

Module 22

WELDING METALLURGY OF STAINLESS STEELS

**PART OF THE CERTIFICATE PROGRAM IN
WELDING METALLURGY**



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MODULE 22

**WELDING METALLURGY
OF
STAINLESS STEELS****CONTENTS**

Introduction and objectives	1
Effect of chromium	2
Effect of nickel	4
Basic structures of stainless steels	6
Austenitic grades	8
Martensitic grades	8
Ferritic stainless steels	10
Duplex stainless steels	11
Potential welding problems	18
Sensitization	18
Stress corrosion cracking	21
Weld metal solidification cracking	22
Weld metal structure	25
Schaeffler diagram	26
DeLong diagram	27
WRC diagram	28
Estimating weld metal composition	30
Welding austenitic stainless steels	34
Selecting the electrode	34
Weld properties	35
High temperature strength	36
Welding martensitic stainless steels	37
Welding ferritic stainless steels	40
Welding duplex stainless steels	42
Welding precipitation hardening stainless steels	44
Procedures for welding stainless steel	45
Shielding	45
Joint preparation	48
Welding clad steel	51
Summary	54
Additional resources	55
Guides and exercises	57

MODULE 22

WELDING METALLURGY OF STAINLESS STEELS

Introduction

The majority of stainless steels can be readily welded; but only if the correct consumables and procedures are used. The special properties of stainless steels allow them to be used in aggressive environments, corrosive media, at very high or very low temperatures, and the consequences of incorrect procedures or filler metal can be serious. Rapid corrosive attack, cracking or premature failure are all possible. Yet most mistakes would be easily avoided if a few simple guiding principles were followed. The welding engineer, responsible for specifying welding procedures, must have a sound understanding of the metallurgy involved in welding stainless steels, and it is the objective of this module to provide this. It is not the intent to give a recipe or recommendations for specific cases—the engineer must study each case thoroughly before selecting a procedure—but rather to describe the underlying principles involved.

We will start by discussing the effects of chromium and nickel, the two most important elements in stainless steels; then describe the main classes and properties of stainless steels; discuss problems arising in welding; examine what determines the weld metal structure and explore the practical aspects of welding procedures for stainless steels.

Objectives

After successfully completing this module you will be able to:

- Explain the role of various alloying elements in stainless steels
- List the major groups of stainless steels and their properties
- Explain the major problems in welding stainless steels and how to overcome them
- Select welding procedures for stainless steels

Welding Metallurgy of Stainless Steels

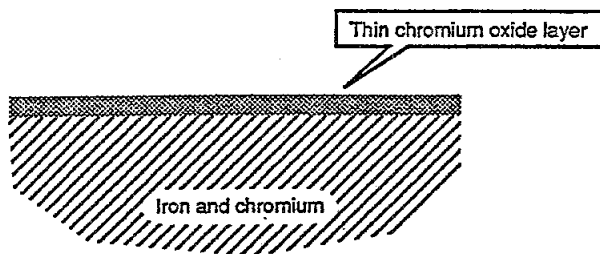


Figure 1. A thin layer of chromium oxide is the origin of the corrosion resistance of stainless steels.

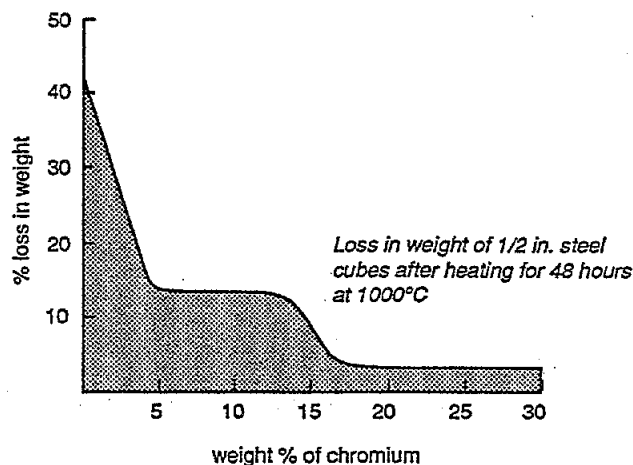


Figure 2. The oxidation resistance increases markedly with increasing chromium content.

Stainless steels

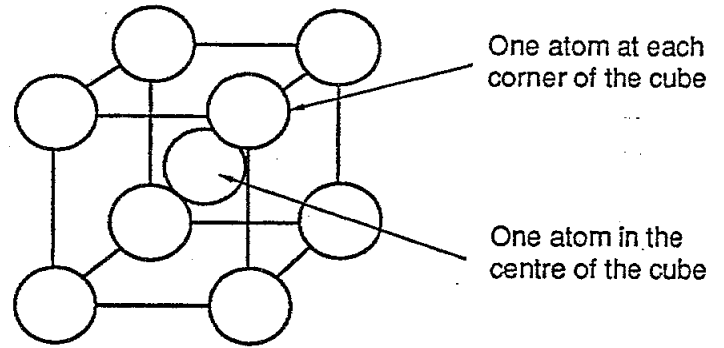
Stainless steels acquire their special stainless properties from the presence of the element chromium. We could, in fact, define stainless steels as simply those steels containing more than 10% chromium. Stainless properties allow these steels to be used for a wide range of applications including chemical plant, high temperature exposure, cutlery, food processing equipment, and many others. They are not, however, stainless under all conditions and some environments can cause corrosive attack.

Effect of chromium

Chromium provides these special properties by forming a thin, tight, impervious layer of oxide on the surface of the metal which protects it from the environment. Fig. 1 illustrates this schematically. The oxide forms very rapidly and if the metal is scratched, breaking the film, it quickly reforms. We call the film a passive oxide layer since it passivates the metal, i.e., makes it inert to corrosive attack. Should the oxide layer be removed, passivity is lost and the steel would immediately lose its stainless qualities. This can happen under certain conditions such as exposure to hydrochloric acid or intermediate concentrations of sulphuric acid. Fig. 2 shows the effect of increasing the level of chromium in the steel on the weight loss of heated specimens due to oxidation. For chromium contents above 10% the oxidation resistance increases rapidly.

In addition to corrosion resistance, stainless steels may have many other desirable properties making them useful for other applications. Some have excellent low temperature toughness rendering them suitable for cryogenic tanks, i.e., tanks containing low temperature liquids such as liquid natural gas (LNG). To understand the properties of these steels we must first appreciate the role of chromium and nickel, the two most important alloying elements in the metallurgy of stainless steels.

Figure 3. The bcc structure of chromium. The closest atomic spacing is 2.498 Å, similar to that of bcc iron (2.481 Å) and chromium has complete solubility in the bcc form of iron.



Body-centred cubic structure (bcc)

Iron-chromium phase diagram

Chromium is a metal having a body-centred cubic structure (Fig. 3) and when dissolved in iron it tends to stabilize the bcc structure (ferrite) of the iron. We can see this in the iron-chromium phase diagram shown in Fig. 4. The region in which fcc (γ -gamma phase) austenite is stable forms a closed loop and above about 14% chromium austenite cannot form at all. An iron-chromium alloy of more than 14% is ferritic (alpha phase) over the complete temperature range up to the melting point. The phase diagram shows an additional phase known as sigma, stable at temperatures below 800°C when chromium is in the range of about 30-60%. The sigma phase only forms after prolonged heating.

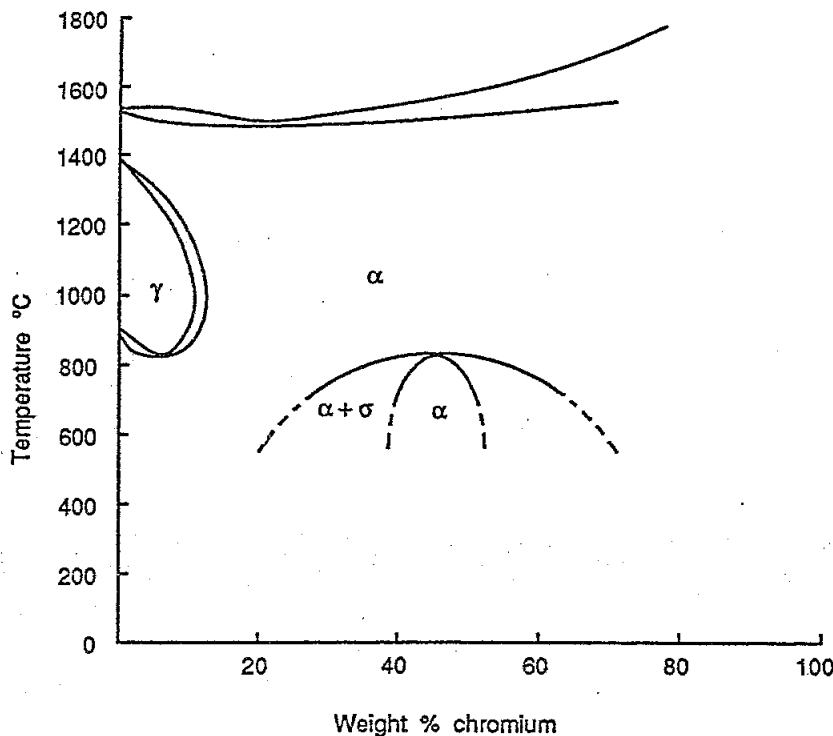


Figure 4. Phase diagram for iron and chromium. Note the closed gamma (γ) loop up to about 14% chromium. The sigma (σ) phase only appears after prolonged heating.

The iron-chromium phase diagram in Fig. 4 assumes that no other elements are present which is not the case in practical steels. The presence of other elements changes the shape of the phase diagram and in particular will shift the range over which austenite is stable. Some elements, such as carbon and manganese, tend to stabilize austenite thus expanding the gamma loop as we see in Fig. 5, while others like silicon tend to stabilize ferrite and reduce the gamma loop.

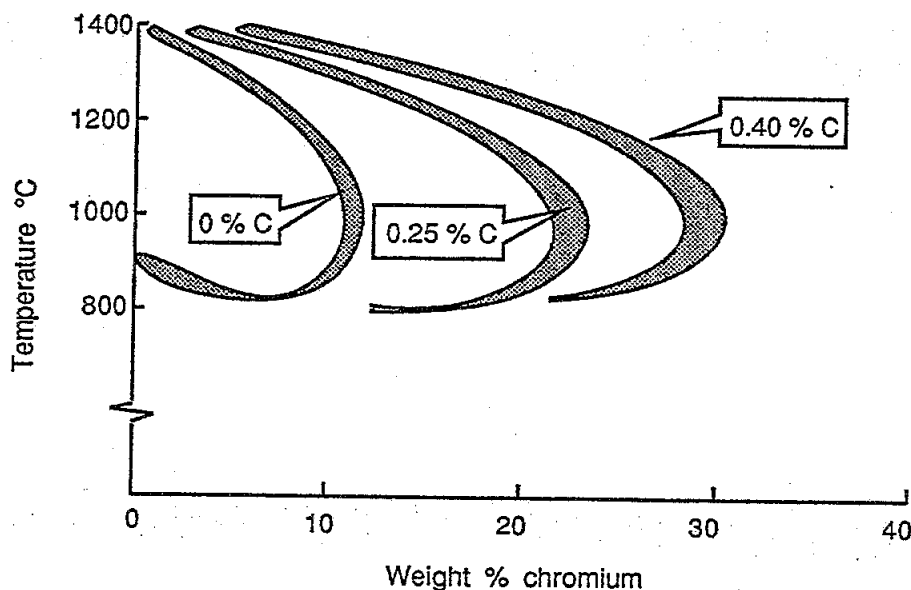
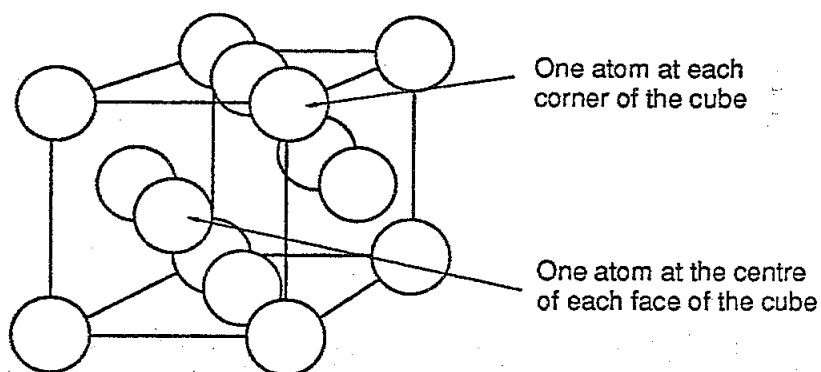


Figure 5. Iron-rich end of the iron-chromium phase diagram showing the effect of carbon on the size of the gamma (γ) loop.

Effect of nickel

Nickel is a face-centred cubic metal (Fig. 6) and when dissolved in iron tends to stabilize the fcc austenite structure. Normally, in pure iron, austenite is stable only above 910°C. Increasing the nickel content allows austenite to remain stable at lower temperatures and as we see in the nickel-iron phase diagram in Fig. 7 forms an open gamma loop. From the equilibrium phase diagram it would appear that very high nickel contents are needed to retain a completely austenitic structure down to room temperature. But this is not the case in practice. An iron-nickel alloy is austenitic at room temperature for nickel contents above 28%. In addition, the presence of chromium makes the rate of transformation to ferrite so sluggish that in practice the alloy remains austenitic at room temperature with even lower nickel contents. With 18% chromium a stainless steel is austenitic with only 8% nickel present. The austenite stabilizing effect of nickel may be assisted by other elements such as manganese.

Figure 6. Nickel has a fcc structure and stabilizes the fcc form of iron. There is complete solubility of nickel and iron in the fcc form.



