

**A DESIGNERS'
HANDBOOK SERIES
N° 9002**

WELDING OF STAINLESS STEELS AND OTHER JOINING METHODS

NiDI

Distributed by
NICKEL
DEVELOPMENT
INSTITUTE



Produced by
AMERICAN IRON
AND STEEL
INSTITUTE

Much of the information in this handbook was presented at a symposium sponsored by the Committee of Stainless Steel Producers, American Iron and Steel Institute, 1133 15th Street, NW, Washington, DC 20005, U.S.A., in co-operation with ASM International (formerly American Society of Metals), Metals Park, OH 44073, U.S.A.

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.

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

The Nickel Development Institute reprinted it for distribution in August 1988.

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.

The Nickel Development Institute and American Iron and Steel Institute, their members, staff and consultants do not represent or warrant the material's suitability for any general or specific use and assume no liability or responsibility of any kind in connection with the information herein.

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

INTRODUCTION	2		
STAINLESS STEEL WELDING CHARACTERISTICS	4		
Austenitic Stainless Steels	4		
Preservation of Corrosion Resistance	6		
Carbide Precipitation	6		
Stress-Corrosion Cracking	7		
Prevention of Cracking	7		
Welding Procedures	9		
Martensitic Stainless Steels	9		
Welding Procedures	10		
Ferritic Stainless Steels	11		
Preservation of Corrosion Resistance	11		
Welding Procedures	11		
Precipitation Hardening Stainless Steels	11		
Influence of Elements in Weld Environment	12		
Oxygen	12		
Carbon	12		
Nitrogen	12		
Hydrogen	12		
Copper or Lead	12		
Influence of Alloying Elements on Weldability	12		
Influence of Alloying Elements on Weld Structure ..	12		
Weld Rod Selection	13		
Austenitic Stainless Steels	13		
Martensitic Stainless Steels	13		
Ferritic Stainless Steels	13		
Precipitation Hardening Stainless Steels	13		
WELDING PROCESSES FOR STAINLESS STEELS ..	15		
Fusion Welding	15		
Shielded Metal Arc Welding	15		
SMAW Electrodes	15		
Gas Tungsten Arc Welding	16		
Filler Rod Selection	18		
GTAW Equipment	18		
Gas Metal Arc Welding	18		
Spray Arc Welding	18		
Short Circuiting Type Transfer	19		
Pulsed Arc Welding	20		
Welding Wires	20		
Minimizing Hot Cracking	21		
Summary	21		
Submerged Arc Welding	21		
Description of Equipment	22		
Strip Electrodes	22		
Plasma-Arc Welding	22		
Circumferential Pipe Welding	23		
Plasma-Arc Welding Equipment	23		
Gases	23		
Low-Current Plasma-Arc Welding	24		
Electron Beam Welding	24		
Equipment	24		
Laser Welding	25		
Resistance Welding	26		
Spot Welding	26		
Electrodes	28		
Precautions	28		
Seam Welding	28		
Projection Welding	28		
Butt Welding Process	30		
Flash Welding	30		
Upset Welding	31		
High Frequency Resistance Welding	32		
Percussion Welding	32		
Conclusion	32		
Friction Welding	32		
Electroslag Welding	32		
STAINLESS STEEL PIPE WELDING	32		
Backing Rings	33		
WELD OVERLAYS	33		
Welding Electrodes	33		
WELDING OF STAINLESS STEEL-CLAD PLATE	33		
WELDING DISSIMILAR METALS	35		
Austenitic Stainless Steels to Low Carbon Steels	35		
Procedures for Welding Transition Joints	36		
Ferritic and Martensitic Stainless Steels to			
Carbon or Low-Alloy Steels	36		
USE OF CHILL BARS	37		
JOINT DESIGN	37		
Preparation	38		
POST WELD CLEANING AND FINISHING	38		
Weld Spatter	38		
Flux Removal	38		
Finishing Welds	39		
MECHANICAL PROPERTIES	40		
CUTTING STAINLESS STEEL	42		
Iron Powder/Flame Cutting	42		
Plasma Jet Cutting	42		
SOFT SOLDERING	42		
Proper Cleaning a Must	43		
Selection of the Proper Flux	43		
Selection of the Proper Solder	43		
Cleaning After Soldering	43		
BRAZING	43		
Heating Methods	45		
Joint Design	45		
Precleaning	45		
Selection of Brazing Filler Metal	46		
Brazing Flux	46		
Postcleaning	46		

