier piece.

Almost all stainless steels are weldable by the projection spot weld process. Most of the work has been done with Types 309, 310, 316, 317, 321, 347 and 348 and operating data have been published, as shown in Tables 20 and 21. Other types not listed are weldable, but a review of current literature revealed that there are no published operating data available.

When welding the ferritic and martensitic stainless steels, special procedures may be necessary, such as controlling the time and temperature while welding. As in spot welding, preheat is used on some applications to bring the workpieces into more intimate contact and thus provide better electrode contact with the workpieces.

A postheat or a quench and temper is used to eliminate porosity and reduce hardness in the welded structure. When working with such materials, test welds and operating data should be developed before going into production.

The recommended type machine for projection welding is the press-type welder in which the movable electrode and welding head are moved in a straight line and guided by bearings or ways. The press-type welder is a combination spot and projection welder. Generally, press-type welders up to 300 kva are operated by air, and welders between 300 and 500 kva are operated by either air or hydraulic power. Above 500 kva, the machine will generally be operated by hydraulic power.

Fast follow-up is desirable when welding stainless steel; therefore, air operation, which is quicker in response, is recommended where possible. The platens will accept dies or fixtures to hold or position the work parts.

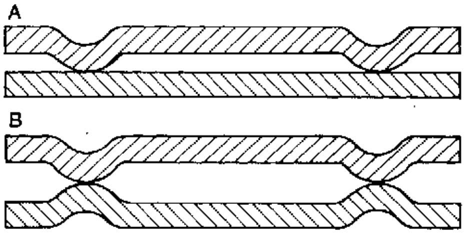


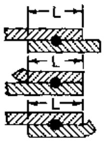
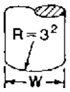
Figure 24
Methods of Preparing Sheet Metal for Projection Welding

The current required for projection welding is slightly less than used for spot welding. It is suggested that as high a current as possible, without excessive splashing, be used in conjunction with proper pressure. The time should be adjusted after the current and pressure are established.

If large, flat electrodes and high currents of short time duration are used, the work parts will show less discoloration than for longer durations with lower currents. The high current will cause higher current density and quicker collapse of the projection, while the surface is protected by the large, flat, water cooled electrode. The designs for projections are shown in Table 20.

The testing of projection welds can be accomplished by tension, impact, fatigue, macroetch, radiographic, torsion, hardness and peel tests. It is believed the peel test shown in Figure 22 is most commonly used to maintain process control and quality in the shop.

Table 19
Suggested Practices for Seam Welding Stainless Steels

Thickness "T" of Thinnest Outside Piece, in. (a), (b), (c), (d)	Elec-trode Width and Shape W, in., min (e)	Net Electrode Force, lb	On-time, Cycles (60 per sec)	Off-time for Maximum Speed (Pressure-Tight), Cycles		Maximum Welding Speed, in. per min		Welds per in.		Welding Current, amp (approx)	Minimum Contacting Overlap, in. (f) 
				2 "T"	4 "T"	2 "T"	4 "T"	2 "T"	4"T"		
0.006	3/16	300	2	1	1	60	67	20	18	4000	¼
0.008	3/16	350	2	1	2	67	56	18	16	4600	¼
0.010	3/16	400	3	2	2	45	51	16	14	5000	¼
0.012	¼	450	3	2	2	48	55	15	13	5600	5/16
0.014	¼	500	3	2	3	51	46	14	13	6200	5/16
0.016	¼	600	3	2	3	51	50	14	12	6700	5/16
0.018	¼	650	3	2	3	55	50	13	12	7300	5/16
0.021	¼	700	3	2	3	55	55	13	11	7900	3/8
0.025	3/8	850	3	3	4	50	47	12	11	9200	7/16
0.031	3/8	1000	3	3	4	50	47	12	11	10,600	7/16
0.040	3/8	1300	3	4	5	47	45	11	10	13,000	½
0.050	½	1600	4	4	5	45	44	10	9	14,200	5/8
0.062	½	1850	4	5	7	40	41	10	8	15,100	5/8
0.070	5/8	2150	4	5	7	44	41	9	8	15,900	11/16
0.078	5/8	2300	4	6	7	40	41	9	8	16,500	11/16
0.094	5/8	2550	5	6	7	36	38	9	8	16,600	¾
0.109	¾	2950	5	7	9	38	37	8	7	16,800	13/16
0.125	¾	3300	6	6	8	38	37	8	7	17,000	7/8

(a) Types of steel-301, 302, 303, 304, 308, 309, 310, 316, 317, 321 and 347.
(b) Material should be free from scale, oxides, paint, grease and oil.
(c) Welding conditions determined by thickness of thinnest outside piece "T".
(d) Data for total thickness of pile-up not exceeding 4 "T". Maximum ratio between thicknesses 3 to 1.
(e) Electrode material,
Minimum conductivity –45% of copper
Minimum hardness –95 Rockwell B
(f) For large assemblies minimum contacting overlap indicated should be increased 30%.

BUTT WELDING PROCESS

The butt welding process can be divided into flash welding and upset welding.

Flash Welding

Flash welding is a resistance process wherein coalescence is produced simultaneously over the entire areas of abutting surfaces by the heat obtained from resistance to the flow of electric current between the surfaces and by the application of pressure after heating is completed. The work parts, which touch lightly, initiate a flashing action from the current delivered through the clamping electrodes.

After the work parts are heated sufficiently from the flashing, the camps move toward one another and displace some of the heated metal. The amount of current and the distance the clamps move toward one another depends on the size and type of material being welded.

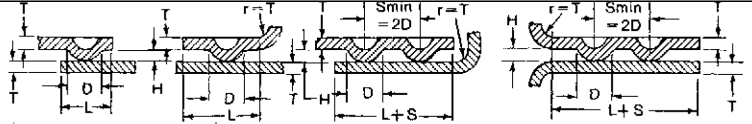
The flash welding process is shown in Figure 25. The sequence of basic operations in flash welding is: 1) load machine; 2) clamp workpiece; 3) apply welding current; 4) parts contact each other (establish flash); 5) flashing; 6) apply upset force; 7) interrupt current; 8) unclamp workpiece; 9) unload; and 10) return platen.

Flash welding machines are capable of performing additional operations such as: pre- and postheating, clamping, pinch-off and shearing, as well as trimming off the flash. Weld flashing is difficult to remove from the inside of tubing and is often left there when it does not interfere with the product use.

All of the stainless steels are weldable by the flash welding process. The 300 Series austenitic grades are readily weldable, while the 400 Series may require special postheating to produce good tough welds.

Machines are either manual, semi-automatic or fully automatic with the majority of equipment produced today being the semi- or fully automatic. If manually operated, the operator will control all of the functions of the process. If the

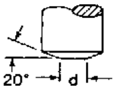
Table 20
Projection Welding Design Data



Thickness "T" of Thinnest Outside Piece, in. (Nominal) (a), (b), (c), (d)	Diameter of Projection D, in. (g), (h)	Height of Projection H, in. (g), (1)	Minimum Shear Strength, lb (Single Projections Only)			Diameter of Fused Zone, in. (min) (at Weld Interface)	Minimum Contacting Overlap L, in. (e), (f)
			Tensile Strength Below 70,000 psi	Tensile Strength 70,000 Up to 150,000 psi	Tensile Strength 150,000 psi and Higher		
0.010	0.055	0.015	130	180	250	0.112	1/8
0.012	0.055	0.015	170	220	330	0.112	1/8
0.014	0.055	0.015	200	280	380	0.112	1/8
0.016	0.067	0.017	240	330	450	0.112	5/32
0.021	0.067	0.017	320	440	600	0.140	5/32
0.025	0.081	0.020	450	600	820	0.140	3/16
0.031	0.094	0.022	635	850	1100	0.169	7/32
0.034	0.094	0.022	790	1000	1300	0.169	7/32
0.044	0.119	0.028	920	1300	2000	0.169	9/32
0.050	0.119	0.028	1350	1700	2400	0.225	9/32
0.062	0.156	0.035	1950	2250	3400	0.225	3/8
0.070	0.156	0.035	2300	2800	4200	0.281	3/8
0.078	0.187	0.041	2700	3200	4800	0.281	7/16
0.094	0.218	0.048	3450	4000	6100	0.281	½
0.109	0.250	0.054	4150	5000	7000	0.338	5/8
0.125	0.281	0.060	4800	5700	8000	0.338	11/16
0.140	0.312	0.066	6000	. . .	. . .	7/16	¾
0.156	0.343	0.072	7500	. . .	. . .	½	13/16
0.171	0.375	0.078	8500	. . .	. . .	9/16	7/8
0.187	0.406	0.085	10,000	. . .	. . .	9/16	15/16
0.203	0.437	0.091	12,000	. . .	. . .	5/8	1
0.250	0.531	0.110	15,000	. . .	. . .	11/16	1¼

(a) Types of steel:
Low-carbon–SAE 1010.
Stainless–Types 309, 310, 316, 317, 321 and 347.
(Max carbon content 0.15%.)
(b) Material should be free from scale, oxides, paint, grease and oil.
(c) Size of projection normally determined by thickness of thinner piece, and projection should be on thicker piece where possible.
(d) Data based on thickness of thinner sheet, and for two thicknesses only.
(e) Contacting overlap does not include any radii from forming, etc.
(f) Weld should be located in center of overlap.
(g) Projection should be made on piece of higher conductivity when dissimilar metals are welded.
(h) For diameter of projection D a tolerance of ±0.003 in. in material up to and including 0.050 in. in thickness and ±0.007 in. in material over 0.050 in. in thickness may be allowed.
(i) For height of projection H a tolerance of ±0.002 in. in material up to and including 0.050 in. in thickness and ±0.005 in. in material over 0.050 in. in thickness may be allowed.