Face-centred cubic structure (fcc)

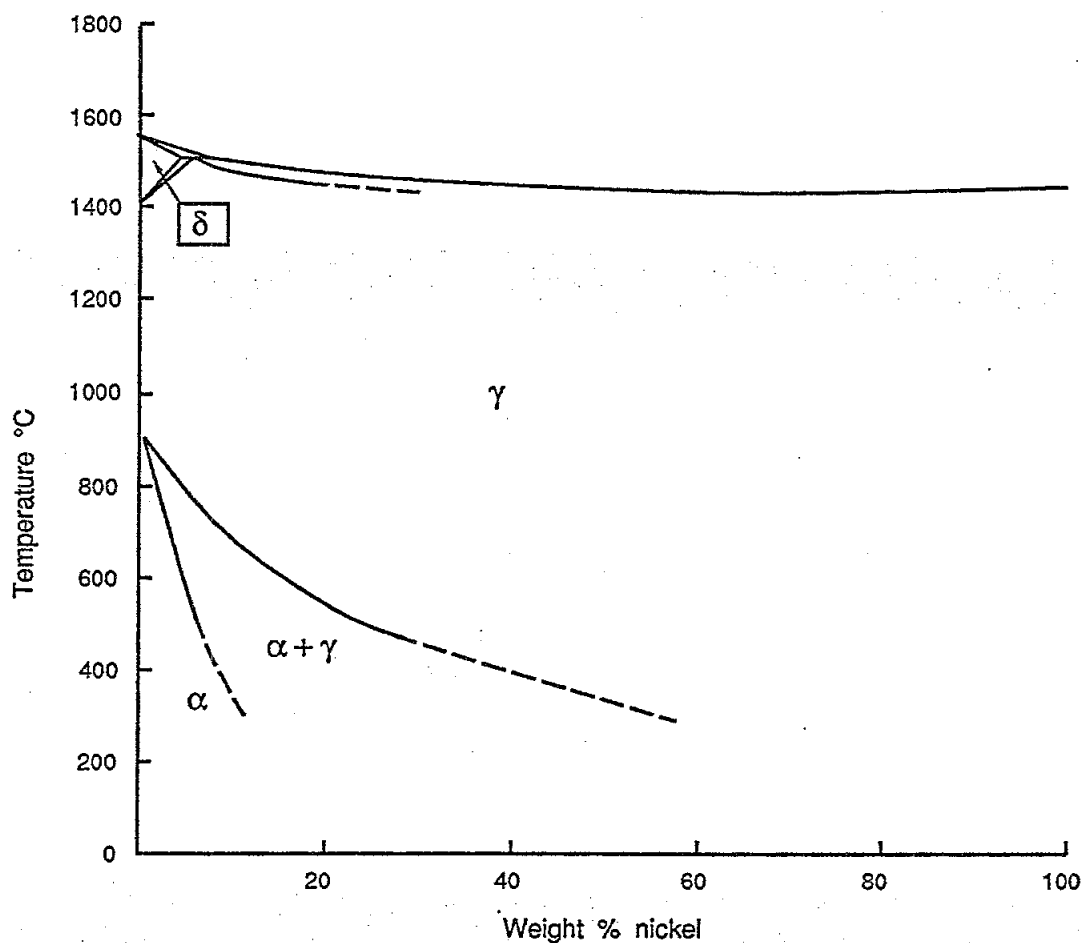


Figure 7. Phase diagram for iron and nickel. Note the open gamma region. With high nickel contents the transition to ferrite occurs too slowly to be observed. In practice alloys with more than 28% nickel will remain austenitic down to room temperature.

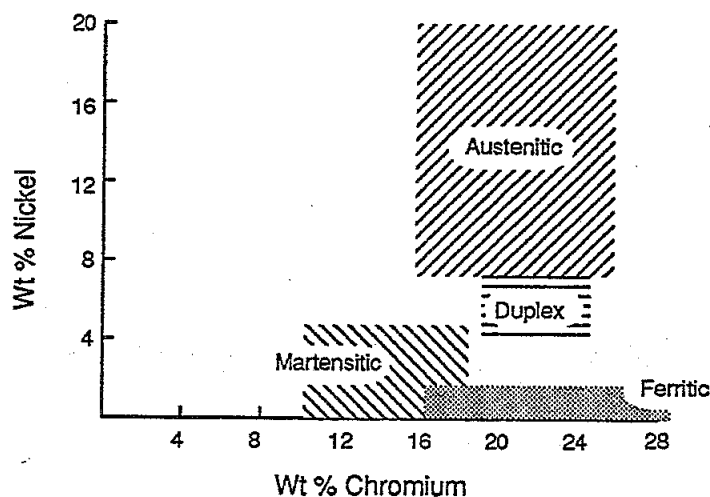


Figure 8. Diagram illustrating how the four basic types of stainless steel structures depend on the amounts of chromium and nickel present.

Basic structures of stainless steels

The behaviour of chromium and nickel in stabilizing ferrite and austenite, respectively, is the basis for practical stainless steels which fall into four basic types determined by the dominant structure formed. Fig. 8 illustrates this schematically. The basic types are:

- 1) Those with high chromium levels that have a ferritic structure over the whole temperature range and do not, therefore, transform on heating or cooling.
- 2) Those with lower chromium levels that form a closed gamma loop and therefore transform to austenite on heating and to martensite on cooling. These are known as martensitic stainless steels.
- 3) Those with chromium and enough nickel to remain austenitic over the whole temperature range and therefore do not transform on heating or cooling.
- 4) Those with chromium and intermediate nickel levels such that a mixture of austenite and ferrite is obtained on cooling. These are known as duplex stainless steels.

In addition there is a group of stainless steels that rely on precipitation hardening for increased strength through special heat treatments. These may have a martensitic, semi-austenitic, or austenitic structure. Of course there may be intermediate compositions in which more than one phase is present and the secondary phases, particularly in weld metal, may have significant effects on the properties.

Classification of stainless steels

Wrought stainless steels are classified by the American Iron and Steel Institute (AISI), and stainless steel castings are classified by the Steel Founders Society of America. There are corresponding wrought alloys for many of the cast types.

Austenitic steels with chromium and nickel as the main alloy elements are designated as AISI 300 series. Where manganese is used as a main alloy element in addition to chromium and nickel, austenitic steels are designated as 200 series. The ferritic and martensitic steels in which chromium is the major alloying element are designated as 400 series. The precipitation hardening alloys have a designation based on their composition. Additional letters may be placed after the AISI series number to denote special composition requirements, the most important being the designation L for low carbon.

Table 1. Compositions of common types of austenitic stainless steels.

Type	UNS number	Composition weight %							
		C	Mn	Cr	Ni	Si	P	S	Other
201	S20100	0.15	5.5-7.5	16.0-18.0	3.0-5.5	1.00	0.06	0.03	0.25 N
202	S20200	0.15	7.5-10.0	17.0-19.0	4.0-6.0	1.00	0.06	0.03	0.25 N
301	S30100	0.15	2.00	16.0-18.0	6.0-8.0	1.00	0.045	0.03	
302	S30200	0.15	2.00	17.0-19.0	8.0-10.0	1.00	0.045	0.03	
302B	S30215	0.15	2.00	17.0-19.0	8.0-10.0	2.0-3.0	0.045	0.03	
303	S30300	0.15	2.00	17.0-19.0	8.0-10.0	1.00	0.20	0.15 min	0-0.6 Mo
303Se	S30323	0.15	2.00	17.0-19.0	8.0-10.0	1.00	0.20	0.06	0.15 Se min
304	S30400	0.08	2.00	18.0-20.0	8.0-10.5	1.00	0.045	0.03	
304L	S30303	0.03	2.00	18.0-20.0	8.0-12.0	1.00	0.045	0.03	
305	S30500	0.12	2.00	17.0-19.0	10.5-13.0	1.00	0.045	0.03	
308	S30800	0.08	2.00	19.0-21.0	10.0-12.0	1.00	0.045	0.03	
309	S30900	0.20	2.00	22.0-24.0	12.0-15.0	1.00	0.045	0.03	
309S	S30908	0.08	2.00	22.0-24.0	12.0-15.0	1.00	0.045	0.03	
310	S31000	0.25	2.00	24.0-26.0	19.0-22.0	1.50	0.045	0.03	
310S	S31008	0.08	2.00	24.0-26.0	19.0-22.0	1.50	0.045	0.03	
314	S31400	0.25	2.00	23.0-26.0	19.0-22.0	1.5-3.0	0.045	0.03	
316	S31600	0.08	2.00	16.0-18.0	10.0-14.0	1.00	0.045	0.03	2.0-3.0 Mo
316L	S31603	0.03	2.00	16.0-18.0	10.0-14.0	1.00	0.045	0.03	2.0-3.0 Mo
317	S31700	0.08	2.00	18.0-20.0	11.0-15.0	1.00	0.045	0.03	3.0-4.0 Mo
317L	S31703	0.03	2.00	18.0-20.0	11.0-15.0	1.00	0.045	0.03	3.0-4.0 Mo
321	S32100	0.08	2.00	17.0-19.0	9.0-12.0	1.00	0.045	0.03	5 X %C Ti min
329	S32900	0.10	2.00	25.0-30.0	3.0-6.0	1.00	0.045	0.03	1.0-2.0 Mo
330	N08330	0.08	2.00	17.0-20.0	34.0-37.0	0.75-1.5	0.04	0.03	
347	S34700	0.08	2.00	17.0-19.0	9.0-13.0	1.00	0.045	0.03	10 X %C Nb(Cb) + Ta
348	S34800	0.08	2.00	17.0-19.0	9.0-13.0	1.00	0.045	0.03	0.2 Cu, 10 X %C Nb(Cb) + Ta
384	S38400	0.08	2.00	15.0-17.0	17.0-19.0	1.00	0.045	0.03	

Welding Metallurgy of Stainless Steels

Austenitic grades

The compositions of some of the more common austenitic steels are given in Table 1 and we should note several important features.

- 200 series steels have a substantial manganese content which partially substitutes for nickel and a significant nitrogen content to increase the strength of the steel.
- Within the 300 series several steels have about 18% Cr and 8% Ni and are often known by the popular term 18-8 stainless steels. Types 303 and 303Se are machining grades, the former having high phosphorus and sulphur while the 303Se contains selenium.
- Types 304 and 304L are very common austenitic grades and differ only in their carbon content, the 304L having a maximum carbon of only 0.03%. The 316 and 316L have additional molybdenum which improves the strength at high temperatures and the corrosion resistance under some conditions.
- Type 347 is known as a stabilized stainless steel and contains niobium (columbium) or tantalum in sufficient quantity to tie up carbon as carbides. The specified minimum niobium plus tantalum is 10 times the carbon content.

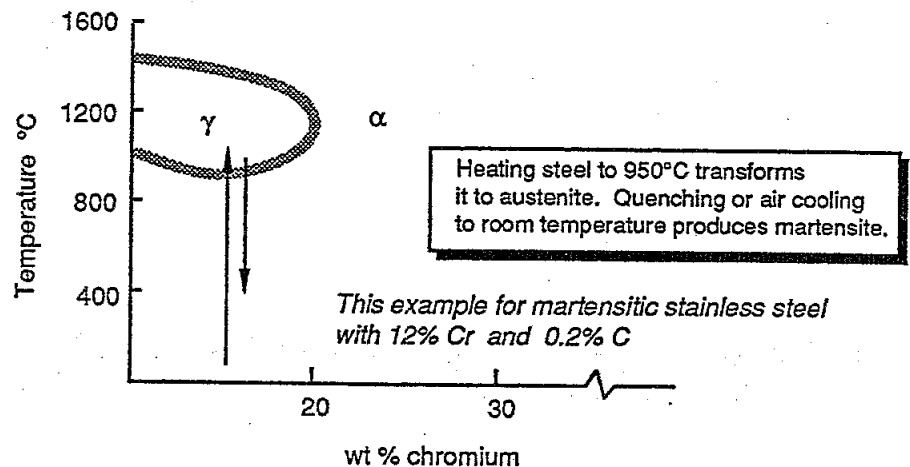
Martensitic grades

Some typical martensitic stainless steels of the 400 series are listed in Table 2. They can be heat treated to produce martensite (Fig. 9) and are hardenable even under air cooling conditions. The hardness can be

Table 2. Compositions of common wrought martensitic stainless steels.

Type	UNS number	Composition weight %							
		C	Mn	Cr	Ni	Si	P	S	Other
403	S40300	0.15	1.00	11.5-13.0		0.50	0.04	0.03	
410	S41000	0.15	1.00	11.5-13.0		1.00	0.04	0.03	
414	S41400	0.15	1.00	11.5-13.5	1.25-2.50	1.00	0.04	0.03	
416	S41600	0.15	1.25	12.0-14.0		1.00	0.04	0.03	
420	S42000	0.15 min	1.00	12.0-14.0		1.00	0.04	0.03	
422	S42200	0.20-0.25	1.00	11.0-13.0	0.5-1.0	0.75	0.25	0.025	0.75-1.25 Mo; 0.75-1.25 W; 0.15-0.3 V
431	S43100	0.20	1.00	15.0-17.0	1.25-2.50	1.00	0.04	0.03	
440A	S44002	0.60-0.75	1.00	16.0-18.0		1.00	0.04	0.03	0.75 Mo
440B	S44003	0.75-0.95	1.00	16.0-18.0		1.00	0.04	0.03	0.75 Mo
440C	S44004	0.95-1.20	1.00	16.0-18.0		1.00	0.04	0.03	0.75 Mo

Figure 9. Martensitic stainless steels can be hardened by heat treatment involving heating into the austenitic region followed by cooling. The hardenability is so great that even air cooling is sufficient to produce martensite.



Heat treatment

varied by adjusting the austenitizing temperature and by tempering after cooling. Maximum hardness is achieved by heating to above 950°C and quenching. Fig. 10 shows an isothermal transformation diagram for a typical martensitic stainless steel, type 410, where we see that an air cool to less than about 500°C within one hour will not cause transformation to ferrite. Thick sections of these steels are, therefore, easily hardened right through. Annealing—that is, heating to above 900°C and slow cooling—produces a ferritic structure.

The hardness is determined largely by the carbon content, and very high carbon levels, for instance in 440 A, B, and C, are found primarily in abrasion resistant alloys. Martensitic stainless steels are used for cutlery, hydraulic gates and similar applications where good corrosion and wear resistance are required.

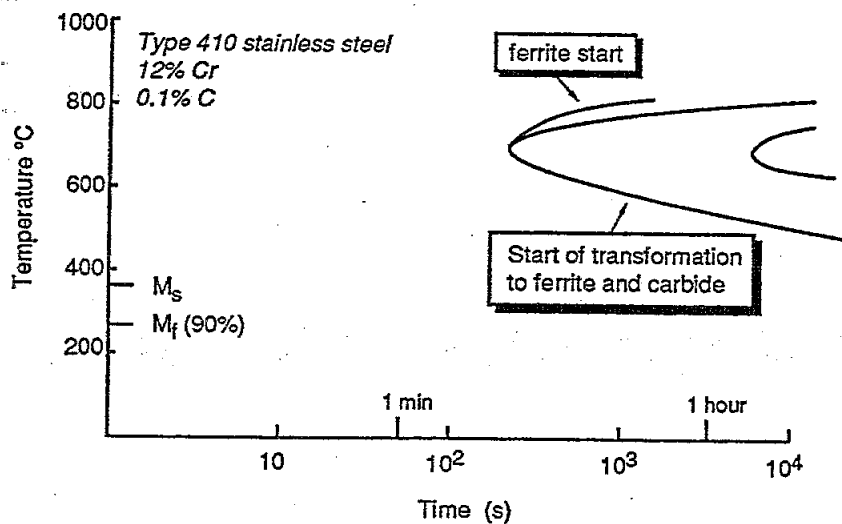


Figure 10. TTT curve for 12% Cr steel. Note that the steel is air hardening and only very slow cooling rates (eg., a furnace cool) would prevent martensite formation.

Welding Metallurgy of Stainless Steels

Table 3. Compositions of typical ferritic stainless steels.