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

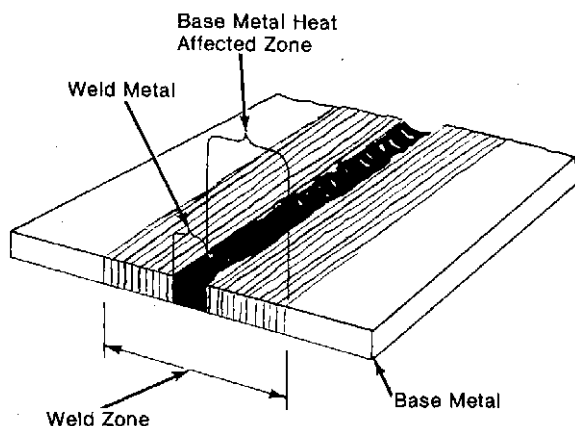


Figure 1
Thermal Affected Area of Metal Due to Welding

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.

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) (Microhm-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)						
AISI Type (UNS)	C	Mn	P	S	Si	Cr	Ni	Mo	Other	Tensile Strength		Yield Strength (0.2% offset)		Elon- gation in 2" (50.80 mm)	Hard- ness (Rock- well)	Prod- uct Form
										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.

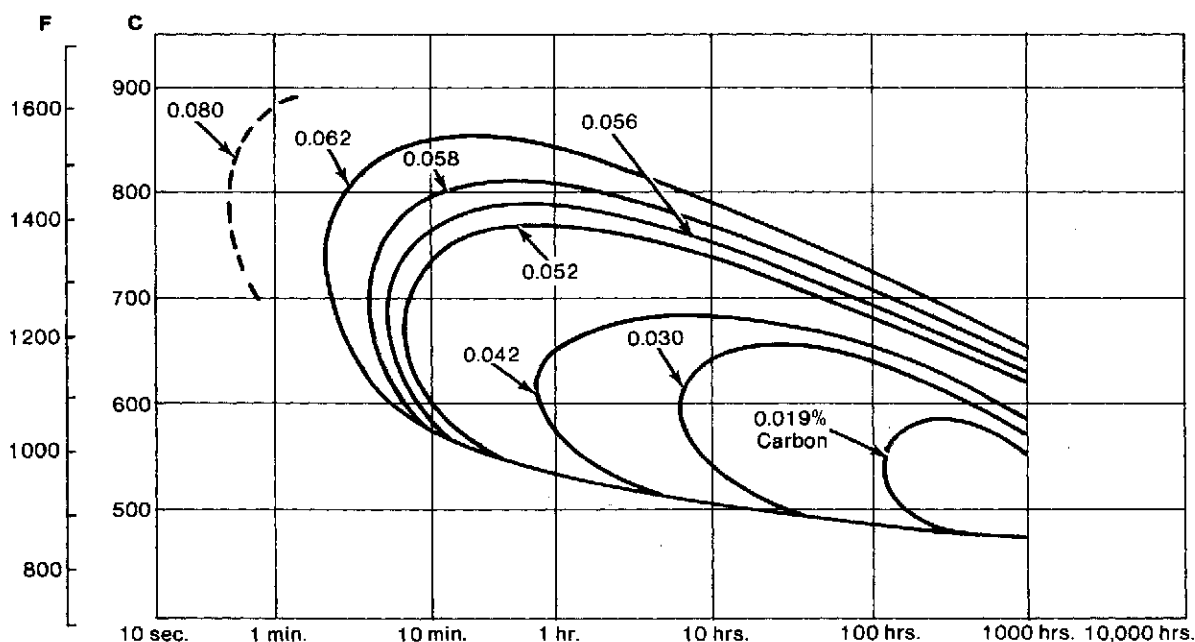
Carbide Precipitation - A characteristic of an annealed austenitic stainless steel, such as Type 304 is its susceptibility to an important microstructural change if it is exposed to temperatures within an approximate range of 800-1650°F. Within this range, chromium and carbon form chromium carbides, 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 800-1650°F is one factor. Chromium carbides form most rapidly at about 1200°F, 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 2150°F) (above the sensitizing range) followed by rapid cooling. Stress relieving a weldment at 1500-1700°F 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							
	302	17.0/19.0	8.0/10.0	X			X			X
	301	16.0/18.0	6.0/ 8.0	X			X			X
	305	17.0/19.0	10.5/13.0		Note 1			Usually X	X	
	308	19.0/21.0	10.0/12.0		X			Same	X	
	316	16.0/18.0	10.0/14.0							
	317	18.0/20.0	11.0/15.0							
	309	22.0/24.0	12.0/15.0							
	309S	22.0/24.0	12.0/15.0		X		X		Note 1	
	310	24.0/26.0	19.0/22.0	X			X		Note 1	
Extra Low Carbon Compositions	314	23.0/26.0	19.0/22.0	X			X		Note 1	
	304 L	18.0/20.0	8.0/12.0			Note 4		X	X	
	316 L	16.0/18.0	10.0/14.0			Note 4		X	X	
Stabilized Compositions	347	17.0/19.0	9.0/13.0			Note 2				
	321	17.0/19.0	9.0/12.0			Note 2				
	309 C	22.0/24.0	12.0/15.0			Note 2				
	318	17.0/19.0	13.0/15.0			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