Table 21
Manufacturing Process Data for Projection Welding Stainless Steels

Thickness "T" of Thinnest Outside Piece, in. (Nominal) (a), (b), (c)	Electrode Face Diameter, d, in. (d ± 2 × Proj. Diam.) (d) 	Net Electrode Force, lb	Weld Time, Cyles (60 per sec)	Hold Time, Cycles (60 per sec)	Welding Current (at Electrodes), amp 60 Cycles AC (Approx)
0.014	1/8	300	7	15	4500
0.021	3/32	500	10	15	4750
0.031	3/16	700	15	15	5750
0.044	¼	700	20	15	6000
0.062	5/16	1200	25	15	7500
0.078	3/8	1900	30	30	10,000
0.094	7/16	1900	30	30	10,000
0.109	½	2800	30	45	13,000
0.125	9/16	2800	30	45	14,000

(a) Types of steel-309, 310, 316, 317, 321 and 347 (nonhardenable; max carbon content-0.15%).
(b) Material should be free from scale, oxides, paint, grease and oil.
(c) Data based on thickness of thinner sheet, and for two thicknesses only. Maximum ratio between two thicknesses 3 to 1.
(d) Electrode material, Class 2 or Class 12
Mimimum conductivity – 75 29% of copper
Maximum hardness – 75 100 Rockwell B

operator starts the flashing action and the machine completes the cycle, it is semi-automatic. In fully automatic machines, loading and unloading are the only functions performed by the operator.

Alignment of the parts is important, and parts should be arranged so the interfaces will line up and generate heat over the entire interface. If parts are misaligned, the cross-sectional area of the weld will be reduced and trimming of the flash will be most difficult and noticeable on the finished part. Effect of alignment is shown in Figure 26.

Testing of flash welds is accomplished by hardness, strength, tension, impact, fatigue, bending, cupping, corrosion resistance, radiographic and visual. Visual inspection is the most widely used and bending a joint beyond that required in service will determine satisfactory weld joints.

Upset Welding

Upset welding is a resistance welding process wherein coalescence is produced simultaneously over the entire area of abutting surfaces or progressively along a joint by the heat obtained from resistance to the flow of electric current through the area of contact of the abutting surfaces. Force is applied before heating is started and is maintained throughout the heating period.

The upset welding process differs from the flash welding process in that no arcing or flashing takes place. The parts, when clamped,are brought together under pressure and current applied until the correct upset takes place and then current is interrupted. Upset welding is shown in Figure 27.

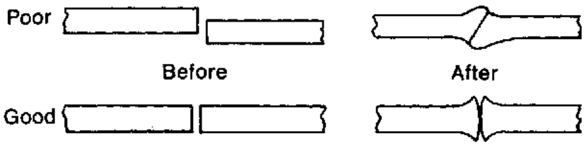


Figure 26
Effect of Alignment

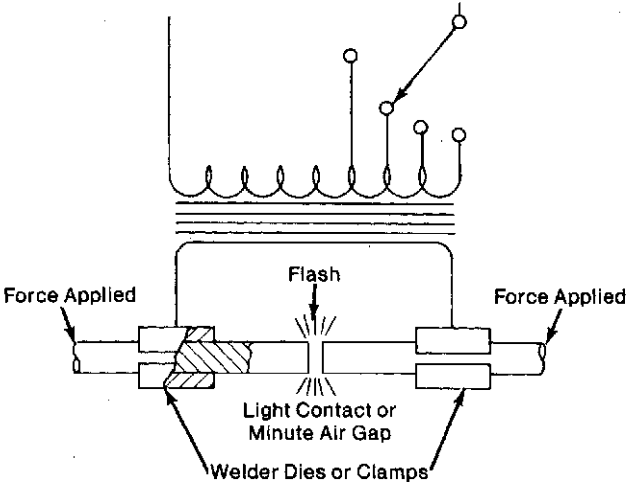


Figure 25
Essential Features of Flash Butt-Welding

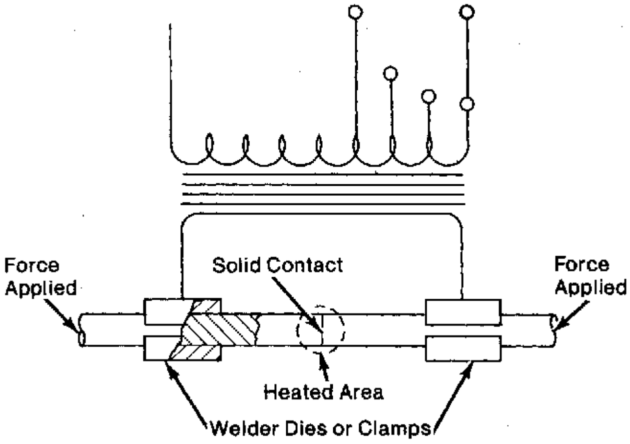


Figure 27
Upset Butt Welding

The essential sequence of operations related to upset welding is: 1) load machine; 2) clamp workpiece; 3) apply welding force; 4) apply welding current; 5) apply upset force; 6) interrupt current; 7) maintain location; 8) unclamp workpiece; and, 9) return platen.

The same conditions relative to conductivity and size of material and the location of the current-carrying clamping dies that apply to flash welding also apply here.

The non-heat treatable (austenitic) stainless steels are readily weldable by this process. If the work parts can be postheated, quenched and tempered, the hardenable stainless steels may produce satisfactory welds.

Continuous tube mills use this process quite extensively. A set of electrode wheels, which provide the current to heat the edges of the strip, are located with a couple of squeeze rolls that supply the upset pressure and weld. Immediately after the welding station is a scarfing tool for removing the upset material from the outside of the tube. If the tube is large enough and quality dictates scarfing on the inside diameter, small tools are used.

Inspection of upset butt welding can be accomplished by visual inspection (removing a section and macroetching), and by tension testing. Tension testing and elongation of tubes is accomplished by flare or expansion of the end of the tube. Expansion to approximately 15% greater than the original tube is considered satisfactory.

HIGH FREQUENCY RESISTANCE WELDING

High frequency resistance welding is a force welding process in which the heating of a faying* surface to welding temperatures is accomplished through the use of power in the 400 to 450 KHZ range. The power is introduced to the weldment through small contacts sliding or rolling directly on the metal to be welded or through induction coils. The process is continuous, with a strong forge weld produced when the heated parts are passed in line through squeeze rolls. In this process, the current follows the low reactance path, rather than the low resistance path, which produces a skin effect of localized heating of very high intensity. The harder-to-weld metals will weld more readily using this process because the depth of material heated to a plastic state is shallow. Most of this material is forced from the joint when squeezed to make the weld, resulting in a narrow heat affected area.

The process is particularly well suited for continuous production of large volumes of tubular and similar products.

PERCUSSION WELDING

Percussion welding is a resistance welding process wherein relatively intense discharge of electrical energy and the application of high pressure (usually a hammer-like blow) occurs simultaneously or with the electrical discharge occurring slightly before the application of pressure or hammer blow.

The parts to be welded are heated instantly by the sudden discharge of a heavy electric current from a condenser. At the very moment when the current is discharged from the condenser, the two parts to be welded together are forced together with a rapid blow. The sudden rush of the current momentarily melts the portions of the pieces that are to be joined, and by forcing them together at the moment, a weld is made.

CONCLUSION

Stainless steel can, in most cases, be readily welded by all the resistance welding processes. The higher resistance to flow of electricity will require less current than for carbon steel for the same thickness and the squeeze pressure will be approximately 50% greater than for carbon steel. Greater squeeze pressure is needed for stainless steel because of its higher strength at elevated temperatures than that of carbon steel.

FRICTION WELDING

Friction welding is a process wherein the heat required for welding is generated by rotating one of the pieces to be welded with an applied load along its axis of rotation against another piece that is clamped in a stationary chuck. The heat of friction between the two pieces becomes sufficient to make welding possible when rotation is stopped.

Friction welding is possible for stainless and other metals to stainless steels.

In making a friction weld, the following sequence of events takes place: (1) rotation is started, (2) an axial force is applied between the two members being welded, (3) the application of a load generates heat at the interface and upsetting of the metal occurs at the heated interface and, (4) the weld is then completed by suddenly stopping rotation while maintaining or increasing the axial force.

ELECTROSLAG WELDING

Electroslag welding is used to weld plates ranging in thickness from 1 to 14 inches. The process involves the fusion of the base metal and the continuously fed filler wires under a layer of electrically conductive molten flux.

The plates are set up in a vertical plane, with a parallel space between square-cut edges of about 1 to 1-5/16 inches, depending upon the plate thickness. The open gap is enclosed with water-cooled copper shoes, forming in effect a mold for the molten metal. One or more welding wires, which can be set to oscillate to fill the space evenly, are fed into the weld zone. An arc is struck to start the process. The arc energy, however, is used only initially to fuse the flux into the molten slag, which then, owing to its temperature, becomes a highly ionized mass offering a low-resistance path for the electric current. Electric energy is expended in the slag and weld metal to maintain continuous fusion. Penetration is controlled by the width of the gap between the plates and by the voltage across the weld.

Stainless Steel Pipe Welding

The welding method used to join stainless steel pipe depends upon the size and thickness of the material. It also depends upon whether the pipe can be rotated so welding can be done in a downhand or "2 or 3 o'clock" position. Pipe or tubing under 4 inches in diameter is frequently welded by tungsten-inert-gas since this type welding is much easier for small diameters. For larger diameters, stick electrodes are considered more satisfactory since the larger diameter pipe usually has heavier wall thickness so the stick electrode fills the gap faster. For high-production pipe welding, fully automatic methods are generally used.

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*Faying surface: the surface of the base metal comes in contact with another part of the base metal to which it is fastened.

BACKING RINGS

Backing rings are shaped strips of metal that are formed into a ring and fitted into the inside surface of the pipe or tube prior to welding, and they become filler for the weld. For this reason, the backing ring should have essentially the same chemical analysis as the pipe or tube. The backing ring insures complete fusion of the weld without the formation of slag, icicles or spatter within the bore. A backing ring also assists materially in securing proper alignment of the pipe ends being joined.