Type	UNS number	Composition weight %							
		C	Mn	Cr	Ni	Si	P	S	Other
405	S40500	0.08	1.00	11.5-14.5		1.00	0.04	0.03	0.10-0.30 Al
409	S40900	0.08	1.00	10.5-11.75		1.00	0.045	0.045	6X%C Ti min
429	S42900	0.12	1.00	14.0-16.0		1.00	0.04	0.03	
430	S43000	0.12	1.00	16.0-18.0		1.00	0.04	0.03	
434	S43400	0.12	1.00	16.0-18.0		1.00	0.04	0.03	0.75-1.25 Mo
436	S43600	0.12	1.00	16.0-18.0		1.00	0.04	0.03	0.75-1.25 Mo; 5X%C Nb(Cb)+Ta
442	S44200	0.20	1.00	18.0-23.0		1.00	0.04	0.03	
444	S44400	0.025	1.00	17.5-19.5	1.00	1.00	0.04	0.03	1.75-2.5 Mo; 0.035 N
446	S44600	0.20	1.50	23.0-27.0		1.00	0.04	0.03	0.2+4X%(C+N) Nb(Cb)+Ti
26-1 E Brite	S44625	0.01	0.40	25.0-27.5	0.50	0.40	0.02	0.02	0.25 N
26-1 Ti	S44626	0.06	0.75	25.0-27.0	0.50	0.75	0.04	0.02	0.75-1.5 Mo; 0.015 N; 0.2Cu
29-4	S44700	0.010	0.30	28.0-30.0	0.15	0.20	0.025	0.02	0.5 Ni+Cu
29-4-2	S44800	0.010	0.30	28.0-30.0	2.0-2.5	0.20	0.025	0.02	0.75-1.5 Mo; 0.04 N; 0.2 Cu
									0.2-1.0 Ti
									3.5-4.2Mo; 0.02Ni; 0.15Cu
									3.5-4.2Mo; 0.02Ni; 0.15Cu

Ferritic stainless steels

Ferritic steels are listed in Table 3. Several of the ferritic stainless steels do actually form austenite on heating, and subsequent cooling results in the presence of some martensite. But because of the low carbon in these steels this does not cause a great increase in hardness, and the steels are regarded as non-hardening and classed as ferritic steels rather than martensitic.

Some of the ferritic steels are essentially straight chromium types (430, 442 and 446) while others include other ferrite stabilizers such as aluminum and titanium (405, 409). These latter types have a reduced tendency to form austenite on heating (and subsequently martensite) and have improved resistance to intergranular corrosion. Because there is no complete phase transformation in ferritic stainless steels they can suffer from excessive grain growth when heated (especially during welding) and as a result many of them have rather low toughness. To improve the properties of ferritic steels, low interstitial (i.e., low nitrogen and carbon) grades have been developed. Together with strong carbide formers the low interstitial content leads to much improved toughness, better weldability, and better resistance to intergranular corrosion, pitting and stress corrosion.

Duplex Stainless steels

Duplex stainless steels were developed with the aim of combining the mechanical and corrosion resistance properties of austenite and delta ferrite phases. These steels consequently have superior toughness and corrosion resistance compared to ferritic stainless steels. Duplex stainless steels also exhibit better stress corrosion cracking resistance than the austenitic stainless steels in chloride-containing fluids. Duplex stainless steels have consequently found increasing application in highly corrosive environments in oil and natural gas production, and in chemical industries. Table 4 illustrates typical duplex stainless steel compositions, i.e., in the range 18-26% Cr, 4-8% Ni and 1.50-3% Mo.

Table 4. Compositions of duplex ferritic-austenitic stainless steels.

Designation	UNS number	ASTM specification	Composition weight %									
			C (max)	Mn	P (max)	S (max)	Si	Cr	Ni	Mo	N	Other
XM-26	S31100	A 276	0.06	1.00 max	0.040	0.03	1.00 max	25.0-27.0	6.00-7.00	...	...	Ti, 0.25 max
...	S31200	A 240	0.03	2.00 max	0.045	0.03	1.00 max	24.0-26.0	5.50-6.50	1.20-2.00	0.14-0.20	...
...	S31260	A 240	0.03	1.00 max	0.030	0.03	0.75 max	24.0-26.0	5.50-7.50	2.50-3.50	0.10-0.30	Cu, 0.20-0.08; W, 0.10-0.50
...	S31500	A 790	0.03	1.20-2.00	0.030	0.03	1.40-2.00	18.0-19.0	4.25-5.25	2.50-3.00	0.05-0.10	...
2205	S31803	A 240, A 790	0.03	2.00 max	0.030	0.02	1.00 max	21.0-23.0	4.50-6.50	2.50-3.50	0.08-0.20	...
2304	S32304	A 790	0.03	2.50 max	0.040	0.04	1.00 max	21.5-24.5	3.00-5.50	0.05-0.60	0.05-0.20	Cu, 0.05-0.60
255	S32550	A 240, A 790	0.04	1.50 max	0.040	0.03	1.00 max	24.0-27.0	4.50-6.50	2.90-3.90	0.10-0.25	Cu, 1.50-2.50
2507	S32750	A 790	0.03	1.20 max	0.035	0.02	0.80 max	24.0-26.0	6.00-8.00	3.00-5.00	0.24-0.32	Cu, 0.50 max
329	S32900	A 240, A 790	0.08	1.00 max	0.040	0.03	0.75 max	23.0-28.0	2.50-5.00	1.00-2.00	...	...
...	S32950	A 240, A 790	0.03	2.00 max	0.035	0.01	0.60 max	26.0-29.0	3.50-5.20	1.00-2.50	0.15-0.35	...
CD-4MCu	...	A 743	0.40	1.00 max	0.040	0.04	1.00 max	24.5-26.5	4.75-6.00	1.75-2.25	...	Cu, 2.75-3.35

Welding Metallurgy of Stainless Steels

Table 5. Compositions of typical precipitation hardening stainless steels.

Type	UNS number	Composition weight %								
		C	Mn	Cr	Ni	Si	P	S	Al	Other
PH 13-8 Mo	S13800	0.05	0.10	12.25-13.25	7.5-8.5	0.10	0.01	0.008	0.9-1.35	2.0-2.5 Mo; 0.01 N
15-5 PH	S15500	0.07	1.00	14.0-15.5	3.5-5.5	1.00	0.04	0.03		2.5-4.5 Cu; 0.15- 0.45 Nb(Cb) + Ta
17-4 PH	S17400	0.07	1.00	15.5-17.5	3.0-5.0	1.00	0.04	0.03		3.0-5.0 Cu; 0.15- 0.45 Nb (Cb) + Ta
17-7 PH	S17700	0.09	1.00	16.0-18.0	6.5-7.75	1.00	0.04	0.03	0.75-1.5	

Precipitation hardening stainless steels

Precipitation hardening stainless steels derive additional strength from the precipitation of small particles in the matrix during an aging treatment at some specified temperature. The matrix structure of the steel may be martensitic, semi-austenitic, or austenitic. The elements used for precipitation include aluminum, copper and niobium (columbium). Some typical compositions are given in Table 5 and the corresponding heat treatments in Table 6.

Table 6. Examples of typical heat treatments for precipitation hardening stainless steels.

Type	Austenitizing temperature		Quenching medium	Aging treatment °C (°F)
	°C	°F		
17-4 PH	1040	1900	Oil, air	480 (900) for 1 hour or 500-620 (925 -1150) for 4 hours
15-5 PH	1040	1900	Water	480 (900) for 1 hour or 550-620 (1025-1150) for 4 hours
17-7 PH	950	1750	Air	(1)—32 (90) for 8 hours (2)— 510-600 (950 -1100) for 1 hour

Properties of stainless steels

We would expect stainless steels to have quite different properties from conventional carbon steels because the structures are different. The first characteristic of austenitic steels, and one that allows them to be quickly identified, is that they are non-magnetic. They cannot be lifted by a magnetic crane and do not suffer from residual magnetism that sometimes hinders welding of alloy steels by causing arc

blow. They may be slightly magnetic when they contain small amounts of ferrite and we can use this to advantage, particularly in weld metals, employing a sensitive magnetic measuring device to estimate the amount of ferrite present. Martensitic and ferritic steels are magnetic like conventional carbon steels.

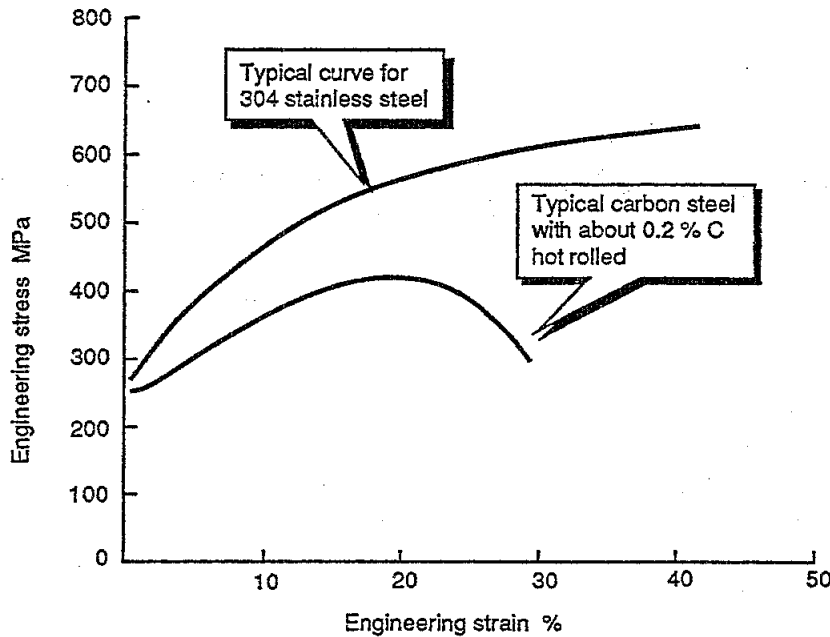


Figure 11. Stress-strain curve for austenitic stainless steel compared with that for carbon steel. The greater work hardening rate for the stainless steel may have important effects during fabrication such as greater spring-back after cold forming.

Tensile properties

Austenitic steels behave somewhat differently from carbon steels when undergoing tensile deformation. Compare the stress strain curves shown in Fig. 11. That for the austenitic steel has a high work hardening index and the stress rises considerably before the ultimate tensile stress is reached. This behaviour may have implications in fabrication. For example an austenitic steel will suffer a far greater spring-back on releasing the load after cold forming.

Figure 12. Austenitic stainless steels do not show the sharp toughness transition at low temperatures that is typical of carbon steels.

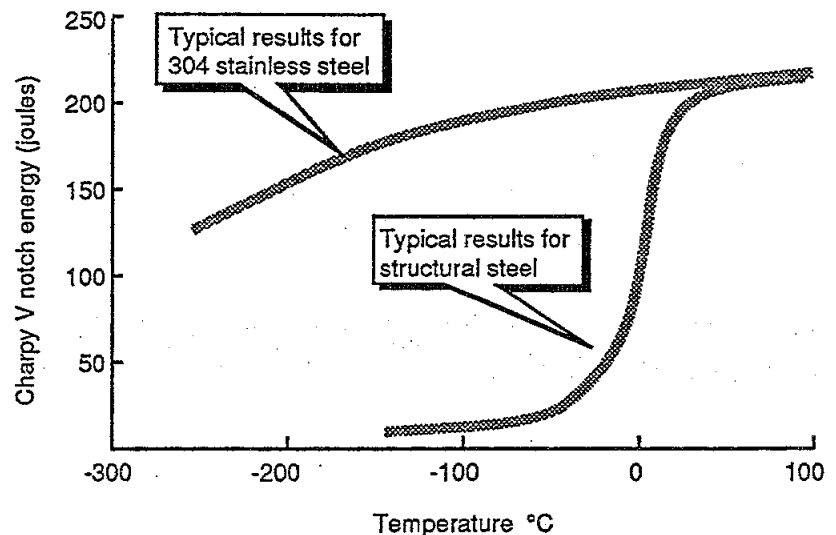
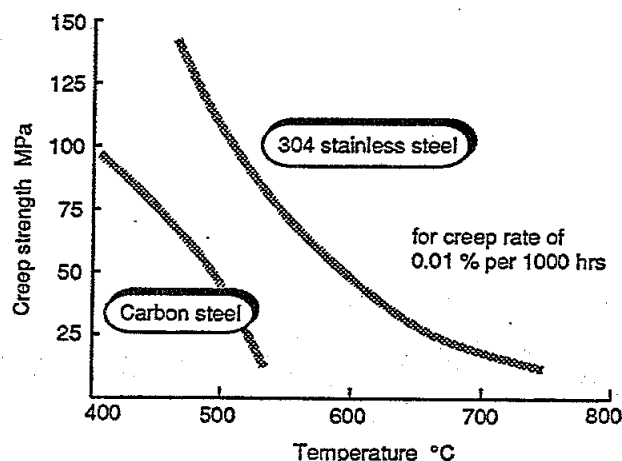


Figure 13. Typical creep strength of carbon and stainless steels at elevated temperatures.



Toughness

A major beneficial feature of austenitic steels is that they have excellent toughness. The fcc structure of austenite does not become brittle at low temperatures like the bcc structure of conventional carbon steels. The toughness of austenitic steels, therefore, remains good down to very low temperatures. As the temperature decreases, however, there is an increasing tendency to form martensite which offsets the otherwise good toughness, and this sets a practical limit to the properties achievable at the lowest temperatures. An example of the charpy properties of a typical austenitic steel at low temperatures is shown in Fig. 12.

High temperature strength

At the other end of the temperature range we also find austenitic steels having superior properties to carbon steels. The high temperature strength and creep strength permit stainless steels to be used in high pressure steam piping, chemical plant, and other high temperature applications. Fig. 13 shows some creep strength data for a carbon steel and an austenitic stainless (304 type) steel. In Fig. 14 we show a typical creep rupture curve for an austenitic steel. Curves of this type are used to estimate the expected life of components operating at high temperature.

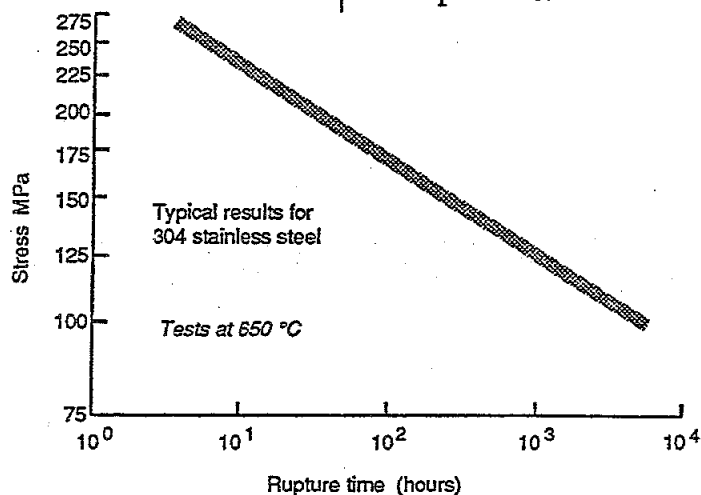


Figure 14. Typical creep rupture data for austenitic stainless steel at 650°C.

Basic considerations in welding

A comparison of some of the properties of stainless steels with those of carbon steel can assist in understanding the welding behaviour of these steels and determining the appropriate welding procedures. In particular we shall address the austenitic stainless steels.

Table 7. Approximate values for thermal properties of carbon and stainless steels.