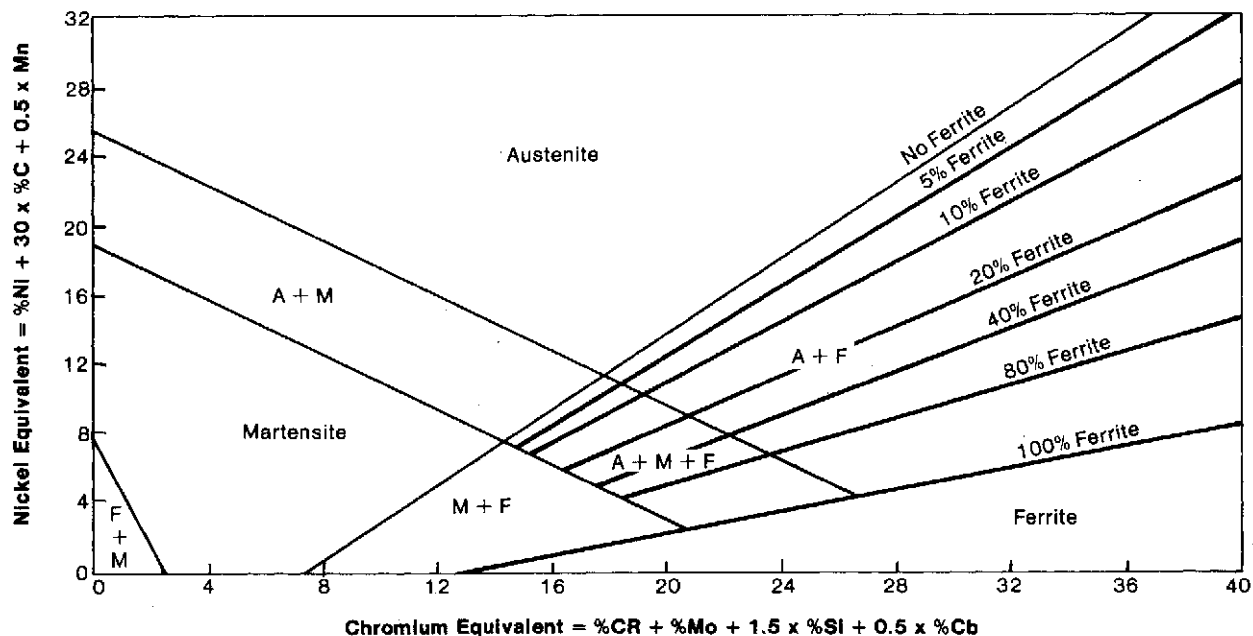
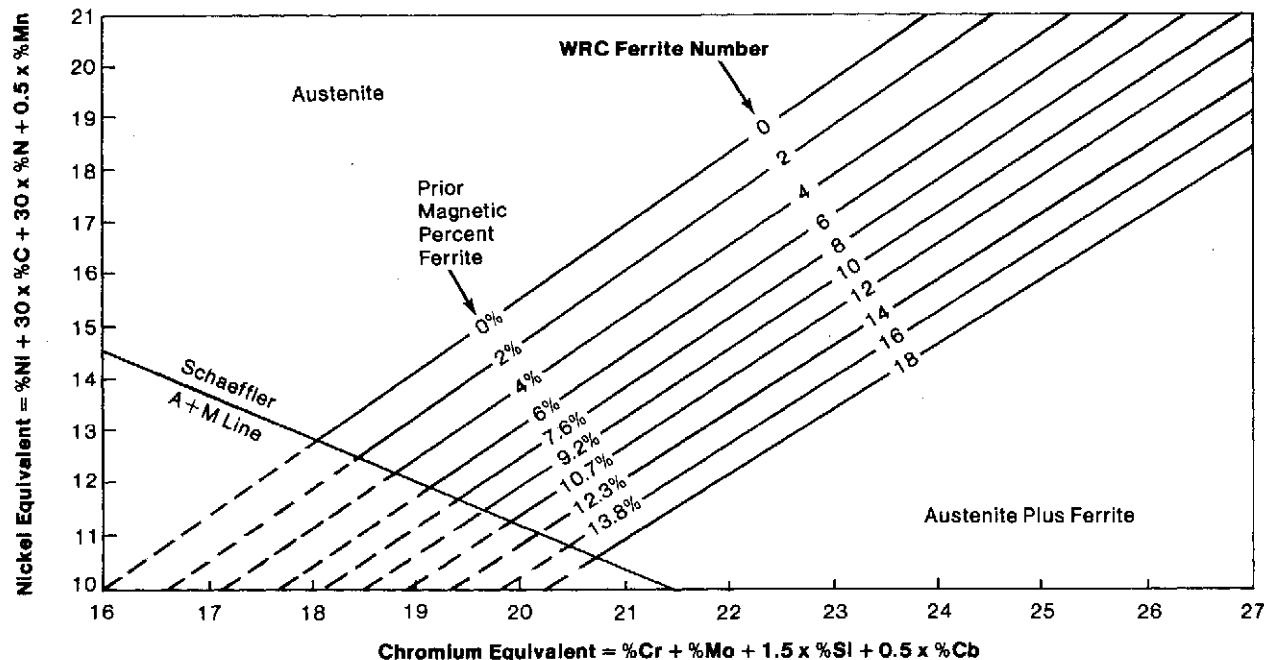