Two types of backing rings are commonly used: split or solid. The split types are designed to fit the inside diameter of the pipe or tube without any machining of the pipe ends for proper fit up. Because they are split, they can be slightly expanded or contracted to fit the inside diameter closely. Solid or machined backing rings require the pipe to be properly prepared (machined) to receive them. Because this type of pipe or tube end preparation is expensive and the solid rings themselves are more expensive than the split type, their use is usually confined to systems designed for severe service conditions.

Weld Overlays

Since the cost of solid stainless steel plate is sometimes a consideration, designers may specify clad carbon steel components. Shells can be made from mill clad plate or from carbon steel plate that is clad by overlay welding after being formed into the shell. Forgings are almost always clad by overlay welding.

The welding rods and electrodes and procedures used in the cladding of carbon and low alloy steels are of utmost importance to prevent cracks from forming in the base metal and in the deposited stainless steel weld metal.

On large components that can be positioned for downhand welding, the submerged arc method is successfully employed. For smaller items or items that require welding in other than the downhand position, the SMAW method with covered electrodes is generally used.

A point to remember in selecting a welding method is to choose the one that gives the minimum amount of penetration into the base metal, thus minimizing the amount of dilution of the deposited weld metal by the base metal.

The submerged arc method employs continuously fed converging welding electrodes that are connected electrically in series to a power source. The location and positioning of the converging welding electrodes are regulated so that a common puddle is formed on the base metal between the electrodes by the arc that passes from one electrode to the other.

The shielded metal arc method using covered electrodes has been successfully used on items that cannot be positioned for downhand welding, where an item is too small for series submerged arc welding, or where a small fabrication shop does not have equipment required for other welding methods.

WELDING ELECTRODES

Although the various fabricators of power equipment have some differences in the specific electrode composition employed for the deposition of the first layer of weld-deposited cladding on carbon steel, there is generally agreement on the requirements of such an electrode.

1. The alloy content of the electrode should be high enough to permit a considerable amount of dilution by carbon steel without developing a hard martensitic structure.

2. The electrode should not be of a composition which gives inherent welding difficulties.

3. When a deposit of lower alloy content is deposited over the first layer, dilution of the second layer by the first should not cause difficulties in the second layer. Specifically, the following electrodes are used:

For the first layer: Type 309, Type 309-Mo, or Type 312 are commonly used by various fabricators. Type 309 contains a nominal 25Cr-12Ni, Type 309-Mo contains 25Cr-12Ni-2Mo, and Type 312 contains a nominal 29Cr-9Ni.

For the second layer: Type 308, Type 308L, or Type 347 are commonly used, the choice generally being made by the purchaser of the vessel. Type 347 may cause difficulties with cracking.

The alloys with lower alloy content such as Types 308 or 308L (nominal 18% Ni) should not be used as the first layer over carbon steel because they will tolerate little dilution without becoming brittle due to martensite formation.

When dilution of the carbon steel base metal into the stainless steel weld metal interferes with the corrosion resistance of the clad metal joint, try the following suggestion: Chip out one half the first pass or welding bead and possibly even one half the second pass. This reduces the volume of dilution by the carbon steel into the weld metal.

Welding of Stainless Steel-Clad Plate

Many thick-wall structures are fabricated of clad plates in which the cladding is one of the austenitic stainless steels and the backing material is carbon or low-alloy steel. Depending on the thickness of the clad plate and the ultimate usage of the item fabricated from the plate, the welds may be made by either of two methods:

1. The carbon steel or low-alloy steel backing material is joined with carbon steel or low-alloy steel weld metal, and the region where the stainless steel cladding was removed during joint preparation is overlaid with stainless steel weld metal.
2. The entire thickness of the clad plate is joined with stainless steel filler metal.

Where the backing steel is thick, as in the case of vessels for high-pressure service, it is more economical to use the first method. In the case of relatively thin clad plate, the second method might be the easier way to make the joint at little or no increase in cost. However, in the case of elevated-temperature operation or cyclic-temperature operation, the possibility of difficulties arising from the difference in coefficients of expansion of the base plate and the weld metal should be considered. Butt welds of clad material may have the carbon steel backing welded with stainless steel, providing the service conditions are limited to a maximum service temperature of 450ºF.

All stainless steel deposits on carbon steel should be made with filler metal of sufficiently high alloy content so that normal amounts of dilution by carbon steel will not reduce the alloy content to such an extent that a brittle composition will result. In general, Types 308, 316 or 347 weld metal *should not* be deposited directly on carbon or low-alloy steels. It should be remembered that Type 310 is a fully austenitic material subject to hot cracking when there is high restraint in a welded joint. Consequently, Type 310 welds should be carefully inspected.

Welds of Types 309 and 312, being partially ferritic, are highly resistant to such cracking.

When stainless steel is deposited over carbon steel at joints in the clad plate, sufficient thickness of weld must be employed to prevent migration of carbon from the base metal to the surface of the stainless steel weld that will be in contact with the service environment. Since different welding methods result in different penetration characteristics, tests should be conducted to determine the welding procedure that minimizes deep penetration and resulting weld-zone dilution.

Figure 28 illustrates the most commonly used method for making welded joints in stainless steel-clad carbon or low-alloy steel plate where, for economy or stress reasons, it is desirable to deposit stainless steel weld metal only in the area of the stainless steel cladding. The plate edges are beveled for welding as indicated in Step 1, the bevel ending 1/16 in. minimum above the stainless cladding. The carbon or low-alloy steel weld is then deposited as shown in Step 2, care being taken not to penetrate any closer than 1/16 in. to the cladding. It is good practice to use a low hydrogen process for the first carbon steel or low-alloy steel layer to minimize the danger of cracking in the event that there is accidental penetration to the vicinity of the cladding.

The joint is next backgouged from the stainless steel side, as indicated in Step 3, removing the minimum amount of material necessary to reach sound carbon steel weld metal. In Step 4, the groove resulting from the backgouging operation is filled with stainless steel weld metal in a minimum of two layers, with an additional layer recommended if projection of the weld above the cladding surface can be tolerated. The first layer of stainless steel weld metal should be sufficiently high in alloy content to minimize difficulties from weld metal dilution by the carbon steel base metal. Penetration into the carbon steel should be held to a minimum. If the cladding is Type 304 stainless steel, the first layer of weld metal should be Type 309. (Type 310 would also be acceptable provided that each layer of weld metal is carefully inspected for cracks.) Subsequent layers may be Type 308.

Where the cladding material is Type 316 stainless steel, deposition of the first layer with Type 309 will make it easier to achieve the proper composition in subsequent layers that should be deposited with Type 316.

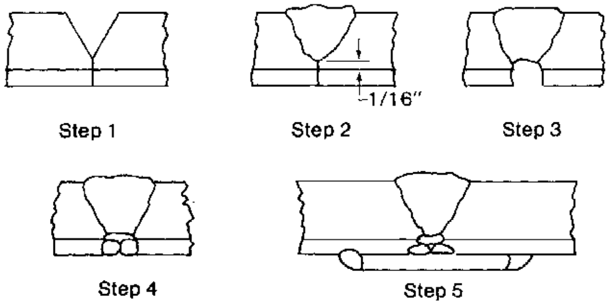
Where the cladding material is Type 304L or Type 347, the welding procedure must be carefully controlled to obtain the required weld metal chemistry in the outer layers of weld metal. The procedure should be confirmed by chemical analysis of sample welds prior to use in a vessel for severely corrosive conditions.

In some cases, a strap of wrought material having the same compositions as the cladding is welded over the completed weld, as shown in Step 5. This assures that there are no areas of lower corrosion resistance in the lining. The fillet welds joining the strap to the cladding should be carefully inspected after deposition.

Figure 29 illustrates an alternative method for the welding of clad plate in which a carbon steel or low alloy steel weld joins the base metal portion of the plate and limits the use of stainless steel to replacing the cladding where it has been removed prior to making the carbon or low-alloy steel weld. This method would be more expensive in that an additional operation is required to strip back the cladding and to replace the stripped-back cladding with stainless steel weld metal. This method allows the use welding methods such as submerged arc in the deposition of the carbon steel weld since there is no danger of alloy contamination from the cladding layer.

Great care must be taken in depositing the stainless steel weld to replace the cladding removed adjacent to the weld. The first layer of stainless steel weld metal should be sufficiently high in alloy content that cracking problems will not result from normal dilution by the carbon steel base metal. A stringer bead

Figure 28
Clad Metal Joint Design



Joint design for stainless clad-steel plate employing stainless steel weld metal only in portion where stainless steel cladding is removed for fabrication.

Step 1. Tight fit-up is desirable. Point of groove should be 1/16 in. (min) above the stainless steel cladding.

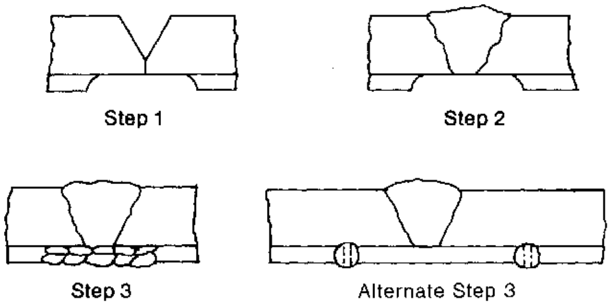
Step 2. Deposit carbon steel weld from carbon steel side. First pass should be deposited with a low-hydrogen type electrode to minimize possibility of cracking in the event that penetration accidentally reaches cladding. Penetration should not extend beyond 1 /16 in. from cladding.

Step 3. Gouge from stainless steel side until sound carbon steel weld metal has been reached. Do not gouge deeper than necessary.

Step 4. Deposit stainless steel weld metal to fill groove resulting from gouging operation.

Step 5. Some plants require for severely corrosive services that a strip of stainless steel of the same composition as the cladding be fillet welded to cladding to cover the weld.

Figure 29
Clad Metal Joint Design



Alternative method to that shown in Fig. 28. This method requires stripping back of cladding in region of joint.