Metal	Thermal conductivity		Melting point °C (°F)	Coefficient of thermal expansion /°C (°F)
	W / (m. K)	BTU/hr/sq ft/°F/ft		
304 type	16.2 (@100°C/212°F)	9.4	1425 (2597)	17.6 X 10 ⁻⁶ (9.8 X 10 ⁻⁶)
Stainless steel	21.5 (@500°C/932°F)	12.5		
Carbon steel	46.0 (@100°C/212°F)	26.8	1510 (2750)	11.7 X 10 ⁻⁶ (6.5 X 10 ⁻⁶)

Thermal properties

First let us consider the thermal properties. Table 7 shows some thermal properties of type 304, a typical austenitic stainless steel, and a carbon steel. The melting temperature and thermal conductivity of the 304 are considerably lower than those of the carbon steel, making it easier to melt during welding. Less heat is required to make the same size weld. Fig. 15 illustrates this by showing the size of fusion zone made with the same heat input in stainless steel and in carbon steel.

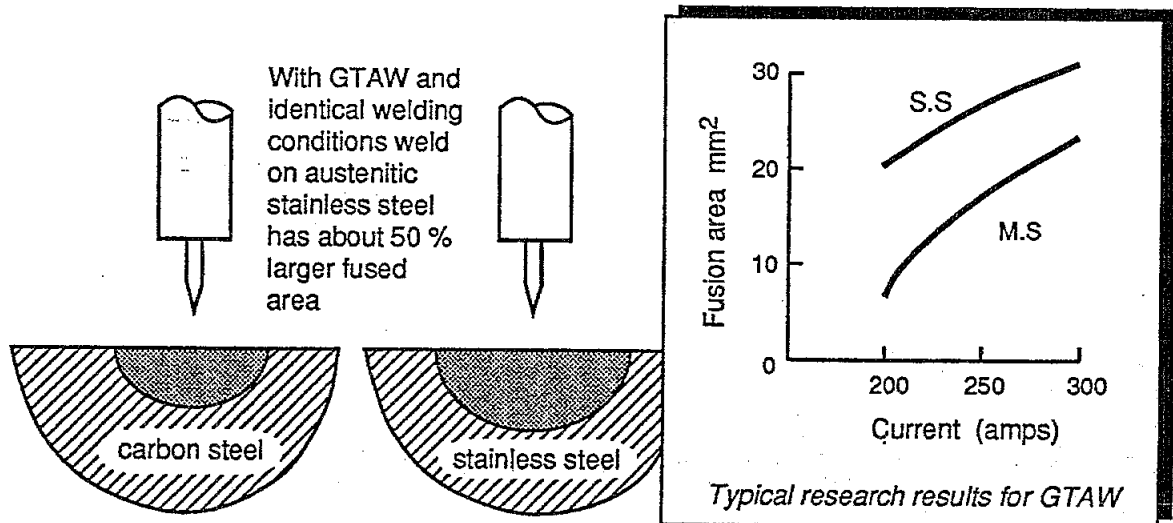


Figure 15. Effect of steel type on the size of weld fusion zone.

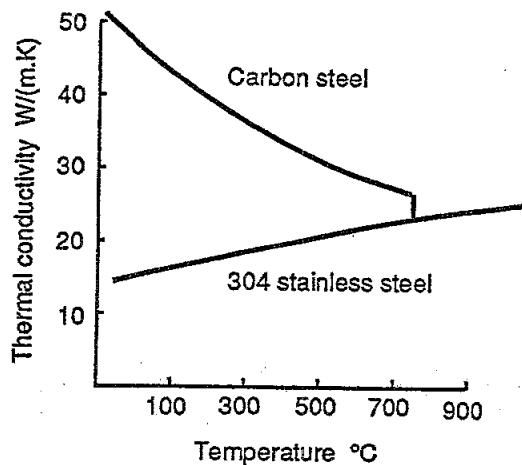


Figure 16. Thermal conductivity as a function of temperature for carbon and austenitic stainless steels.

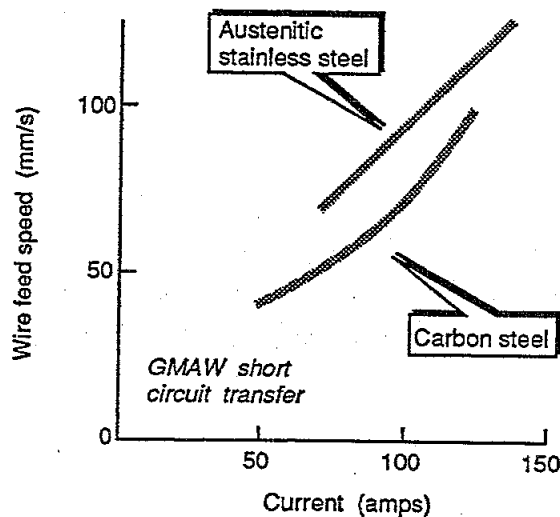
Effects of thermal properties

The thermal conductivity of the 304 is about one third that of carbon steel at room temperature and about two thirds at temperatures over 700°C (Fig. 16). The lower thermal conductivity leads to a greater concentration of heat during welding, narrower heat affected zones and slower cooling rates. On the other hand the coefficient of thermal expansion is about 50% greater in stainless steel. The result of this could be increased distortion and risk of buckling.

Melting rate

The electrical resistivity of the austenitic steel is about five times that of a carbon steel at room temperature but about the same above 910°C where, of course, the carbon steel is also austenitic. This results in greater heat generation in electric welding and facilitates resistance welding. The easier melting of the stainless steel implies a higher deposition rate in arc welding for the same current i.e. a faster wire feed rate in SAW and GMAW for the same current as Fig. 17 shows. The greater resistivity also implies a covered electrode would tend to overheat more than one of mild steel.

Figure 17. Wire feed speeds in GMAW are higher for stainless steel than for carbon steel at the same current. This results from the difference in thermal properties of the two types of steel.



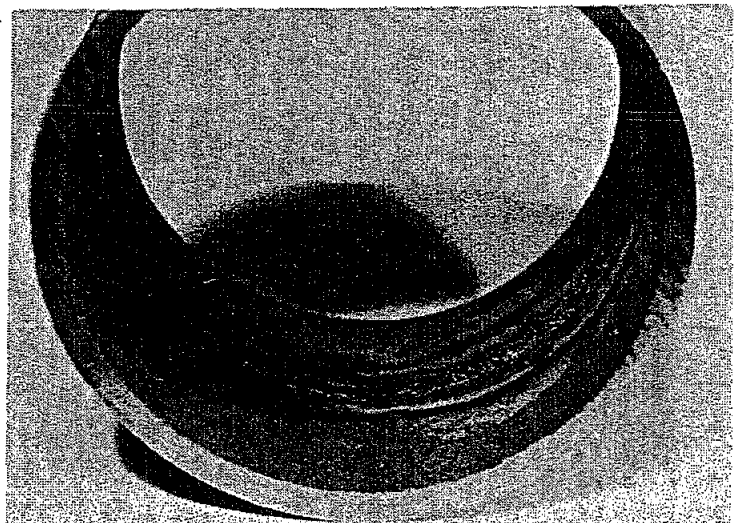
Chemical effects

Some of the welding characteristics of stainless steels may be anticipated from a consideration of the chemical properties of the alloys. Of prime importance is the oxidation of chromium. This element has a great affinity for oxygen, rapidly oxidizing when heated. It is this property, it will be recalled, that provides the corrosion resisting layer on stainless steels. If oxygen is available during welding the chromium forms chromium oxide which, unlike iron oxide, is not liquid at the temperature of the liquid weld pool. A solid, refractory oxide, such as this does not flux out easily and can cause defects in the weld. Even if the oxide were not a problem a loss of chromium due to oxidation may result in a weld with unacceptable properties. Furthermore, other highly oxidizable elements such as titanium are frequently used in stainless steels.

Stainless steel welding is, consequently, less tolerant to oxygen than carbon steel welding. Some of the restrictions this imposes are:

- For arc stability with the GMAW process an oxidizing component (O_2 or CO_2) is usually added to argon shielding gas. However, the oxidizing gas component should be kept to a minimum to avoid loss of alloying elements during droplet transfer and an oxidized weld surface. Ar + 2% O_2 (or similar additions of CO_2) is a commonly used shielding gas for the GMAW process.
- Fluxes for submerged arc and shielded metal arc welding have low oxygen potential and contain fluorides to assist in fluxing chromium oxide. Submerged arc fluxes for carbon steels are not appropriate for stainless steels.
- One side welding (e.g., the root run of a pipe weld) requires shielding on the reverse side to prevent contamination. An example of a weld made with and without reverse side shielding is shown in Fig. 18.

Figure 18. Appearance of the reverse side of a root pass in stainless steel made with back shielding (left half) and without back shielding (right half). Note the extent of oxidation and resulting poor quality weld bead when back shielding is omitted.



Sensitization

POTENTIAL WELDING PROBLEMS

Some grades of stainless steel may be prone to a problem of sensitization which can locally destroy their corrosion resistance exposing them to very rapid attack. As we have discussed the corrosion resistance of stainless steels depends on chromium and the formation of a chromium oxide layer to protect the steel. When such a steel is heated in the temperature range 500° to 850°C carbon in solution in the steel forms carbides with the chromium and precipitates out as small particles. These carbides form preferentially at the grain boundaries and cause the interior of the grain to be depleted of chromium. The lower chromium levels result in a loss of corrosion resistance and the steel is said to be sensitized. Fig. 19 illustrates schematically how sensitization takes place.

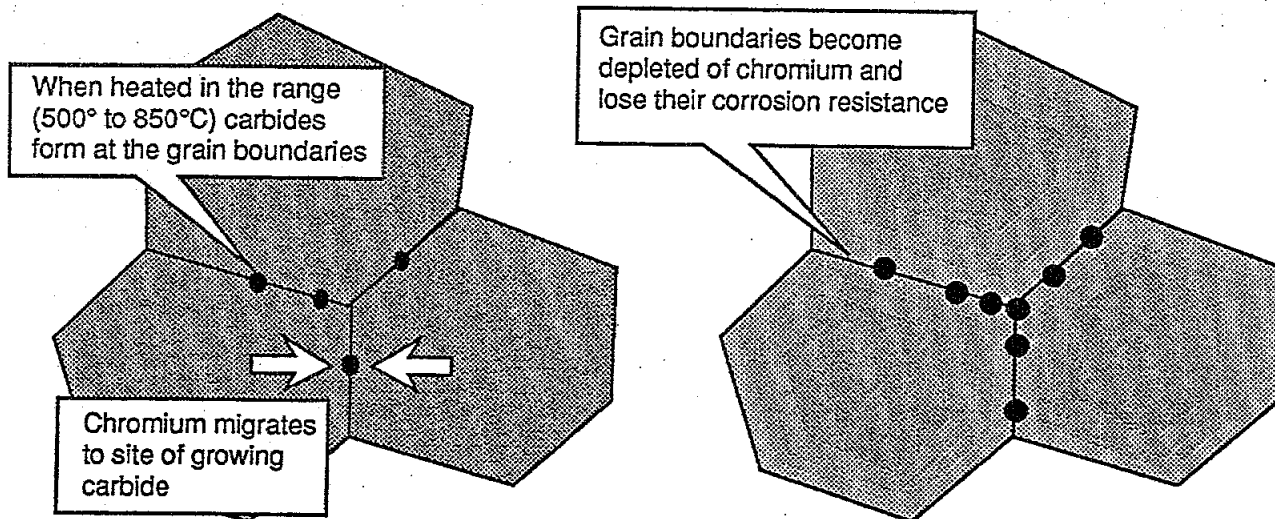


Figure 19. Illustration showing the mechanism of sensitization in stainless steels.

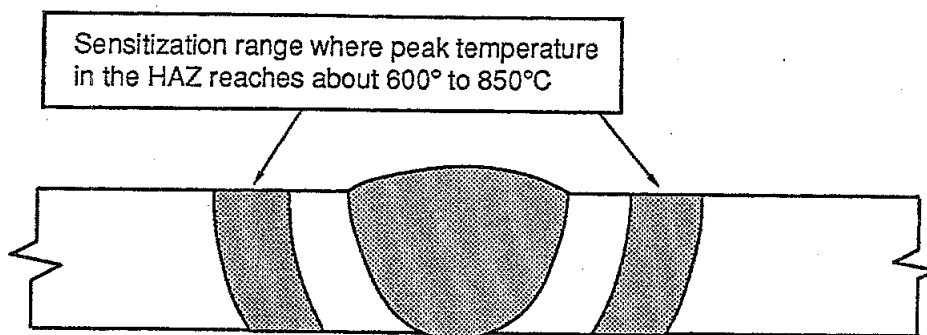


Figure 20. Part of the heat affected zone where sensitization can occur. Because of the short time at peak temperature during welding, a narrower temperature range is at risk than in a furnace heated specimen.

Sensitization in the HAZ

In parts of the heat affected zone of welds the temperature reaches the sensitization range and the time at temperature may be long enough to cause carbide precipitation. These parts of the heat affected zone, identified in Fig. 20, would suffer a loss of corrosion resistance. When exposed to certain media the joint could exhibit weld decay in which intergranular attack of the HAZ takes place. An example of intergranular weld decay is shown in Fig. 21.

The degree of sensitization depends mainly on the carbon level, the temperature and time of heating. The carbide precipitation range is shown in Fig. 22 and it is apparent that with sufficiently low carbon

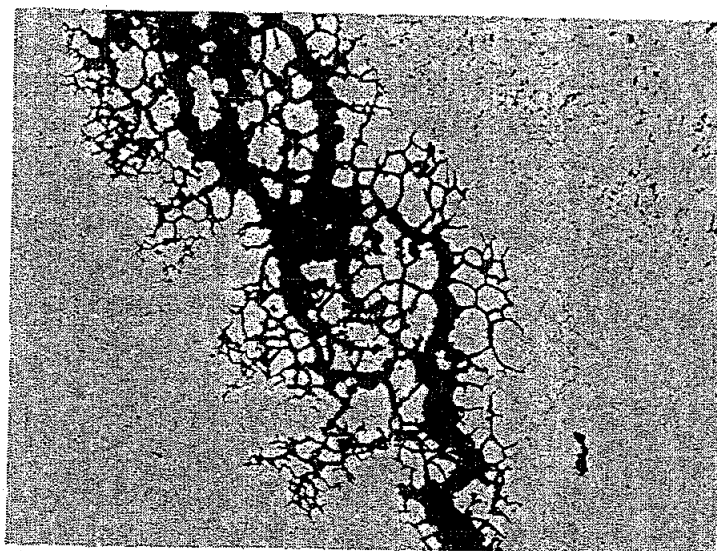


Photo courtesy of Ontario Hydro

Figure 21. An example of weld decay where rapid corrosion of the heat affected zone has occurred because of sensitization.