Figure 4
DeLong Constitution Diagram for Stainless Steel Weld Metal



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 $30 \times \%N$ 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 or the 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)							
AISI Type (UNS)	C	Mn	P	S	Si	Cr	Ni	Mo	Other	Tensile Strength		Yield Strength (0.2 % offset)		Elong- ation in 2" (50.80 mm)	Hard- ness (Rock- well)	Prod- uct Form	
										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 2700°F, which compares with 2800°F 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 1500°F, the metallurgical structure begins to change to austenite; at approximately 1850°F the structure is completely austenitic. Cooling from these temperatures results in the transformation of austenite to martensite, a hard, strong, nonductile structure. Rapid cooling from 1850°F results in maximum martensite content. Cooling from temperatures between 1500-1850°F 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 1500-1850°F). 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 600°F. 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 500°F, weld, and cool slowly.
- 0.20 to 0.50%C* – Preheat to 500°F, weld, and heat treat after welding.
- Over 0.50%C* – Preheat to 500°F, 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 1500°F or higher followed by controlled cooling to 1100°F at a rate of 50 degrees per hour and then air cooling.
- 2) Heat to 1350-1400°F 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 MPa	Yield Strength (0.2% offset) ksi 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 700°F. may cause intergranular precipitation (similar to carbide precipitation in austenitic 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 1450°F. 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 1100°F, followed by rapid cooling. Slow cooling through a temperature range of 1050°F down to 750°F 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 jiggling, 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 300-450°F 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)						
AISI Type (UNS)	C	Mn	P	S	Si	Cr	Ni	Mo	Other	Tensile Strength		Yield Strength (0.2% offset)		Elongation in 2" (50.80 mm)	Hardness (Rock well)	Product Form
										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	B99	