Step 1. Strip cladding back 3/8 in. (min) from each side of joint. Bevel and fit up. Tight joint as shown or root gap may be used.

Step 2. Deposit carbon steel weld by any of the conventional methods and grind root flush with underside of carbon steel plate.

Step 3. Overlay area where cladding has been removed with at least two layers of stainless steel weld metal.

Alternative Step 3. Instead of overlay welding in the area where cladding has been removed, an inlay of a strip of wrought stainless steel can be welded in place.

technique should be employed with care being taken to hold penetration to a minimum.

Since the stainless steel weld metal layer is rather thin, the proper weld metal chemistry might not be achieved after the second layer has been deposited. It might be necessary to grind off a portion of the second layer and deposit additional weld metal to assure that the desired composition has been achieved.

Alternative Step 3 involves the use of an inlay of wrought stainless steel rather than deposited weld metal to cover the exposed carbon steel. The edges of the stainless steel strip are welded to the edges of the cladding.

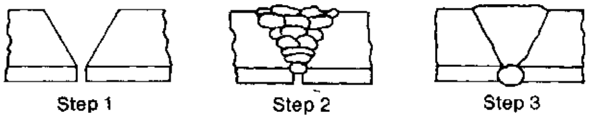
Figure 30 illustrates the most common method of joining stainless steel-clad carbon steel or low-alloy steel plate with a weld that consists entirely of stainless steel. This method is most frequently used when thin clad plate is being fabricated.

After the plate has been beveled and fitted up for welding as shown, a stainless steel weld is deposited from the carbon steel side. The welding filler metal should be sufficiently high in alloy content to minimize the difficulties, such as cracking, which could result from dilution of the stainless steel weld by carbon steel. Type 309 would be suitable for this application and Type 310 could be used if the weld is carefully inspected for cracks. The stainless steel welding procedure should result in minimum weld metal dilution by the carbon steel.
Since the stainless steel weld is under restraint, cracking may result if excessive dilution occurs.

After the stainless steel weld has been deposited from the stainless steel side as shown in Step 2, the root of the weld is cleaned by chipping or grinding, as required, and one or more layers of stainless steel weld metal deposited, as shown in Step 3. The weld metal composition should be that normally employed to weld the type of stainless steel used for the cladding. If the cladding is Type 304, the final layer of weld metal should be Type 308. If the cladding is Type 316, it might be necessary to backgouge prior to deposition of the final weld metal layers in Step 3 to assure that the proper weld metal chemistry is achieved at the surface of the weld.

Figure 31 illustrates a method of making a full penetration corner joint which utilizes a solid stainless steel weld. After beveling and fitting up as shown in Step 1, the weld from the carbon steel side is deposited with a stainless steel electrode, such as Type 309, which is sufficiently high in alloy content to minimize problems that can result from dilution of the stainless steel weld metal by carbon steel. Type 310 could also be used if the weld metal is carefully checked for cracks. In Step 3, the first layer should be deposited with Type 309 or 310, penetrating deeply enough to reach the previously deposited stainless steel weld. One or more layers can be deposited over the first layer, using filler metal composition normally used for welding the type of stainless steel used for cladding. The stainless steel must be deposited carefully in the carbon steel portion of the joint because dilution by carbon steel could cause cracking in this restrained weld. A stringer bead technique should be used.

Figure 30
Clad Metal Joint Design



Common method of joining stainless clad steel plate employing weld consisting entirely of stainless steel.

Step 1. Bevel and fit up as shown.

Step 2. Deposit stainless steel weld from carbon steel side.

Step 3. Clean root of weld to remove slag or oxide. Gouge if necessary. Deposit weld with electrode type normally used to weld cladding composition.

Welding Dissimilar Metals

AUSTENITIC STAINLESS STEELS TO LOW CARBON STEELS

In joining austenitic stainless steels to carbon steels or low-alloy steels for low and moderate temperatures (not over approximately 700ºF) it is customary to use a stainless steel welding rod that is sufficiently high in total alloy content to prevent martensite formation when diluted with carbon steel while at the same time preserving residual amounts of ferrite, which counteract the tendencies for hot cracking (at the time of welding) even under conditions of severe restraint.

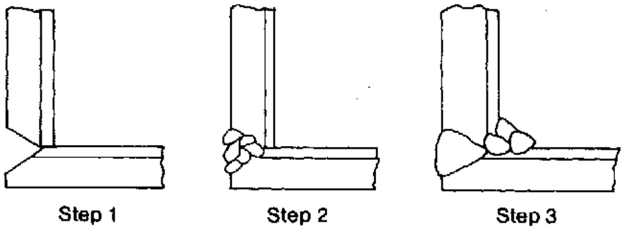
Type 309 is probably used more than any other electrode for joining carbon steel to stainless steel (including overlay welding). Type 312 also enjoys some usage in joining carbon steel to stainless. Type 309 normally contains about 5 to 10% ferrite, while Type 312 is strongly ferritic.

The use of ENiCrFe-2 covered electrodes or ERNiCrFe-6 bare filler metal will also produce satisfactory welds when joining the austenitic stainless steels to low-alloy steel, especially for elevated-temperature service.

When making a transition joint betwen austenitic stainless steel and carbon steel, it is good practice to "butter" the carbon steel surface with a layer of Type 309 or other suitable stainless steel weld metal prior to actually joining it to the stainless steel. In this manner, the portion of the joint where difficulties are most likely to occur is buttered while there is little restraint on the weld metal. Following the deposition and inspection of the buttered layer or layers, the joint between the stainless steel member and the buttered layer will be a conventional stainless steel to stainless steel joint. The welding rod in this case can be the type normally used to weld the stainless steel member of the joint (i.e., Type 308 if the stainless steel member is Type 304).

The deposition of carbon steel or low-alloy steel weld metal on stainless steel can result in hard, brittle weld deposits which frequently crack when deposited and which would be likely to

Figure 31
Clad Metal Joint Design



Full penetration corner joint in stainless clad steel plate utilizing solid stainless steel weld.

Step 1. Bevel and fit up for welding.

Step 2. Deposit stainless steel weld from carbon steel side.

Step 3. Brush, grind, or back gouge as required and deposit remainder of weld from stainless steel side.

fail in service. *Avoid depositing carbon steel or low-alloy steel weld metal on stainless steel.* When this must be done because of service requirements, use the short-circuiting method of metal transfer.

PROCEDURES FOR WELDING TRANSITION JOINTS

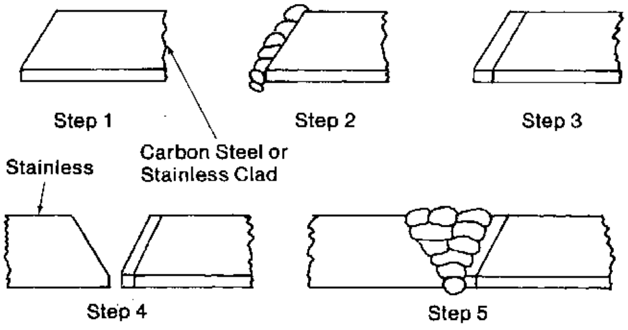
Figure 32 illustrates a method of joining stainless steel components to carbon steel or stainless-clad carbon steel and it is especially useful when stress relief of the carbon steel is needed. This method has been widely used in the welding of stainless steel pipe to stainless steel lined carbon steel or low-alloy steel.

The overlay or buttered layer that is applied to the carbon steel surface should be of sufficient thickness that the subsequent welding operation will not adversely affect the carbon steel base metal. If the right hand member of the joint shown in Figure 32 is solid carbon steel or if the cladding is Type 304 stainless steel, Type 309 should be used for the overlay operation. Great care must be taken in depositing the overlay to keep carbon steel dilution of the stainless steel weld metal to a minimum. Excessive dilution can cause cracking of the stainless steel weld metal. Stress relieving, when required, should be performed after deposition of the stainless steel overlay.

The final weld between the solid stainless steel and the buttered surface on the carbon steel can be made with the filler metal composition that is normally employed for welding the solid stainless steel member or the composition used to apply the overlay on the carbon steel member.

Another method employs a short stainless steel member that is welded to the carbon steel or stainless clad carbon steel member prior to the stress relieving operation. This method insures that the final weld will have no effect on the carbon steel base metal. Stress relieving is performed while there is little restraint on the joint.

Figure 32
Clad Metal Joint Design



Design for joining stainless steel to carbon steel or stainless clad carbon steel. Commonly used for welding stainless steel pipe to stainless steel lined carbon or low-alloy steel.

Step 1. Bevel edge of carbon steel or stainless clad carbon steel plate for welding.

Step 2. Apply overlay or "buttered" layer of stainless steel weld metal of suitable alloy content to avoid problems from dilution by carbon steel. Use welding procedure that results in minimum penetration of weld metal into carbon steel.

Step 3. Machine or grind to restore required dimensions. Stress relieving, if required, may follow this step.

Step 4. Fit-up for welding.

Step 5. Deposit stainless steel weld by any suitable process, using the filler metal which is normally employed for welding the stainless steel member, or the same filler metal that was employed to apply the overlay or "buttered" layer on the carbon steel member.

The final weld is a simple stainless to stainless joint. Figure 33 shows the least desirable of the three methods. In this method the stainless steel and the stainless-clad carbon steel or carbon steel member are beveled and fit up for welding, leaving a suitable root gap. The two are then joined, using an electrode sufficiently high in alloy content that cracking of the stainless steel weld will not occur with normal dilution from the carbon steel.

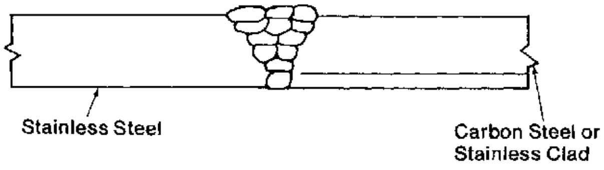
The welding procedure used should hold penetration into the carbon steel to a minimum. One disadvantage with this method is that the most critical portion of the weld is deposited while the weld is under restraint. Another is that local stress relief of the weld must also be performed on a restrained joint. (A point to remember is that stress-relief temperatures can result in carbide precipitation.)