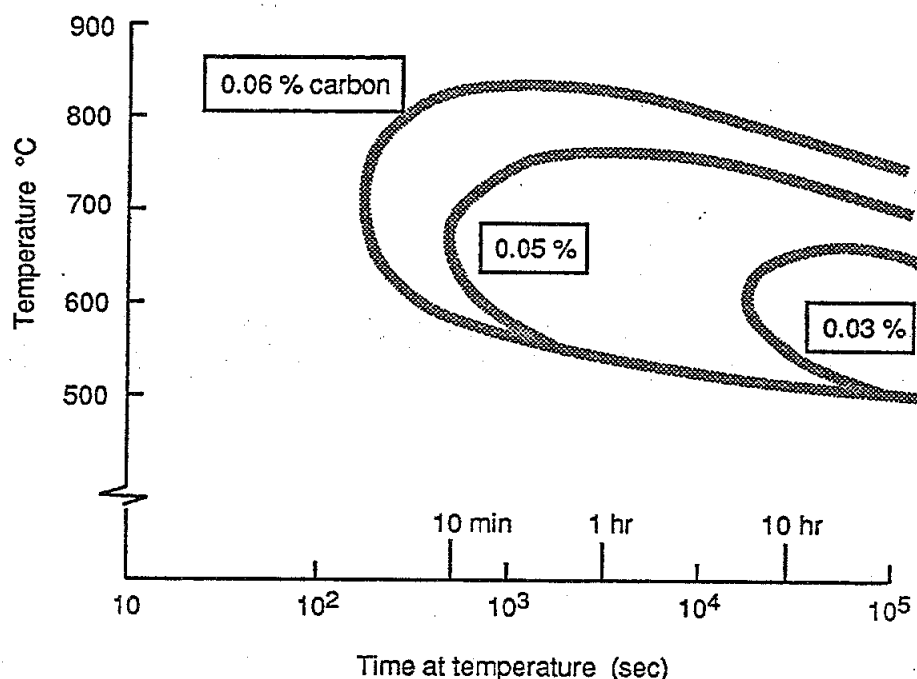


Figure 22. Graph showing the effect of temperature and carbon content on the time to produce carbide precipitation. With a carbon content of less than 0.03% carbide precipitation will not occur within the times at peak temperature normally experienced in welding.

Methods to avoid sensitization

the time for precipitation is far longer than would be experienced during welding. The low carbon steels 304L, 316L, 317L have a maximum carbon of 0.03% and can be successfully welded without sensitization for many applications. For extended service at high temperatures, however, low carbon alone is not enough to ensure freedom from sensitization. For these applications it is common practice to specify stabilized steels such as 321 and 347. Stabilized steels contain strong carbide formers such as titanium and niobium (columbium) which tie up the carbon preventing it from forming carbides with chromium. To ensure complete stabilization the titanium content must exceed five times the carbon, or the niobium plus tantalum must exceed ten times the carbon.

Solution treatment

Another method of overcoming the carbide precipitation problem, suitable for the higher carbon non-stabilized grades, is to solution treat the steel at a temperature high enough to dissolve all the carbides. Solution treatment consists of heating to 1000° to 1150°C followed by rapid cooling. A slow cool runs the risk of allowing re-precipitation of carbides on cooling through the sensitive range. It should be noted that a stress relieving treatment of 800°-900°C will not work and may make the situation worse.

Stress corrosion cracking

Stress corrosion cracking in service can occur as the result of high tensile stresses and specific corrosive environments. It does not require the steel to be sensitized. An example of stress corrosion cracking is shown in Fig. 23. Residual stresses from welding are the prime source of high stresses, and annealing or stress relief heat treatments to reduce residual stresses are the two practical solutions to a stress corrosion cracking problem. The regular carbon steels such as 304 would be annealed at over 1000°C whereas the low carbon and stabilized types would undergo a stress relief at 800°-900°C. The choice of alternate materials should also be considered. For example, duplex stainless steels usually have superior stress corrosion cracking resistance over the 300 series stainless steels.

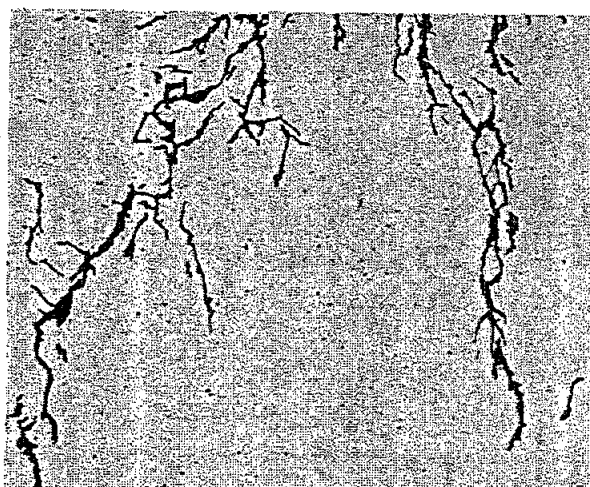


Figure 23. An example of stress corrosion cracking in a stainless steel weld.

Cracking

It is difficult to predict which environments might cause stress corrosion cracking, but it has often been associated with halogen ions, in particular chloride ions. Concern over chlorides warrants special attention during fabrication to avoid any contamination from chloride-containing materials. Machining, for example, should employ a chloride-free cutting fluid.

Cracking during welding or in service is possible in most of the stainless steels, and there are a variety of possible causes. Ferrite and martensite structures are susceptible to hydrogen embrittlement so stainless steels with these as the predominant structures may be susceptible to hydrogen induced cracking in the same way that conventional carbon and alloy steels are. We will discuss the precautions necessary to avoid cracking in more detail later in the section dealing with the welding of specific types of stainless steels.

Always check the
weld crater

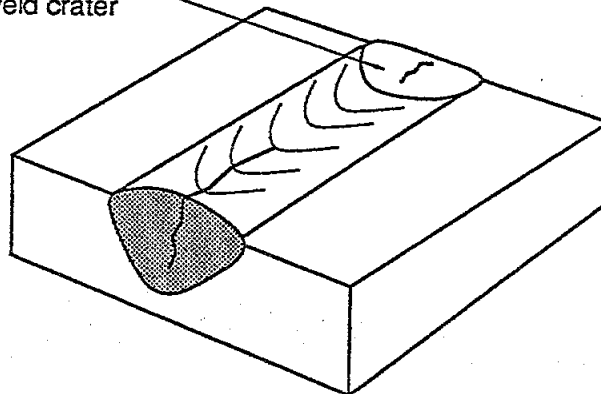


Figure 24. Example of solidification cracking in stainless steel weld metal.

HAZ cracking

Austenite, with its fcc structure does not suffer from hydrogen embrittlement and consequently hydrogen induced cracking is not a problem with the austenitic grades unless martensite is present. But heat affected zone cracking has been observed in austenitic steels in thick section welds, particularly the stabilized types such as 347. HAZ cracks have been seen after welding and also after service at temperature. The former type appears to be due to the formation of low melting point films on the grain boundaries when the steel is subject to the thermal cycles of welding. The latter type is similar to stress relief or re-heat cracking when the grain boundary ductility is reduced because of precipitation hardening within the grain. Titanium and niobium (columbium) seem to be the main contributors to this type of cracking.

Weld metal solidification cracking

Stainless steels may be prone to weld metal cracking which appears as a longitudinal crack in the last part of the weld bead to solidify, i.e., typically at the weld centreline (Fig. 24). Considerable research has gone into finding the cause of these cracks and establishing methods to avoid them. The occurrence of weld metal cracking appears to depend on two major factors: the presence of impurities such as sulphur and phosphorous, and the primary structure formed on solidification. Austenite has a very low solubility for sulphur whereas ferrite has a higher solubility. If the first phase formed on solidification is austenite, the sulphur is rejected to the liquid which gets trapped as a low melting point segregate between the growing dendrites. The sulphur-rich liquid results in cracks along the grain boundaries. If the primary phase on solidification is ferrite, rejection of sulphur does not occur and the weld is crack free.

Solidification mode

The mode of solidification depends on the exact composition of the alloy, even very small changes in composition result in a switch from a ferrite primary phase to austenite. Suppose we draw a phase diagram for iron, nickel and chromium in which the iron content is held constant at 68%. This is about the iron content of many austenitic stainless steels. Fig. 25 shows such a diagram. If we follow the progression of alloy A with 22% Cr and 10% Ni as it solidifies we see that the first solid to form is δ ferrite. On subsequent cooling most of the ferrite transforms to austenite resulting at room temperature in an austenite structure with patches of residual δ ferrite. The weld metal is crack free since the primary solid phase was ferrite which has a high solubility for sulphur.

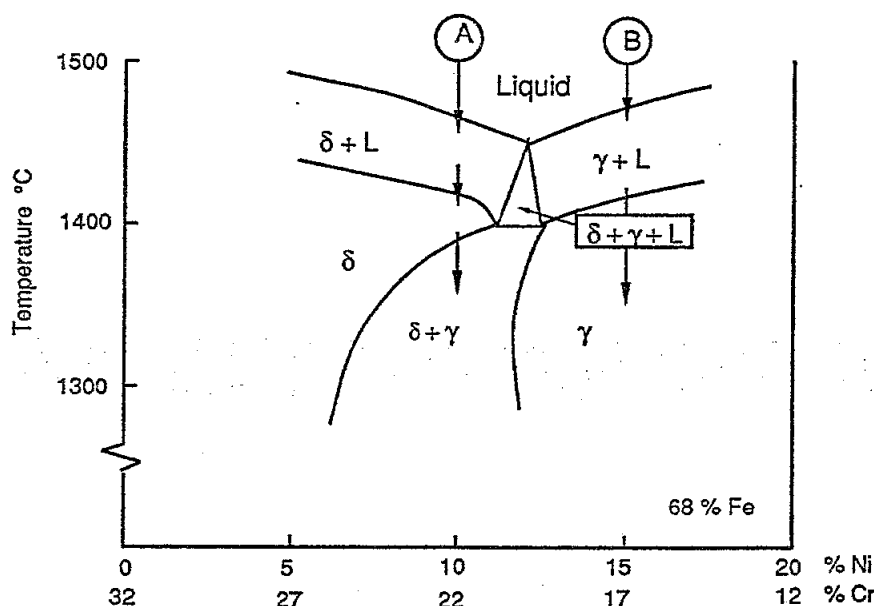


Figure 25. Pseudo-binary phase diagram for chromium and nickel with 68% iron. The diagram shows that small changes in the relative proportions of chromium and nickel can change the primary solidification from (δ) ferrite to (γ) austenite.

Delta ferrite

If, however, we trace the solidification of alloy B with 17% Cr and 15% Ni we see that the primary solid is austenite and there is no further phase transformation as the metal cools. Because the primary phase was austenite rejection of sulphur to the liquid occurs and weld metal fissuring is possible. Until recently the main control for this problem was to ensure that solidification took place as ferrite. The residual δ ferrite measured at room temperature was a good guide to this. By ensuring that a minimum ferrite content was obtained in the completed weld it could be inferred that fissuring was unlikely. Recently, materials with very low sulphur have been developed, allowing fully austenitic weld metal to be obtained with less risk of cracking.

Fissuring

Microfissures occur in an existing weld bead when it is reheated by an additional bead deposited next to or over it. Generally they are very short (less than 2 mm) and difficult to see with the naked eye.

Fissuring (Fig. 26) occurs from a mechanism that is similar to that for solidification cracking (i.e., the presence of a low melting point segregate). Hence, a small amount of ferrite is also helpful in reducing this type of cracking. No service failures appear to have been reported as being caused by microfissures.

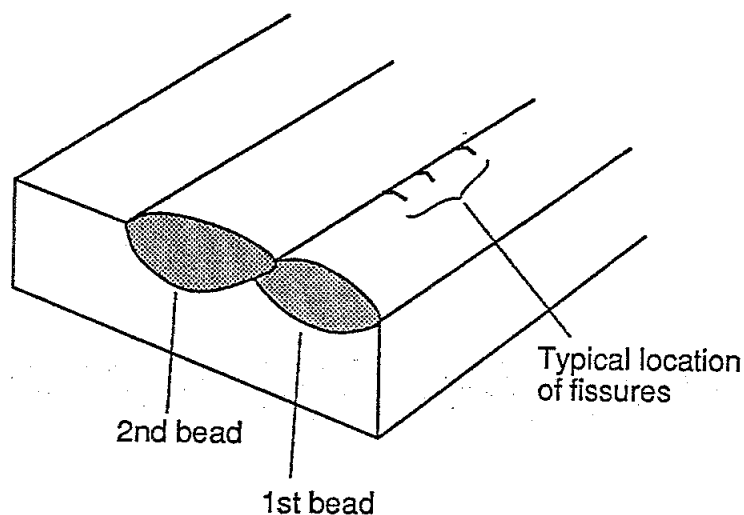


Figure 26. Weld bead showing fissures.

Importance of correct structure

WELD METAL STRUCTURE

The effects of nickel and chromium in promoting austenite and ferrite respectively mean that a wide range of different structures could be formed in a stainless steel weld metal depending on the exact composition. Achieving the correct structure is crucial if the weld is to provide the intended properties and be free of defects and cracks. A clear understanding of the role of composition in determining structure is vital in selecting electrodes and procedures for welding stainless steels. Depending on the exact composition austenite, ferrite, martensite, or combinations of these could form. The structure desired would depend on the application and the steel being welded. In welding an austenitic steel a martensitic weld metal would be completely unacceptable since it is hard, likely to crack and would not have the right mechanical or corrosion properties. Fig. 27 shows an example of a weld made with the wrong electrode where martensite has formed resulting in cracking and premature failure of the joint. On the other hand we have seen one example where an austenitic structure with a small percentage of retained δ ferrite is beneficial in preventing cracks.



Photo courtesy of Ontario Hydro

Figure 27. Cracking in a weld in stainless steel. Incorrect control of weld metal structure resulted in martensite formation and subsequent cracking.

Table 8. Effects of elements on stabilizing austenite or ferrite.

Austenite stabilizers	Ferrite stabilizers
Ni	Cr
Mn	Mo
C	Si
N	Ti
Co	Nb
Cu	V
	Al

Schaeffler diagram

The structure formed in the weld metal is a function of the level of alloy elements that promote ferrite and those that promote austenite. These can be placed in two groups representing the austenite formers as a nickel equivalent and the ferrite formers as a chromium equivalent (Table 8). The effect of these on weld metal structure was first summarized by Schaeffler in what has become known as the Schaeffler diagram. Fig. 28 shows this diagram in which the two axes represent nickel equivalent and chromium equivalent and the various lines divide the diagram into regions where the different microstructures are to be expected. In the mixed region where both ferrite and austenite are formed, lines are marked to indicate the percentage of ferrite present.

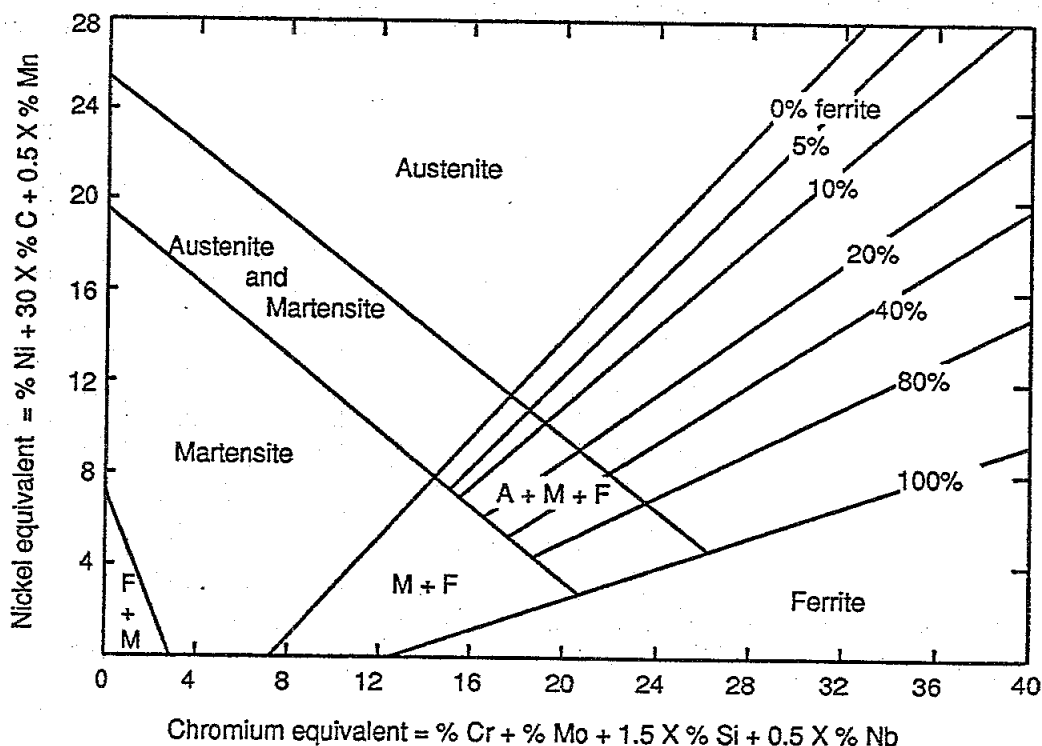


Figure 28. Schaeffler diagram for predicting weld metal structure from the composition.