Documents

Document Sharing Hub

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 page 15) 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	As-welded or fully	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.
202	annealed		
301	As-welded or fully	308	
302	annealed		
304			
305			
308			
302B	As-welded	309	
304L	As-welded or stress-relieved	347	
		308L	
303	As-welded or fully	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.
303Se	annealed		
309	As-welded	309	
309S			
310	As-welded	309	
310S		310	
		316	
316	As-welded or fully	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 1950-2050°F. (2) For Types 316L and (317L) base metal, 1600°F stress-relief. (3) For 316-Cb base metal, 1600-1650°F stabilizing treatment.
	annealed		
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	317	Where postweld heat treatment is not possible, other filler metals may be specially selected to meet the requirements of the application for corrosion resistance.
	annealed		
317L	As-welded or stress-relieved	317-Cb	
321	As-welded or after stablizing and stress-relieving heat treatment	321	
		347	
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	Annealing improves ductility of base metal heat-affected zones and weld metal. Type 405 weld metal contains columbium rather than aluminum to reduce hardening.
		430	
	As-welded	309	
		310	
		410-NiMo	
430	Annealed	430	Annwelding 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	308	
		309	
		310	
		430	
430F	Annealed	430	Remarks on Type 430 base metal apply.
430F Se	As-welded	308	
		309	
		312	
		446	
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	
		310	
Martensitic Stainless Steels			
403	Annealed or hardened	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.
410	and stress-relieved		
	As-welded	309	
		310	
		410-NiMo	
416	Annealed or hardened	410	These austenitic weld metals are soft and ductile in as-welded condition. However, base metal heat-affected zone will have limited ductility.
416 Se	and stress-relieved		
	As-welded	308	
		309	
		312	
420	Annealed or hardened	420	Requires careful preheating and postweld heat treatment to avoid cracking.
	and stress-relieved		
431	Annealed or hardened	410	
	and stress-relieved		
	As-welded	308	
		309	Requires careful preheating. Service in as-welded condition requires consideration of hardened weld heat-affected zones.
		310	

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

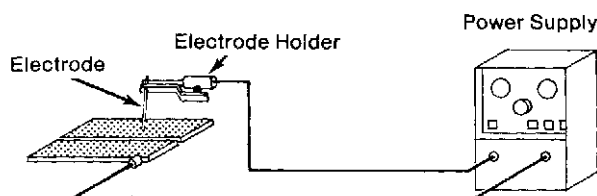
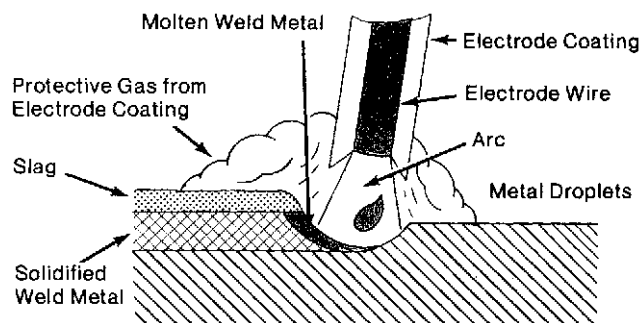


Figure 5
Arc Zone in Shielded Metal Arc Welding

the end of the rod, the operator moves the electrode closer to the work as well as moving it along the joint.

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 atmosphere. (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