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 Type 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.

Figure 33
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.

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.

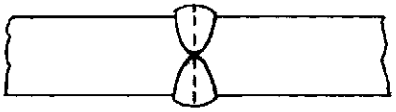
The high heat conductivitiy of such a back-up bar or plate will prevent its sticking to the weld metal, while it's chill-mold effect will assure a clean smooth weld metal surface. Copper back-up bars can be made by cutting pieces from copper plate or sheet. Chill bars serve the best purpose by controlling 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 34 and 35. 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 36. 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 37) double V- and double U- grooves (Figure 38) are used, although they are more costly to prepare.

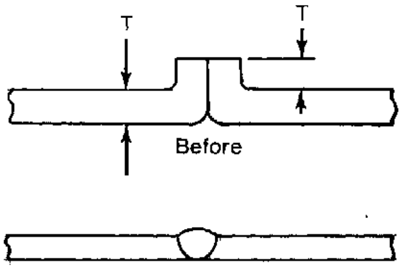
Normally, full penetration welds are essential and therefore conventional backing rings are not used. However, consumable backing rings or inserts (Figure 39), which are melted during the first weld pass and become an integral part of the weld, are used successfully.

Single bead for 14 gage and lighter.



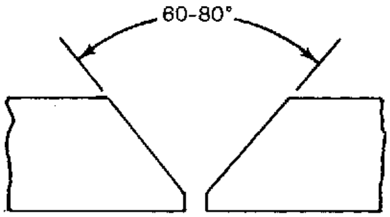
Double bead for 12 gage to 3/16 inch.

Figure 34



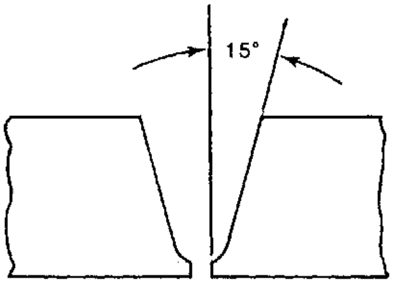
This standing edge or flange joint may be used for light gages. Little or no filler metal need be added.

Figure 35



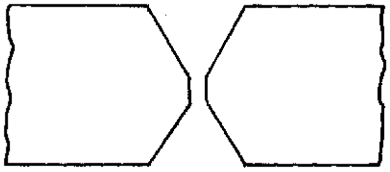
Single "V" joint. For 1/4 to 1/2 inch thick material. Number of beads required is determined by thickness of material.

Figure 36

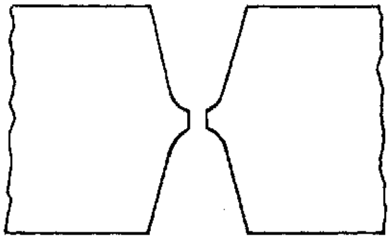


Single "U" joint. For material over about 1/2 inch thick.

Figure 37

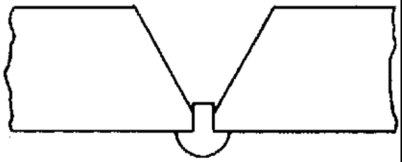


Double "V" joint. For material over about 1/2 inch thick.

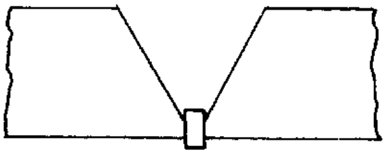


Double "U" joint. For material over about 1 inch thick.

Figure 38



"EB" Insert



Rectangular Insert

Typical Consumable Inserts

Figure 39

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, althought 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 not feasible to construct accurate jigs and fixtures, tack welds may suffice to hold the parts in proper alignment during welding. With light gauge sheet metal, small tack welds every inch or two are used. In heavier plate, the tack welds need not be spaced closely together, but each tack should be substantial.

Post/Weld Cleaning and Finishing

Welds and the surrounding area should be thoroughly cleaned to avoid impairment of corrosion resistance. Weld spatter, flux, or scale may become focal points for corrosive attack if not properly removed, especially in aggressive environments. Also, the residue from welding should be removed before heat treatment for stress relief or annealing. The discoloration by heat, or heat tint, is not necessarily harmful, but should be removed if the weldment is to serve a decorative purpose. This can be accomplished mechanically by using a mild abrasive cleaner, chemically with a phosphoric acid base cleaner, or electrochemically with commercially-available weld-cleaning kits.

WELD SPATTER

When welds are made using stick electrodes, some spatter is normal. However, it is easily removed by light grinding (aluminum oxide) or wire brushing. Spatter-resisting compounds applied before welding reduces this annoyance. Tightly adhering slag or scale is easily removed by light grinding or sandblasting. Cleaning time is reduced or eliminated when welding is done using the inert gas processes.

FLUX REMOVAL

Most welding flux or slag can be chipped off, but it is better to grind the flux off using *clean* grinding wheels. Sandblasting with clean silica sand is also an effective and economical way to remove slag. Where extreme corrosion resistance is required, sand blasting should be followed by brief immersion in a chemical cleaner, such as a solution of nitric acid. A most important aspect of cleaning stainless steel welds is to use stainless steel brushes and clean grinding wheels (wheels not contaminated with carbon steel particles). Contamination can cause rust staining and increased corrosion.

Table 22
Tensile Properties of Coated Electrode Deposits Minimum Requirements* and Typical Values

Minimum Requirements			Typical Values			
AWS-ASTM Classifica-tion	**Tensile Strength, psi**	**Elongation (in 2 in.), %**	**Tensile Strength, psi**	**Yield Strength, psi**	**Elongation (in 2 in.), %**	**Reduction of Area, %**
E308	80,000	35	80,000-90,000	50,000-60,000	35-50	40-60
E308L	75,000	35	80,000	53,000	48	63
E309	80,000	35	85,000-95,000	50,000-60,000	35-45	35-50
E309Cb	80,000	30	80,000	50,000	30	35
E309Mo	80,000	35	80,000	50,000	35	35
E310	80,000	30	85,000-95,000	50,000-60,000	35-45	35-50
E310Cb	80,000	25	80,000	50,000	25	30
E310Mo	80,000	30	80,000	50,000	30	30
E312	95,000	22	105,000-115,000	70,000-85,000	25-35	45-65
E16-8-2	80,000	35	92,000	64,000	38	–
E316	80,000	30	80,000-95,000	55,000-70,000	30-45	35-50
E316L	75,000	30	80,000-90,000	55,000-65,000	35-55	40-65
E317	80,000	30	–	–	–	–
E318	80,000	25	–	–	–	–
E330	75,000	25	80,000-90,000	45,000-60,000	30-40	40-50
E347	80,000	30	85,000-95,000	60,000-75,000	30-45	40-60

*Specifications: AWS A5.4 and ASTM A 298, as-deposited properties.

FINISHING WELDS

Stainless steels, in particular, Type 304 and similar analysis materials, are widely used in food, dairy, drug and processing equipment. To prevent bacterial growth, all fractures, cracks and crevices in the weld should be removed, and exposed surfaces be ground and polished to match the parent metal. If welds are made in prefinished stainless steel, the weld beads should be held to a minimum size to avoid excessive and expensive finishing costs. The chrome-nickel grades are more difficult to grind than the straight chromium grades, so weld metal deposits should be as flat as possible. Heat from grinding should be held to a minimum also to avoid distortion of thin gauge materials. If the grinding wheels or belts were used previously on carbon steel, chemical cleaning should follow to remove any iron particles that might have become imbedded in the stainless steel surface.

A technique of butt-welding polished sheets from the reverse or unpolished side has been successful. Sheets are first sheared from the back side so that any "shear drag" is on the polished side. Full penetration of the joint is achieved with a minimum of welding alloy penetrating the polished side. Relatively light grinding can then be used to prepare the weld on the polished side for final polishing and blending with the surrounding area.

The gas-tungsten-arc welding method allows a good welder to produce smooth uniform beads that are easy to grind, polish or finish. (Welds on surfaces that have mill-rolled finishes

Table 23
Charpy Impact Properties of Austenitic Stainless Steel Weld Metals Deposited from Coated Electrodes

Test No.	Type of Plate	Type of Electrode	Heat Treatment*	Charpy Impact (Keyhole Notch), ft-lb Room Temp
1	304	308	As welded	31-33
			Annealed	36-38
2	310	310	As welded	35-38
			Annealed	30-34
3	316	316	As welded	27-35
			Stress relieved	30-34
			Stabilized	26-30
			Annealed	32-36
4	316	316	As welded	31-32
			Stress relieved	25-27
			Stabilized	11-12
			Annealed	32-41
5	317	317	As welded	21-23
			Annealed	21
6	317	317	As welded	10-15
			Annealed	10-12
7	318	318	As welded	28
			Stress relieved	23-30
			Stabilized	21-22
			Annealed	30-33
8	318	318	As welded	15-23
			Stress relieved	17-22
			Stabilized	8-10
			Annealed	25-26
9	321	347	As welded	32
			Annealed	29-32
10	347	347	As welded	26-29
			Stress relieved	25-27
			Stabilized	22
			Annealed	24-26
11	347	347	As welded	27-33
			Stress relieved	24-27
			Stabilized	19-22
			Annealed	25-27
12	347	347†	As welded	25-28
			Annealed	28-31

* Heat treatments were as follows:
As welded.
Stress relieved 1200 ºF 2 hr.
Stabilized 1550 ºF 2 hr.
Annealed 1950 ºF ½ hr water quenched.

† Titania type coating. All other electrodes had lime type coating.

cannot be blended to match the surrounding base metal. Ground or polished finishes, however, can be matched by using the same grit and polishing techniques.)