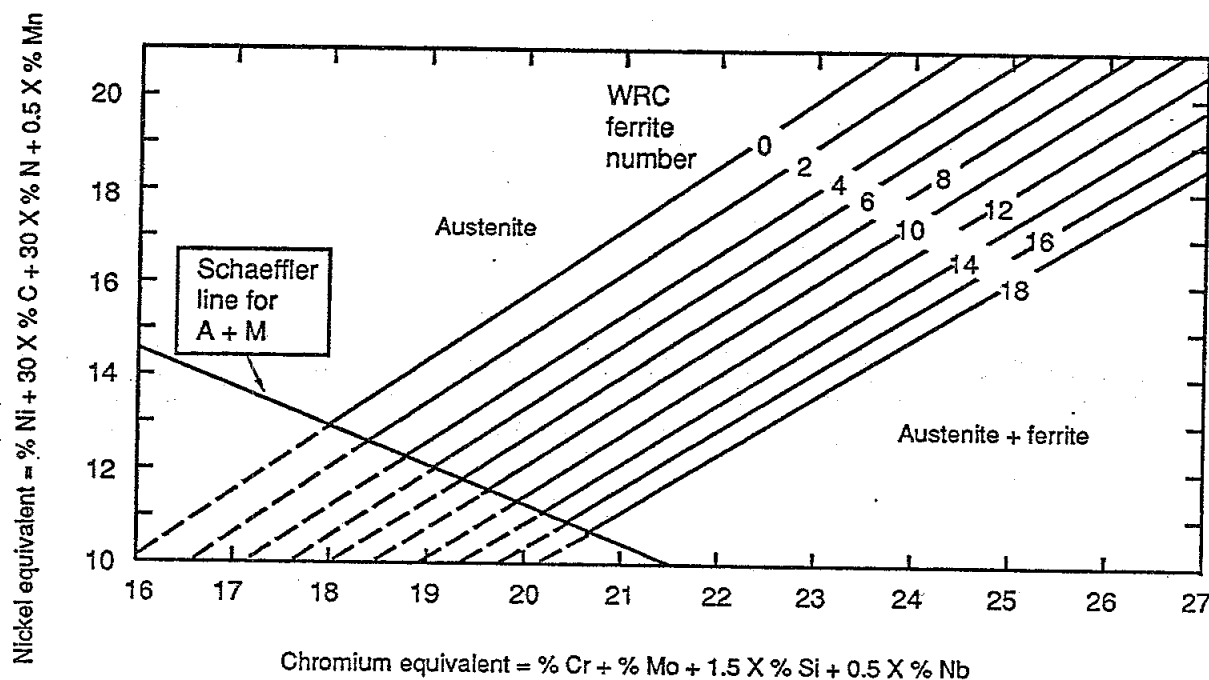


Figure 29. The DeLong diagram for predicting ferrite content (ferrite number) from composition. Note that the nickel equivalent includes the effect of nitrogen.

DeLong diagram

Ferrite number

The Schaeffler diagram does not include the very important effect of nitrogen which can be picked up in weld metal, particularly with the SMAW process. This shortcoming was corrected in a more recent version known as the DeLong diagram shown in Fig. 29. In addition to the inclusion of nitrogen, the DeLong diagram also redrew the ferrite lines and, rather than designating them as percentage, assigns them ferrite numbers. The ferrite numbers are a measure of the amount of ferrite but do not necessarily correspond exactly to the percentage that would be measured in a metallurgical section under the microscope. They do correlate with the amount measured by non-destructive magnetic methods and this makes the ferrite number system of practical benefit. The magnetic methods for determining ferrite content have been standardized by the American Welding Society in AWS A4.2-91, Standard Procedure for Calibrating Magnetic Instruments to measure the Delta Ferrite Content of Austenitic and Duplex Austenitic Ferritic Stainless Steels Weld Metal.

The WRC diagram

Further improvements to predictive diagrams were made in 1988 with the introduction of the WRC Diagram. This version is continuous over the range from 0 to 100 FN and hence is particularly useful for high ferrite materials such as duplex stainless steels. In this diagram manganese and silicon have been omitted and the weighting for carbon, nitrogen and niobium (columbium) have been changed with respect to earlier diagrams. The WRC Diagram is considered to be the most accurate constitution diagram for the prediction of ferrite content of austenitic and duplex stainless steel weld metals from chemical composition. However, like any other predictive diagram there are limitations. The diagram may be inaccurate for some levels of manganese, silicon and molybdenum, and since there is no martensite line it may not be appropriate for welding some dissimilar metals or other situations where martensite is a consideration. The latest version (1992) is shown in Fig. 30.

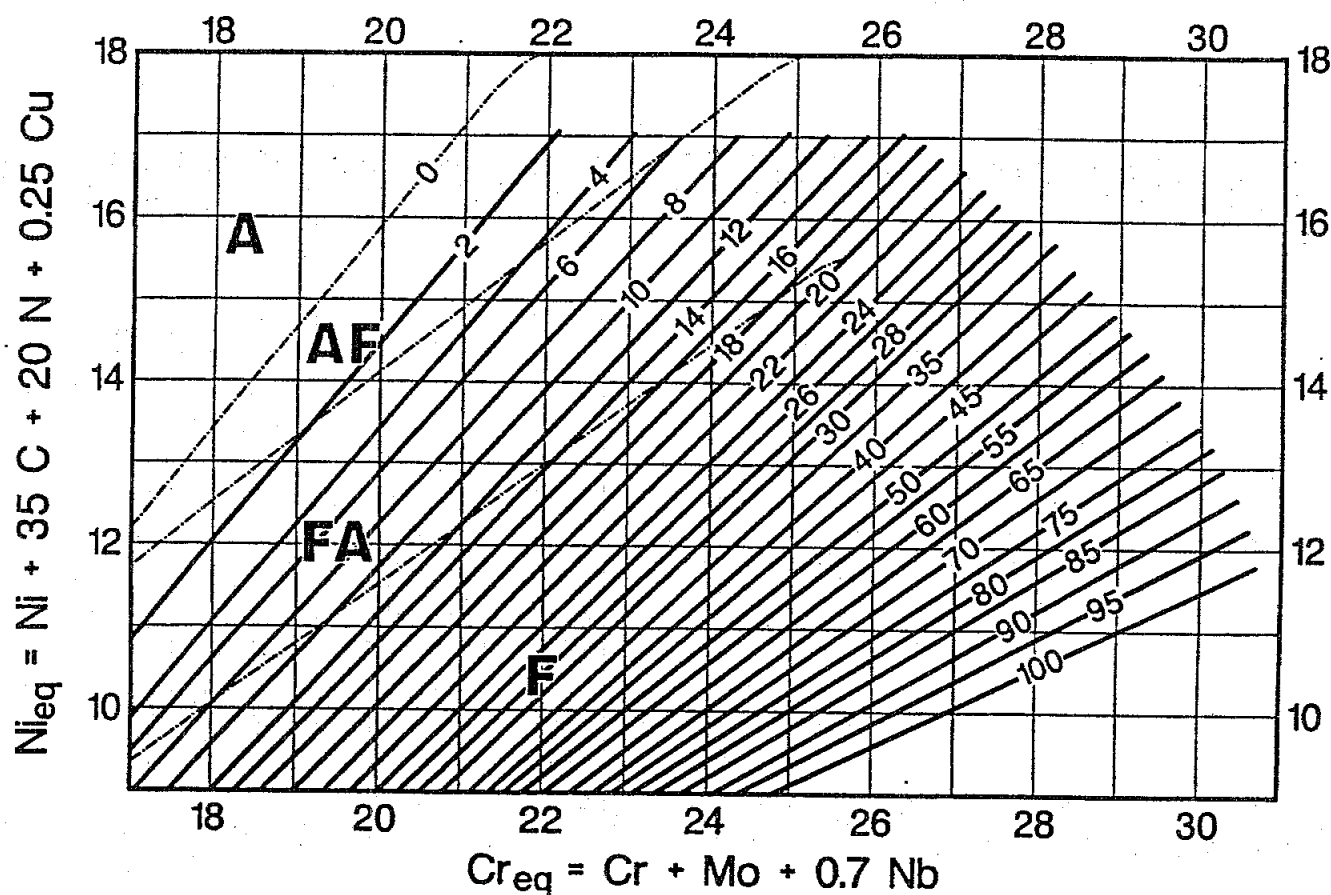


Figure 30. The WRC Diagram. Reference diagram from Kotecti and Siewert.

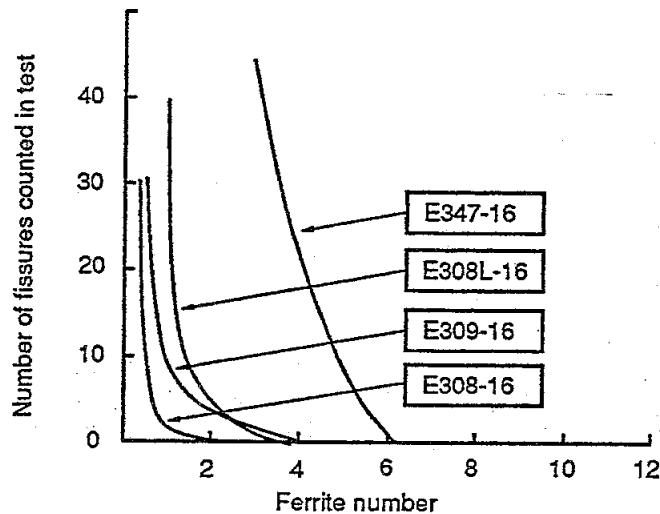


Figure 31. The number of fissures observed in bend tests plotted against the δ ferrite content.

Ferrite control

As we have seen, δ ferrite is important in austenitic weld metals because small quantities can prevent hot cracking. The exact amount of ferrite required depends on the composition of the weld metal, but values are typically in the range 3-6 FN (ferrite number) as the results in Fig. 31 show. Electrodes are available that have been formulated to meet minimum ferrite requirements. An example is shown plotted on the DeLong diagram in Fig. 32. As you see the composition has to be held within tight limits if the ferrite number is to be accurately controlled. If there are increased losses of chromium during welding resulting from oxidation, the lower weld metal chromium content tends to reduce the ferrite content thus increasing the risk of fissures.

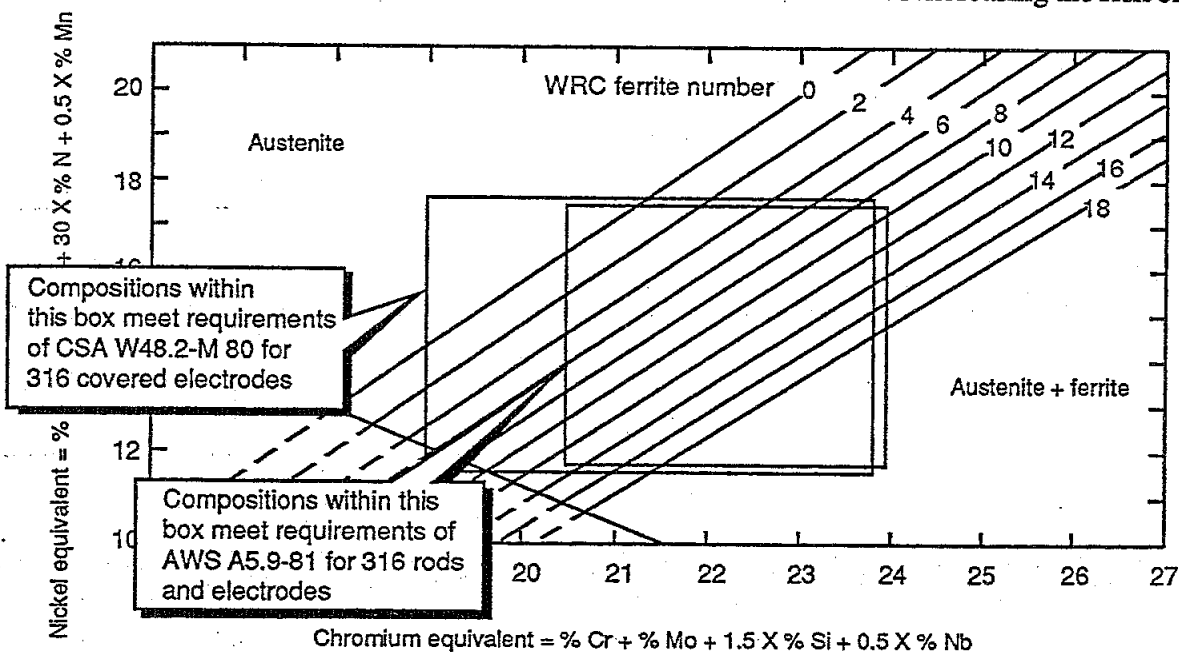


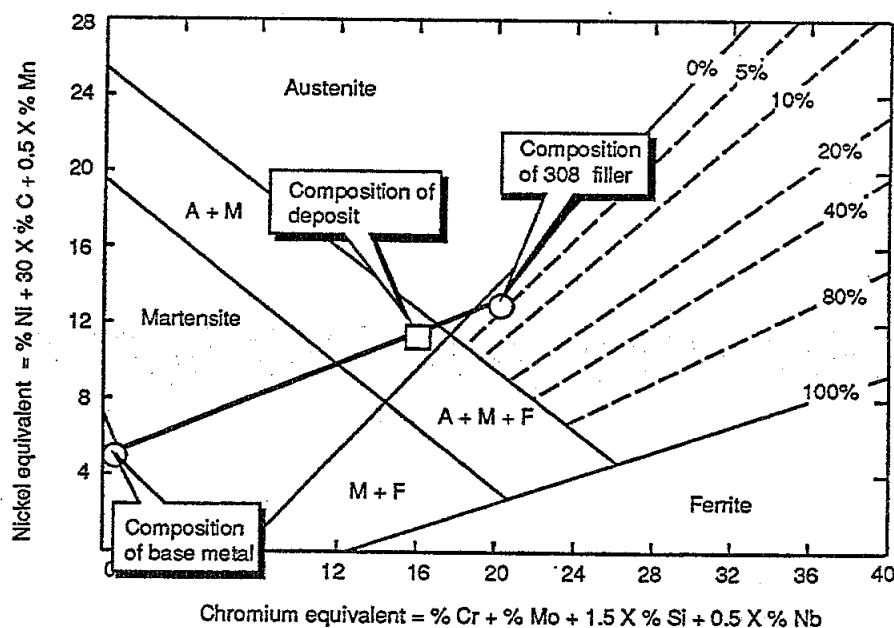
Figure 32. Range of compositions allowed by standards plotted on DeLong diagram showing the wide range of ferrite contents that could be obtained. For ferrite control, manufacturers impose very tight control of weld metal composition.

Welding Metallurgy of Stainless Steels

Maximum ferrite

In some cases the presence of ferrite is not desirable in the weld metal. For example, welds subject to long term high temperature service may become embrittled as the result of sigma phase formation from the ferrite. Sigma is a very brittle phase that only appears after prolonged heating. In those applications where the weld is designed to operate in the temperature range 500°-900°C sigma formation must be prevented by avoiding the presence of ferrite. Completely austenitic weld metal is specified for such applications. Ferrite may also be detrimental in some environments such as hot, oxidizing acids where it causes increased corrosion. In such cases where ferrite free weld metal is specified other precautions are necessary to prevent the occurrence of fissures. Among these are very low allowable levels of sulphur, phosphorus and controlled silicon.

Figure 33. The effect of depositing E308 weld metal on mild steel. The resulting weld metal will have a composition giving martensite that is likely to crack.



Estimating weld metal composition

The Schaeffler diagram can be of great assistance in estimating the effect of dilution on the likely weld metal structure and hence in providing a guide to electrode selection. The effect of dilution can be taken into account by assuming that the weld pool composition results from a straight mixing of metal from the electrode and metal from the parent metal. Slight losses of chromium due to oxidation occur and these can be estimated and corrected for if necessary.

As an example, consider a weld bead deposited on a mild steel plate using a 308 austenitic stainless steel electrode. Suppose the mild steel has 0.2 % carbon, 1% manganese and 0.2% silicon. The nickel and chromium equivalents can be calculated for both the mild steel and the stainless steel electrode and marked on the diagram in Fig. 33 (chromium losses have been neglected). If these two points are joined by a line it is known that the composition of the resulting weld metal

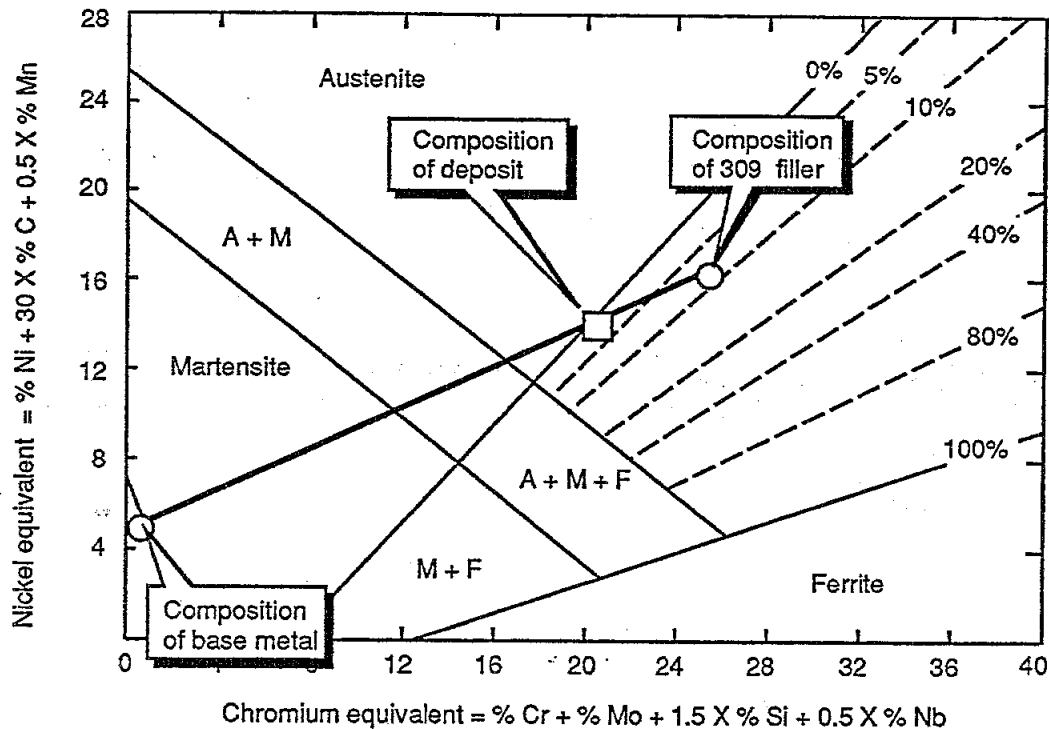


Figure 34. Effect of depositing E309 weld metal on mild steel. For normal dilution levels the resulting weld metal composition will not produce martensite.

Effect of dilution

must lie somewhere along this line. If the dilution factor of the weld is 20% this means that the weld metal is 20% parent and 80% electrode, and the composition will be given by a point 20% of the way along the line from the electrode end. It is seen that this point is in the mixed austenite/martensite region. Such a composition would be hard and likely to crack.

In order to move the weld metal composition out of the martensite region into the austenite/ferrite region an electrode higher in alloy content is required. If we draw a line between the mild steel point and that for a 309 electrode shown in Fig. 34, we see that a 20% dilution results in a weld metal in the austenite/ferrite region which would be acceptable. In practice a weld between a carbon steel and a 304 austenitic stainless steel would be made with a 309 electrode and not with a 308 even though a 308 may be perfectly acceptable for a stainless to stainless weld. Even with a 309 electrode care is required to maintain an acceptable level of dilution. If the dilution becomes very high (e.g., 50%) then the same problem as the 308 electrode arises i.e. the weld metal has a composition putting it in the martensite region of the diagram and the weld is likely to crack (Fig. 35).

Welding Metallurgy of Stainless Steels

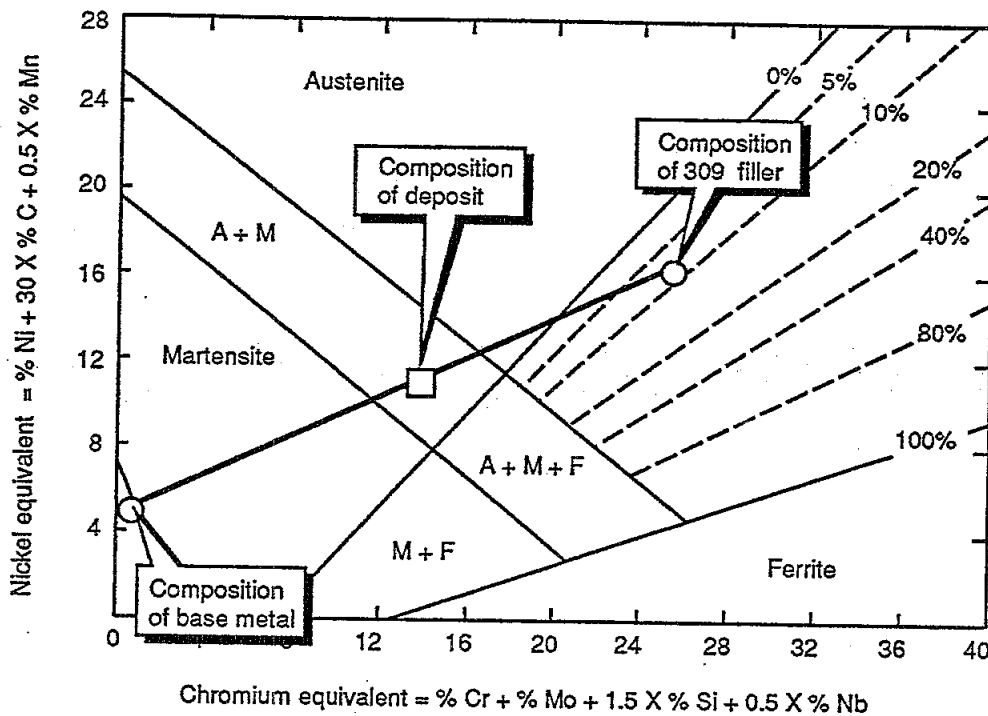


Figure 35. Effect of E309 deposit on mild steel when dilution is high. Resulting weld metal composition may result in martensite formation and subsequent cracking.

Welds involving two types of electrodes

This same type of analysis may be used to determine the effect of welding with two different types of electrodes in a joint. Suppose that part of a weld was made using a mild steel electrode (e.g., E7018) and was then completed with a 309 stainless steel electrode (Fig. 36). This situation is similar to the previous example of welding on a mild steel. If the dilution is not too high the resulting weld composition puts it in the austenite/ferrite region of the Schaeffler diagram and a satisfac-

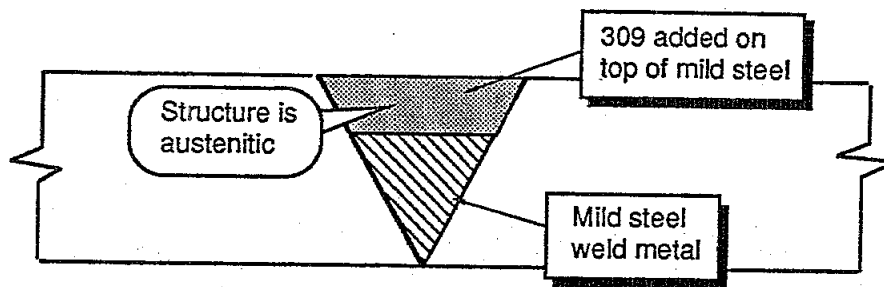


Figure 36. When 309 weld is deposited over mild steel weld metal with normal dilution levels the resulting structure is austenitic with no martensite.

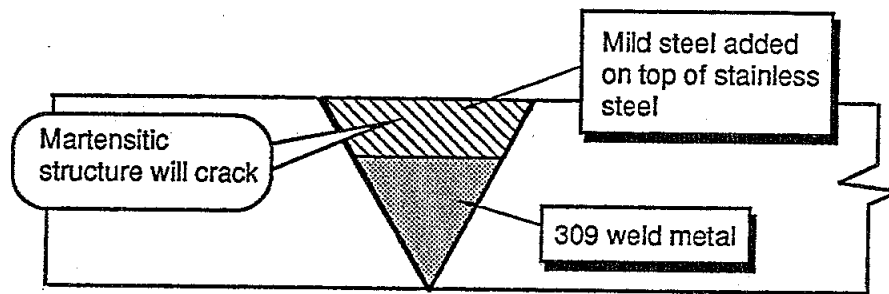
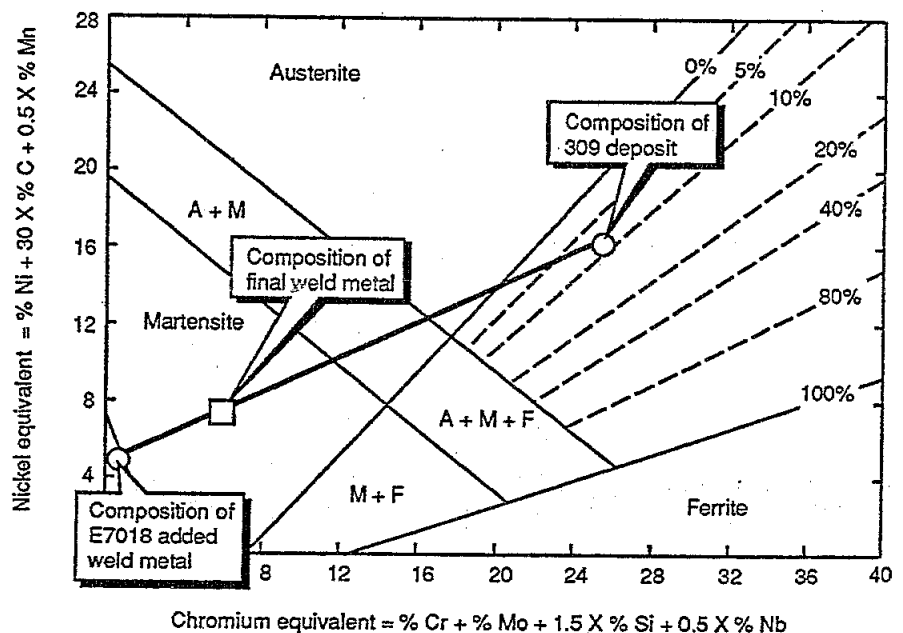


Figure 37. If mild steel is deposited onto stainless steel weld metal the resulting weld metal structure will be martensitic and likely to crack.

tory weld results. If, however, the reverse situation is considered (Fig. 37) with part of the weld being made with a 309 first and a mild steel electrode used to finish, a different result follows. The same line on the diagram (repeated in Fig. 38) applies but now the resulting weld metal composition will be 20% along the line from the mild steel end, right in the martensite region and completely unacceptable. Clearly great care must be taken when two different types of electrodes are specified for a weld. A stainless electrode (309) can be used over mild steel but a mild steel electrode cannot be used over stainless.

Figure 38. Schaeffler diagram shows the effect of using a mild steel electrode over stainless steel weld metal. Resulting weld metal is martensitic and is likely to crack. This simple mistake has been the cause of many serious problems in industry.



WELDING AUSTENITIC STAINLESS STEELS

In some ways austenitic stainless steels are easier to weld than carbon steels since they do not suffer from hydrogen induced cracking. We have seen that the austenitic face-centred cubic structure is not sensitive to hydrogen embrittlement in the same way that martensite is, and therefore welds are not prone to hydrogen induced cold cracking unless martensite is formed. As a consequence preheat is rarely used in welding austenitic grades except to dry off moisture.

The most important aspect of welding austenitic steels is selection of an electrode having the correct alloy composition. In most cases the correct electrode will have a composition similar to that of the base plate but slightly richer in nickel and chromium to compensate for losses during welding, to balance corrosion resistance, and to ensure correct weld metal microstructure.

For the common 304 type steels an E308 grade electrode is normally specified. This has a higher content of nickel and chromium than the 304 base metal. If the steel is a low carbon grade 304L, either a low carbon electrode E308L or a stabilized grade E347 may be suitable. The composition of these electrodes also ensures the presence of some delta ferrite in the weld metal which prevents the occurrence of fissures. For grades containing other alloy elements such as molybdenum (e.g., 316) an electrode with a matching content of that element is needed (e.g., E316 electrode).

When the procedure involves welding onto a carbon steel an electrode with sufficient alloy content to handle the dilution must be used. The Schaeffler diagram can be used to determine the required composition but in many cases with SMAW an E309 is satisfactory. For example, in a weld cladding or surfacing operation on carbon steel the first layer would be deposited with E309 then subsequent layers made with E308. This ensures that martensite is not formed in the first layer. Fig. 39 illustrates this.