Mechanical Properties

Data are available on the property values of weld metals and weldments, including welds by SMAW, GTAW, GMAW, SAW, and resistance welding methods. For purposes of comparison (not for design practice) some data are presented here. For additional information, the reader should consult appropriate specifications, stainless steel producers, and welding consumable (weld rod) suppliers.

Table 24
Tensile Properties of Austenitic Stainless Steel Weld Metals* (GMAW Process)

Type of Weld Metal	Postwelding Treatment[a]	Yield Strength (0.2% Offset), 1000 psi	Ultimate Tensile Strength, 1000 psi	Elongation, % in ...		Reduction of Area, %
				1 in.	2 in.	
308 ELC	None	46.7	80.6	51.0	39.2	61.2[b]
308	None	52.6	87.0	50.0	39.0	58.0
310	None	49.3	83.4	44.0	33.5	47.0
316	None	51.6	81.0	41.5	35.2	55.8
316	Stress relieved	46.0	80.1	42.0	34.8	55.3
316	Stabilized	41.2	79.1	44.5	34.5	52.4
316	Annealed	35.4	74.4	57.5	50.5	64.9
316	Annealed and sensitized	34.9	73.6	54.0	41.5	64.8
321	None	55.5	85.7	44.5	34.5	61.8
347	None	66.2	94.3	40.0	30.2	56.2

* Standard 0.252 in. diameter tensile test specimen, averages of duplicate tests.
[a] Stress relieved–1200 ºF–2 hr; stabilized 1550 ºF–2 hr–AC.
[b] Reduction of area calculated using measured minimum and maximum diameters because reduced section was oval.

Table 25
Tensile Properties of Austenitic Stainless Steel Weldments* (GMAW Process)

Type of Weld Metal	Postwelding Treatment[a]	Tensile Strength, 1000 psi	Elongation, % in ...		Location of Fracture
			1 in.	2 in.	
308 ELC	None	84.5	78.7	63.3	Weld
308	None	86.0	64.5	51.0	Plate
310	None	77.8	39.3	40.8	Plate
316	None	85.7	61.5	45.7	Weld and plate [b]
316	Stress relieved	87.1	50.0	37.5	Weld
316	Stabilized	85.8	50.0	38.0	Weld
316	Annealed	81.6	64.0	44.7	Weld
316	Annealed and sensitized	84.0	49.5	36.8	Weld and plate [b]
321	None	80.7	67.0	57.7	Plate
347	None	87.1	58.3	50.5	Weld and plate [b]

* ½ in. plate–Transverse Tensile Specimens.
[a] Stress relieved–1200 ºF–2 hr; stabilized 1550 ºF–2 hr–AC.
Annealed and sensitized: annealed plus 2 hr at 1200 ºF–AC.
[b] One specimen failed in weld metal, the other(s) in plate metal.

Table 26
Charpy Impact Properties of Austenitic Stainless Steel Weld Metal (GMAW Process)

Type of Weld Metal	Heat Treatment	Charpy Impact (Keyhole Notch), ft-lb*			
		+75F	–40 F	–100 F	–320 F
308 ELC	As welded	46.7	36.0	33.0	26.3
308	As welded	56.3	48.7	43.3	32
310	As welded	50.3	50.7	44.7	26.7
316	As welded	47.7	43.0	41.0	23.3
316	Stress relieved	42.7	35.2	–	–
316	Stabilized	30.8	26.7	19	9.3
316	Annealed	49.8	46.3	48	31
316	Annealed and Sensitized	54	49	45	32.3
321	As welded	39.7	29.8	27.2	18.7
347	As welded	34.5	28.5	21.8	16

* Average values are for three specimens at each test temperature.

It should not be assumed that the mechanical properties developed in the weld deposit made using one process can be indiscriminately applied to weldments made with a different welding process. Such factors as the chemical composition of the deposited metal as well as size and shape of the bead must be considered before transposing data from one process to another.

The filler metals that are used for welding austenitic stainless steels are listed in AWS Specifications. Table 22 lists the mechanical property requirements as well as typical values for coated electrodes, while Table 23 shows Charpy impact properties, in both as-welded and annealed conditions. Tensile properties of weldments and weld metals, deposited by the GMAW process, are listed in Tables 24 and 25, respectively, while Chancy impact properties of the weld metal appear in Table 26.

Table 27 gives base metal and weldment tensile properties for ¼ and ½ hard Types 301 and 304, with joints made by a single-pass GTAW process without filler metal in 0.03 to 0.062 inch material.

Data are also available on the mechanical properties of austenitic stainless steels when resistance welded (Table 28). However, before using the data it is important to understand the testing techniques used since there are important variations. As a general guide, Table 28 lists the potential shear strengths obtainable on the thicknesses indicated.

Table 28
Shear Strength of Spot Welded Austenitic Stainless Steels

Thickness of Thinnest Piece, in.	**Ultimate Tensile Strength of Metal**		
	70,000 up to 90000, psi	**90,000 up to 150,000, psi**	**150,000 and Higher, psi**
	Potential Shear Strength, lb		
0.006	60	70	85
0.008	100	130	145
0.010	150	170	210
0.012	185	210	250
0.014	240	250	320
0.016	280	300	380
0.018	320	360	470
0.021	370	470	500
0.025	500	600	680
0.031	680	800	930
0.034	800	920	1100
0.040	1000	1270	1400
0.044	1200	1450	1700
0.050	1450	1700	2000
0.056	1700	2000	2450
0.062	1950	2400	2900
0.070	2400	2800	3550
0.078	2700	3400	4000
0.094	3550	4200	5300
0.109	4200	5000	6400
0.125	5000	6000	7600

Table 27
Typical Tensile Properties of GTAW Weldments* in Cold Rolled Austenitic Stainless Steel Sheet

Base Metal (AISI Type)	**Condition**	**Gauge, in.**	**Type of Coupon**	**Yield Strength, psi**	**Tensile Strength, psi**	**Joint Strength Efficiency,[a] %**	**Elongation (in 2 in.), %**
301	¼ hard	0.0375	Base Metal	73,250	160,000		44.1
301	¼ hard	0.0375	Weldment	61,820	145,700	91.1 [b]	36.3
301	¼ hard	0.0625	Base Metal	70,600	134,000		57.4
301	¼ hard	0.0625	Weldment	59,880	131,000	97.8	57.4
301	½ hard	0.0375	Base Metal	121,800	184,150		26.6
301	½ hard	0.0375	Weldment	65,130	157,600	85.6	13.5
301	½ hard	0.0625	Base Metal	125,350	177,700		31.1
301	½ hard	0.0625	Weldment	67,540	149,660	84.2	13.7
304	¼ hard	0.0310	Base Metal	110,450	130,300		30.6
304	¼ hard	0.0310	Weldment	66,840	106,190	81.5	5.4
304	¼ hard	0.0420	Base Metal	108,500	131,700		34.9
304	¼ hard	0.0420	Weldment	71,930	107,730	81.8	4.5
304	½ hard	0.0580	Base Metal	132,150	152,250		21.1
304	½ hard	0.0580	Weldment	57,650	89,870	59.0	6.2
304	½ hard	0.0625	Base Metal	135,250	151,400		20.5
304	½ hard	0.0625	Weldment	59,520	92,810	61.3	5.5

* Gas tungsten arc welding, single pass without filler metal added; Strip tensile specimens ½ in. wide; 2 in. gauge length.

[a] Weldment Ulimate Strength x100 = Joint Efficiency, %.
Base Meal Ulimate Strength

[b] All failures of transverse weld coupons failed in base metal, hence the joint efficiency may be assumed to be 100%, for practical purposes.

Cutting Stainless

Naturally, before any joining method is attempted, the material, whether it is sheet, plate or bar stock, will have to be cut. However, such methods of cutting used for mild steel, - oxy-acetylene, oxy-propane, etc. - will not cut stainless steel.

Since stainless steel produces a tenacious slag when heated to the melting point, some means must be used in the flame to break up the slag. This can be done by adding a flux or metal powder to a flame cutting operation, or by ionizing a column of gas with an electric arc (called plasma).

IRON POWDER/FLAME CUTTING

Cutting stainless steel with a flame-fired torch using oxygen and propane in conjunction with iron powder, is clean and fast. Known as the powder jet, it cuts stainless steel up to 9 inches thick quickly and with a very smooth vertical cut. The iron powder is injected directly into the torch tip by the oxygen (similar to Flux/Flame cutting), which cuts material three inches thick at the rate of three inches per minute. The kerf or cut is quite narrow by normal standards, and the bottom of the cut is free of dross. It is being used to stack cut one half inch thick plates stacked six or more at one time. The equipment is readily portable (on wheels) so it can be used for hand cutting, or it can be mounted for automatic or semi-automatic operation.

PLASMA JET CUTTING

Another way to cut stainless steel, particularly the heavy gauge material,is with the plasma jet torch. Plasma torches can be hand held or automated depending on the job requirements. The cut is accomplished by the use of an ionized gas column in conjunction with an electric arc through a small orifice. The resulting gas produces extremely high temperatures (approximately 30,000ºF). When this high-temperature, high-speed plasma stream and electric arc strike the stainless steel, the heat rapidly melts the metal and the high velocity gas blows away the molten metal. The intensely concentrated heat in combination with the high-velocity gas produces a minimum heat-affected zone.

Soft Soldering

Sheet metal soldering today is practically a lost art and has been largely replaced by welding shops; the reason being, soldered joints have relatively low strength. However, soldering still does have some very important practical and economic applications, such as in architecture, food processing, and plumbing. Several applications are suggested in Figure 40.

Soft soldering is an easy method of joining two sections, or pieces, of metal at a low temperature. In the case of stainless . steel, or a dissimilar metal to stainless steel, such joints are used for sealing where strength is not a requirement but a water tight joint or good appearance is desirable.

Stainless steels generally have good solderability; however, some surface finishes and types of stainless are more difficult to flux or wet (tin) than others. Since all metals have a surface oxide as they come from the mill, good joining principles require its removal.

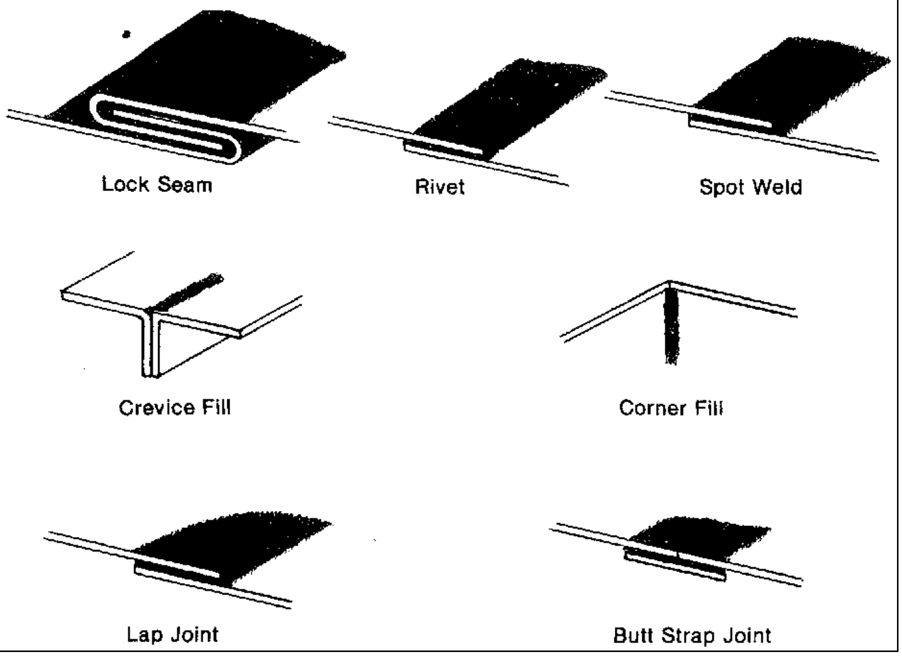
The most common annealed and pickled finishes (#1 or #2) or the polished surfaces (#3 or #4) are easier to flux and solder than the highly polished surfaces such as #7 or #8. Surface finishes that have been temper rolled after conventional annealing and pickling (#2 or #2B) will bond almost as easy as the pickled finishes.

Bright annealed finishes are difficult to solder.

The 300 Series stainless steels solder with relative ease, while the 400 Series types, especially those with high carbon content, are somewhat more difficult.

Also, the molybdenum-bearing stainless steels, such as Type 316, or those containing titanium, may be somewhat difficult.

Figure 40
Soldering Joint Designs



1. Sealing . . . To Provide a liquid- or gas-tight seal in a joint made strong by lock seaming, riveting or spot welding. (Ducts, gutters, roof decks)

2. Filling . . . To fill open crevices and round out corners for sanitary, corrosion resistance or appearance purposes. (Sinks, ornamental trim, baggage racks)

3. Making a low-strength joint . . . To make a lap joint where load carrying ability is not important. (Boxes, sign letters, mock-ups)

PROPER CLEANING A MUST

Cleaning any metal before any form of joining or fabrication is a must. Dirt, dust, grease, scale, finger prints, etc., should always be removed by either mechanical or chemical means. Stainless steel nearly always comes from the mill with a surface film. This film must be removed before fluxing or soldering. Oil or grease can be removed by commercial solvents or alcohol. Before fluxing, the area should be wiped with a cloth soaked with the cleaning agent, then wiped with a clean cloth. (Follow manufacturer's instructions and provide adequate ventilation.)

Where possible, tin. Tinning is the act of coating the metal with tin or solder. It is really spreading out a thin layer of fluxed metal so the following layer will provide a strong bond. After tinning, the solders flow easier and are more controllable. Tinning is accomplished by applying a coat of solder and quickly "wiping" the surface with a cloth or brushing it with a stainless steel wire brush. Tinning will help when using a soldering iron or a torch, because it reduces the amount of time needed to complete the job and it enhances strength and corrosion resistance.

SELECTION OF THE PROPER FLUX

The tenacious oxide film on the surface of stainless steel must be removed before soldering. This is done with an active flux. Commercial acid-type fluxes containing chlorides, such as hydrochloric acid or ammonium chloride, can be used, but with extreme care – and they should not be used if immediate and thorough neutralizing and flushing after soldering is not practical. Residual chloride-containing fluxes can and most often will cause pitting of stainless steel.

The preferred fluxes are those with a phosphoric acid base because the phosphoric acid is active only at soldering temperatures. To enhance the fluxing action, the surfaces to be tinned or soldered should be prepared by sanding with a fine emery cloth.

SELECTION OF THE PROPER SOLDER

Most solders have a melting point under 800ºF; however, this varies several hundred degrees when different combinations of alloys are used. For instance, a 50% tin, 50% lead combination will melt at 361ºF and flow at 421ºF; while a 62% tin, 38% lead will melt at 358ºF; and a 30% tin, 30% lead, 40% bismuth mixture will melt at 198ºF. However, stainless steel requires, in most cases, at least 50-50 and some prefer a 60-40 alloy, while others prefer 70-30 mix. If better color match is required, the higher the tin mix, the better the match. Table 29 suggests soft solders for stainless steel industrial sheet metal work.

As for soldering technique, what applies to other metals also applies to stainless steel, except consideration for the low heat conductivity of stainless steels. This requires a slightly shorter period of heat application to bring the metal up to the temperature at which the solder will flow properly.

CLEANING AFTER SOLDERING

All corrosive flux, vapor and flux residue left on stainless after it is soldered must be removed to preserve its corrosion resistance.

Strong acid-chloride type fluxes may attack and pit stainless steels if left on the work, as well as mar the stainless finish. Remove spilled fluxes immediately by flushing with water.

Vapors from the flux also are corrosive and may settle on cold surfaces some distance from the joint. Thus, any areas exposed to flux vapors should be cleaned thoroughly after soldering. There are several ways of removing traces of corrosive flux and flux residue.

A. *Cleaning Method #*1. (*Use of Neutralizer*)

For field jobs or for shop work where every part cannot be inspected, this method is the safest to insure a corrosion-free joint.

First, wet the work with water, then scrub with a soft bristle brush. Be sure to scrub first with plain water and not with neutralizing solution. If the neutralizing solution is used first, the flux residue may become insoluble in water and much harder to remove.

To neutralize any remaining harmful flux residue, wash the work in a 5% neutralizing solution, rinse with running water and wipe dry. The neutralizing solution can be made up by adding about 3/4 cup (6 ounces) of sodium carbonate (washing soda) or sodium bicarbonate (baking soda) to 1 gallon of water. Also,aqua ammonia can be used.

B. *Cleaning Method #2. (Use of* Water Only)

This method can be used if visual inspection is possible. First wet the work down with fresh water, and scrub hard with a soft bristle brush. Then use plenty of clean water to remove all traces of the flux residue, and dry with a clean cloth.

C. Cleaning Method #3. (Use of Weak Acid Cleaning Solution)

This method is used for shop production work, or for production tinning, but it must be carefully followed to insure complete flux residue removal.

First, the tinned or soldered parts are placed in a solution of hot water and 5% phosphoric acid to make the flux residue soluble in water. After standing for five minutes in this solution, which is agitated, the parts should be thoroughly rinsed in water and wiped dry.

The cleaning solution can be made up by adding about 1/2 cup (4 fluid ounces) of commercial 85% phosphoric acid to one gallon of water. Brand-name cleaning solutions can also be used.

A 2% hydrochloric acid solution is sometimes used for cleaning soldered work, but is not recommended for stainless steel. Hydrochloric acid is strongly corrosive, and if the solution is not removed completely and immediately, it may attack stainless steel.

Brazing

Brazing is a method of joining stainless steels to themselves or to dissimilar metals using a non-ferrous filler wire, powder or thin-shim form of alloy that has a melting point above 800ºF, but below the melting point of the base metal. Silver-brazing alloys are available in many different analyses but, in the case of stainless steel, most contain at least 40% silver. Usually a 45% silver gives good results since it has excellent capillary flow and adheres to most stainless steels easily. The alloys range in melting point from 1145ºF to 1300ºF and are extremely fluid. Nickel-base brazing alloys are also used with melting points up to 2100-2125ºF These permit the use of brazed stainless steel components at considerably higher temperatures than with the lower-temperature silver-brazing alloys.

Table 29

Soft Solders for Stainless Steel Industrial Sheet Metal Work

Common Name	Nominal Composition (Percent)				Short-Time Bulk Solder Strength		Density	Melting Range		Max. Service Temp. (°F)	Color Match To Stainless Steel	Use	Comments
	Tin (Sn)	Lead (Pb)	Antimony (Sb)	Silver (Ag)	Tensile (psi)	Shear (psi)	(lb/cu in)	Melts (°F)	Flows (°F)				
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. Nontoxic. 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. Nontoxic. 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. Nontoxic. 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.

The advantages of brazing include the ability to produce strong corrosion-resistant, leak-tight joints on small parts or thin metals with minimum warpage or buckling so long as the proper technique is used. Also, brazing lends itself to mass production of small or moderate sized parts on various types of continuous heating or assembling equipment.

Most stainless steels can be brazed, however, to obtain a satisfactory braze with some types, extra precaution must be taken with heating and cooling. For example, austenitic stainless steels are susceptible to carbide precipitation at brazing temperatures, so the extra-low carbon or the stabilized types should be used.

The martensitic stainless steels are subject to hardening when brazed in the annealed condition and will lose their hardness if brazed in the hardened condition. The ferritic types are not affected by most brazing operations unless a high-temperature brazing filler metal is used, which will result in a loss of toughness.

All stainless finishes can be brazed, providing they have been cleaned free of all surface contamination and flux has been properly applied. With bright annealed surfaces, it is helpful to abrade the surface lightly to secure better bonding.

HEATING METHODS

The heating methods used in brazing are torch (oxy-acetylene), furnace, or resistance. The specific combination of heat source and equipment depends on the type of materials to be joined, number of parts to be brazed, size of parts and available equipment in the plant.

A. *Torch Heating* is a general-purpose method using an oxy-acetylene flame or some other gas-air mixture for heat. This method can be used on small lots of material to be brazed with little set-up or cost involved. Production setups involving repetitive work can be arranged by moving the work pieces, with preplaced brazing metal preforms and flux, past a torch or series or torches. Torch brazing is also useful in joining unlike thicknesses or dissimilar metals in that the flame can be maneuvered as required to bring the two pieces to the brazing temperature at the same time.

B. *Furnace Heating* is probably the most common heating method used for stainless steel parts. It can be used in continuous operation or batch-type operation. The work is preassembled with preforms and flux in place, then put in the furnace for brazing. Batch-type furnaces for brazing stainless steels include the box-type with in-and-out retorts or built-in muffles, and the pit, bell, bell car, elevator and car types with retorts.

Continuous furnaces are generally of the hump mesh-belt conveyor type with a muffle. These furnaces can braze light-weight stainless assemblies continuously with uniform time and temperature.

For furnace brazing, atmospheres must be capable of preventing oxide formation, and gases must be of high purity and low dew point. Gases commonly used are hydrogen and dissociated ammonia with a dew point of about - 60ºF Argon and helium are used in some applications in connection with vacuum brazing.

Several methods of heating the brazing furnace can be used. These include electrical resistance, direct combustion, forced air circulation and radiant tube.

C. Induction Heating is well suited for brazing stainless. The heating coils can be fashioned to the shape of the preformed sections which limits the heating to the areas to be brazed. The temperature can be closely controlled and brought up so rapidly, that there is little chance of carbide precipitation or excessive surface oxidation.

D. *Resistance Heating* for brazing is similar to spot welding. Parts to be brazed are fluxed and assembled with preforms, then clamped between the electrodes. The current is then passed through the assembly to fuse the brazing filler metal.

Heating by dipping in molten filler metal or molten salt is sometimes used on stainless.

JOINT DESIGN

Service requirements for brazed joints generally break down into several categories: mechanical strength, pressure tightness, corrosion resistance, resistance to thermal shock and electric conductivity. While all joints require the proper clearances for good brazing, the type of joint selected will partially depend on which one or more of the service requirements it must meet.

In the design of brazed joints, the clearance between the sections to be brazed is critical. It is this clearance that allows the molten brazing filler metal to flow between the sections by capillary action. The clearance must be small, 0.001 to 0.003 inch is preferred for the best flow of the alloy and the strongest joint. If the clearance is too large, it is possible to get voids or shrinkage cavities in the filler metal which weakens the joint. If clearance is too small, incomplete wetting will occur and this will also weaken the joint.

The two basic types of joints are the lap and butt. There are several modifications of each for the type of part being joined. The lap joint gives greater strength than the butt joint because the bonding area is larger. In many instances, flat surfaces need little preparation and are self-supporting with only light pressure required to hold uniform joint clearance. The main objection to the lap joint is the double thickness of the joint.

The butt joint has the advantage of single thickness, which may be important in many applications. However, the butt joint has a smaller bonding area than the lap joint and therefore will not meet the same strength requirements. Butt joints are simple to prepare and have adequate strength for many applications.

Two other joints that are sometimes used for single thickness and strength are the butt-lap and the scarf. While preparation of these joints takes more time, they may be worth the extra effort for some applications.

PRECLEANING

The contacting surfaces of brazed joints must be adequately cleaned and free of oil, dirt and oxides before brazing. It is general practice to degrease before assembling, using trichlorethylene or other degreasers, caustic washing with a good rinse, or anodic cleaning. If the parts are drawn before brazing, care should be taken in the selection of lubricants or drawing compounds to be sure they do not contain undesirable constituents, particularly sulfur or lead. These elements could ultimately hinder the wetting and flow characteristics of the brazing alloy.

When brazing the free-machining grades of stainless steels, the surface may become coated with a black film during heating and fluxing. This film is caused by sulfur, selenium, lead or other elements added for machinability. Unless this film is eliminated, the joint will not bond properly. Pre-pickling of the parts to be brazed in a 20% nitric acide solution will remove the surface inclusions which cause the film.

SELECTION OF BRAZING FILLER METAL

Brazing filler metals for stainless steel are available with melting points ranging from 1100 to 2200ºF. The most widely used filler metals are the silver-base alloys containing various amounts of other elements. These are commonly referred to as "silver solder" or "hard solder" and are used in the range from 1150 to 1800ºF. The filler metals used above 1800ºF are sometimes called high-temperature brazing alloys and are generally nickel-base alloys. Tables 30 and 31 give classification and composition of some brazing alloys.

The service temperature at which the joint will be used will affect the choice of the filler metal. The strength of the silver-soldered joint will fall off rather rapidly after service temperature reaches about 500ºF and for many types of filler metal, this is about the maximum temperature. The high-temperature filler metals can be used at higher service temperature.

The filler metal must have the corrosion resistance to stand up to corrosive media in many applications. Most of the filler metals contain elements having high corrosion resistance and since only a small area is exposed, corrosion of the joint should be no problem in the 300 Series.

Brazed joints on the 400 Series types are susceptible to interface corrosion in plain water or in moist conditions if the joints are made using a nickel-free filler metal and flux. Filler metal containing nickel will help prevent this; however, for complete protection, special brazing alloys should be used or the brazing should be done in a protective atmosphere without flux.

When appearance is important, the color of the brazing alloy must match the stainless. Most brazing alloys do not match very well due to the tendency to have a copper color; however, with some experimentation with the different alloys, a fairly good match can be obtained. The choice of joints may also help eliminate the matching problem. If the right joint type is used, there should only be a small line to blend.

BRAZING FLUX

Brazing flux is necessary to prevent the metals from oxidizing during the brazing operation. Most metals exposed to air oxidize, which increases when they are heated. The liquid flux covers the metal surface completely and shields it from the air. Even if oxides start to form, the flux will combine with them and dissolve them. If a flux is not used, these oxides will contaminate the metal surface and prevent the capillary action from distributing the filler alloy uniformly through the joint.

The flux should be fully liquid and active at a temperature below the flow point of the filler alloy. This quality enables it to dissolve all oxides before the filler alloy is applied. This thin, active flux is readily displaced by the molten filler alloy and permits the filler alloy to bond to the clean metal surface.

Brazing fluxes are available in paste, powder and liquid form from various supply houses. The paste form is most common and is applied by brush or other means. The fluxes have varying melting temperatures. When they are chosen so that they liquify just below the melting point of the filler alloy, they act as temperature indicators for the correct brazing temperature.

POSTCLEANING

The corrosive flux residue from the brazing operations must be completely removed from the joint immediately after brazing. This can be done by scrubbing with hot water, chemical cleaning, mechanical cleaning or a combination of these. A chemical cleaner or some abrasive method may be required to remove the oxides in the heat-affected area. If the flux used contains fluoride or chloride compounds, it might be advisable to use a neutralizing solution to insure that the joint will be free of corrosion.

Postcleaning is not necessary on joints which have been furnace brazed in a protective atmosphere with no flux.

Table 30
Silver-Base Brazing Alloys
AWS A5.8-62T and ASTM B260-62T

ASTM AWS Classi-fication	Ag	Cu	Zn	Cd	Ni	Sn	Li	Melting Tempera-ture, ºF	Brazing Temperature Range, ºF	Color	Characteristics
BAg1	45	15	16	24	–	–	–	1145	1145-1400	Whitish yellow	Free-flowing
BAg1a	50	15.5	16.5	18	–	–	–	1175	1175-1400	Whitish yellow	Free-flowing
BAg2	35	26	21	18	–	–	–	1295	1295-1550	Light yellow	Good for nonuniform clearance
BAg3	50	15.5	15.5	16	3.0	–	–	1270	1270-1500	Whitish yellow	Retards corrosion at joint
BAg4	40	30	28	–	2.0	–	–	1435	1435-1650	Light yellow	Flows better than BAg3
BAg5	45	30	25	–	–	–	–	1370	1370-1550	Light yellow	Not free-flowing, cadmium-free, useful in food industry
BAg6	50	34	16	–	–	–	–	1425	1425-1600	Light yellow	Similar to BAg5
BAg7	56	22	17	–	–	5	–	1205	1205-1400	White	Good color for stainless
BAg8	72	bal.	–	–	–	–	–	1435	1435-1650	White	Wetting on stainless is slow
BAg8a	72	bal.	–	–	–	–	0.25	1410	1410-1600	White	For furnace brazing PH stainless
BAg13	54	bal.	5	–	1	–	–	1575	1575-1775	White	Useful to 700 ºF
BAg18	60	bal.	–	–	–	10	–	1325	1325-1550	White	Wets stainless well, for brazing PH stainless
BAg19	92.5	bal.	–	–	–	–	0.25	1635	1610-1800	White	Good for furnace brazing

Table 31
Typical High-Temperature Brazing Alloys
AWS A5.8-62T and ASTM B260-62T

ASTM AWS Classi-fication	Nominal Composition, %							Melting Tempera-ture, º F	Brazing Temperature Range, ºF
	Ni	Si	B	Cr	Fe	Au	Ag		
BNi1	bal.	4	3.4	14	4.5	–	–	1900	1950-2200
BNi2	bal.	4.5	3.1	7	3	–	–	1830	1850-2150
BNi3	bal.	4.5	3.1	–	1.5	–	–	1900	1850-2150
BNi4	bal.	3.5	1.6	–	1.5	–	–	1950	1850-2150
BNi5	bal.	10.1	–	19	–	–	–	2075	2100-2200
BAu1	–	–		–	–	37	63	1860	1860-2000
BAu2	–	–	–	–		80	20	1635	1635-1850
BAu3	3	–	–	–	–	35	62	1885	1885-1995
BAu4	18	–	–	–	–	82	–	1740	1740-1840