Some grades, such as 310, are designed to be fully austenitic and must have completely austenitic weld metal from the appropriate electrodes E310. Because they do not have the assistance of ferrite to

Selecting the
electrode

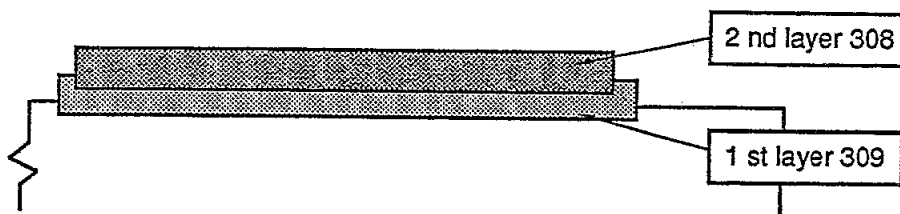


Figure 39. Overlay using two layers. The first layer is 309 to minimize the risk of martensite formation.

Weld properties

prevent cracks, special care is needed to weld them, particularly in high restraint joints. Electrodes for fully austenitic weld metal generally have lower specified phosphorous and silicon.

It will be recalled that the properties of austenitic stainless steels allow them to be used not only in corrosive environments but at high temperatures and at very low temperatures. Fig. 40 shows some typical charpy impact results on 308 weld metal at several temperatures. The curve does not exhibit the sharp transition temperature phenomenon that is characteristic of carbon steels. The low temperature toughness of austenitic weld metal is reduced by the presence of large amounts of ferrite and impurity elements.

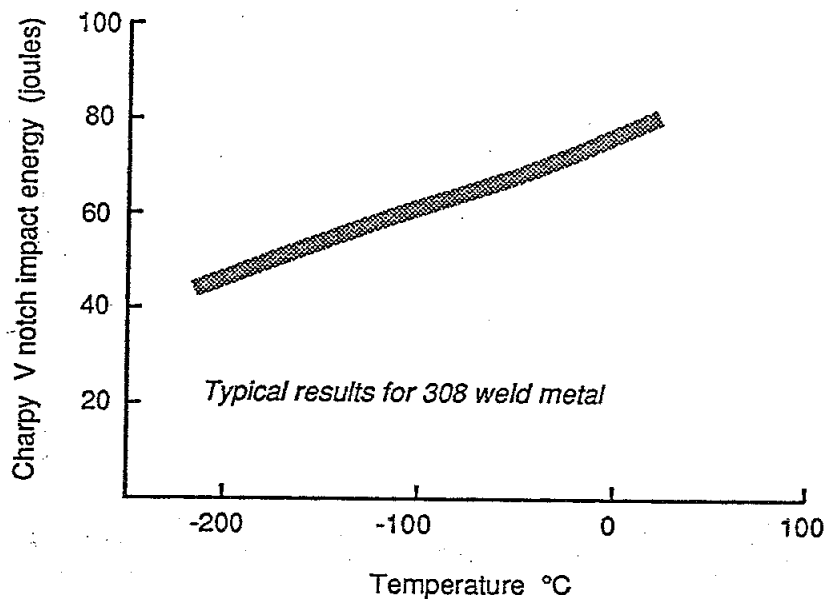


Figure 40. Typical charpy V-notch properties for austenitic weld metal.

Welding Metallurgy of Stainless Steels

Table 9. Typical stress-rupture strengths for austenitic stainless steels.

Type	Stress MPa							
	1000 hour failure				10 000 hour failure			
	Test temperature °C				Test temperature °C			
	540	650	760	870	540	650	760	870
201		145	50		114			
304	241	99	41	19	186	69	27	13
309		138	51	19		103	30	12
310	220	94	35	17	165	59	21	9
316		170	76	28		125	48	12
321		121	39			68	25	
347		120	51	21		77	17	

High temperature strength

The high temperature strength of austenitic weld metal is shown in Table 9 for some typical compositions, and the typical creep rupture strength of 308 weld metal is shown in Fig. 41.

Exposure for long periods at high temperatures can cause a degradation in the toughness (when measured at room temperature) and is associated with the presence of ferrite. Large amounts of ferrite (about 15%) lead to the formation of the brittle sigma phase which lowers the toughness. Smaller amounts of ferrite have less of an effect on the toughness but can revert back to austenite during long term exposure to high temperatures with a corresponding precipitation of carbides.

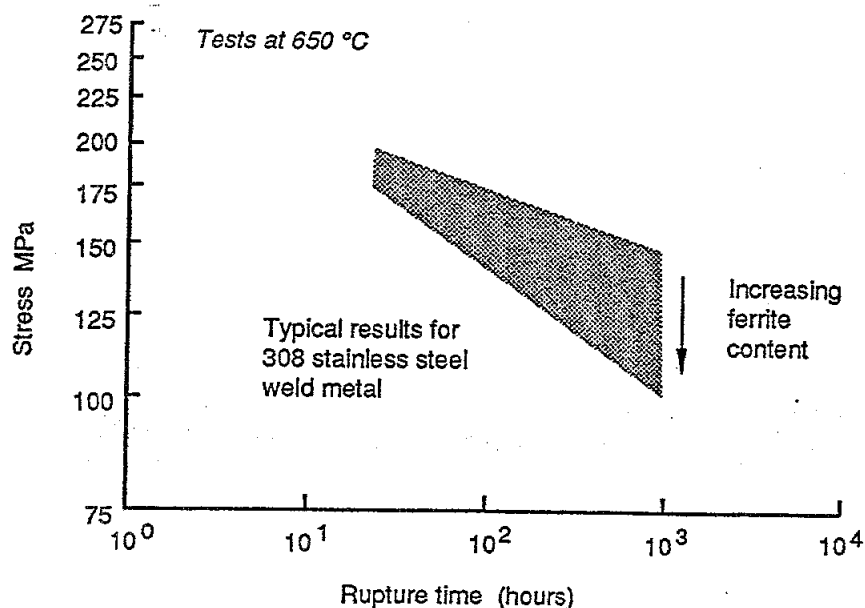


Figure 41. Creep rupture strength of 308 weld metal at 650°C. Strength is lowered by the presence of ferrite.

WELDING MARTENSITIC STAINLESS STEELS

Electrodes

Martensitic stainless steels can be welded with matching electrodes that produce a martensitic weld deposit or with austenitic electrodes. If the weld metal must match the base material in hardness and wear resistance then the martensitic weld metal must be used. If, however, hardness is not a consideration and only corrosion resistance is a factor, then the use of austenitic electrodes facilitates welding.

Cracking

The chief difficulty in welding martensitic steels is the avoidance of cracking. Cracking is the result of the high hardness of martensite in the heat affected zone and weld metal and is assisted by the presence of hydrogen. The welding procedure must control sources of hydrogen such as moisture, dirt, grease, and other contaminants, and an adequate preheat must be applied and maintained. Post-weld tempering or annealing should be carried out immediately without letting the part cool down.

Preheat

The level of preheat required depends on the carbon content in the steel. Some ranges are suggested in Table 10. Since martensitic transformation is 90% complete by the time the weld cools to below about 300°C the level of preheat has little effect on the hardness produced but is effective in removing hydrogen. The carbon content

Table 10. Typical preheat levels for welding martensitic stainless steels.

Carbon content	Typical preheat °C (°F)
< 0.10	preheat and post heat not usually required
0.10-0.20	250 (480); cool slowly
0.20-0.50	250 (480); immediate post weld anneal
> 0.50	250 (480); high heat input, immediate post weld anneal

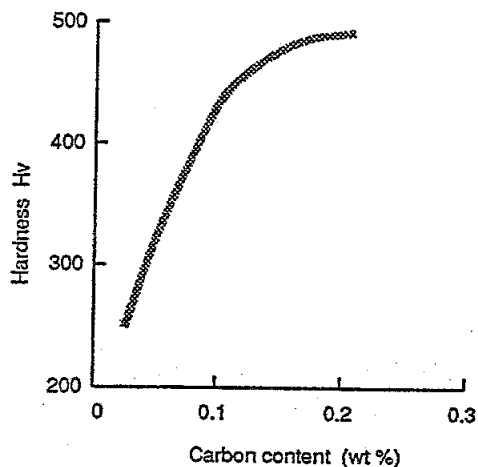


Figure 42. The effect of carbon content on the HAZ hardness of a martensitic stainless steel in the as-welded condition.

Post-weld heat treatment

determines the hardness of the as-welded HAZ and weld metal as shown in Fig. 42. In most cases an immediate post-weld heat treatment is required. A full anneal would involve heating to at least 850°C followed by a controlled furnace cool to 625°C and then an air cool. This treatment gives maximum softening. The more common procedure is to give a temper or sub-critical annealing treatment involving heating at 650° to 750°C for one hour per inch of thickness followed by air cooling (Fig. 43).

The effect of tempering on the hardness of a 12% chromium martensitic steel is shown in Fig. 44. The time temperature parameter can be used to estimate equivalent times and temperatures for equal tempering. For the lower carbon steels (less than 0.2 % C) the post-weld heat treatment is sometimes omitted, but slow cooling of the part after welding is still recommended to avoid cracking.

Figure 43. Typical post-weld heat treatments for martensitic stainless steels.

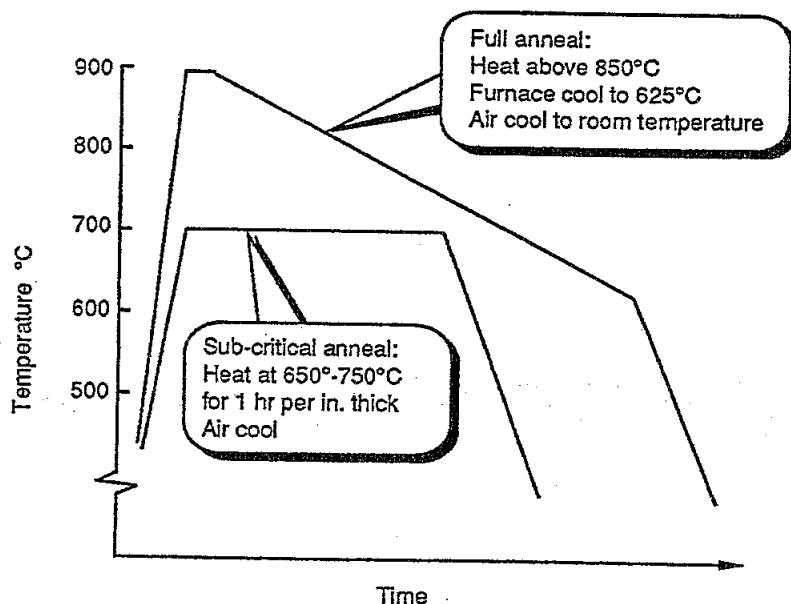
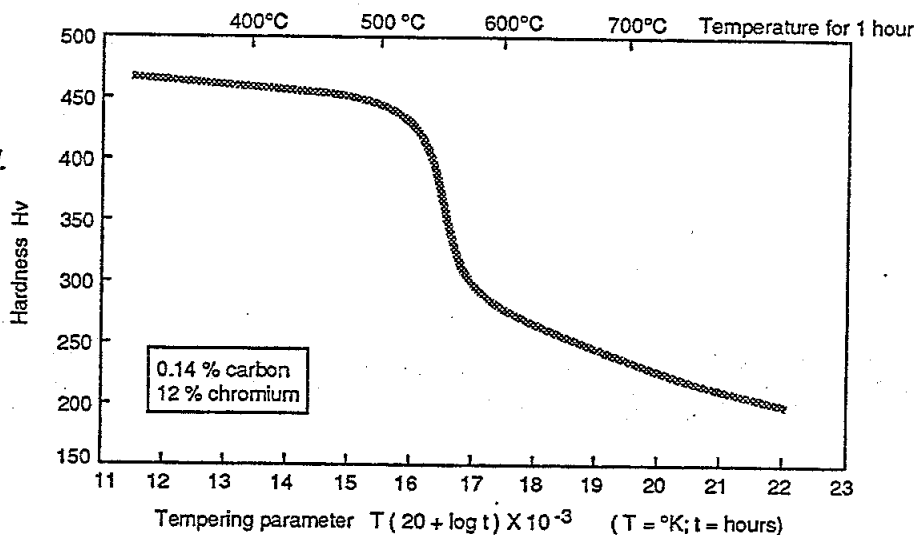


Figure 44. Tempering curve for a typical martensitic stainless steel. The effects of both time and temperature are included in the tempering parameter.



Temper embrittlement

Tempering within certain temperature ranges can result in a decrease in the room temperature toughness of the weld, an effect known as temper embrittlement. Fig. 45 shows some typical results and if toughness is to be maintained the embrittlement range must be avoided during tempering, the part being cooled sufficiently fast through that range.

If austenitic electrodes are employed, a preheat may still be necessary to avoid cracking in the heat affected zone although the joint will be far less sensitive to cracking. Austenitic electrodes of the E309 type are often specified when joining a martensitic stainless steel to another material such as carbon steel or austenitic stainless steel. A typical procedure would involve buttering the martensitic steel with 309 to form a layer of austenitic weld metal before welding to the other material.

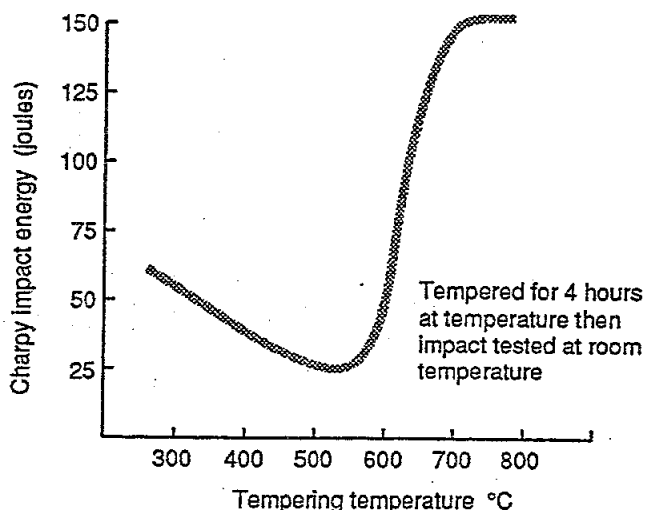


Figure 45. Temper embrittlement may result from tempering within certain temperature ranges. Graph shows the room temperature Charpy properties after tempering at the temperatures indicated. Careful control of the post-weld heat treatment temperature is necessary to avoid the temper embrittlement range.

WELDING FERRITIC STAINLESS STEELS

Grain growth

Most ferritic stainless steels do not undergo any phase change when they are heated and therefore there is no recrystallization of the grains. Without this the existing grains continue to grow as the temperature is raised with the result that large grains exist after the steel is welded. The extent of grain growth depends to a large degree on the heat input of the welding process, and careful control of this may limit grain growth to acceptable levels (Fig. 46). Large grains have a detrimental effect on the toughness of the steel which can exhibit severe embrittlement in the weld and heat affected zone after welding. Remember that grain growth that occurs during welding of a ferritic stainless steel cannot be corrected by a subsequent heat treatment since there is no recrystallization on heating. Damage done during welding is therefore permanent, making it imperative that welding is performed within the heat input restrictions applied.

Some of the ferritic grades having a relatively high carbon content, such as 430, 434, 442 and 446, may undergo partial transformation to austenite on heating and subsequently form small amounts of martensite on cooling. Although this is not enough to make the steels hardenable it does contribute to the degradation of toughness. The risk of cracking associated with the low toughness can be reduced

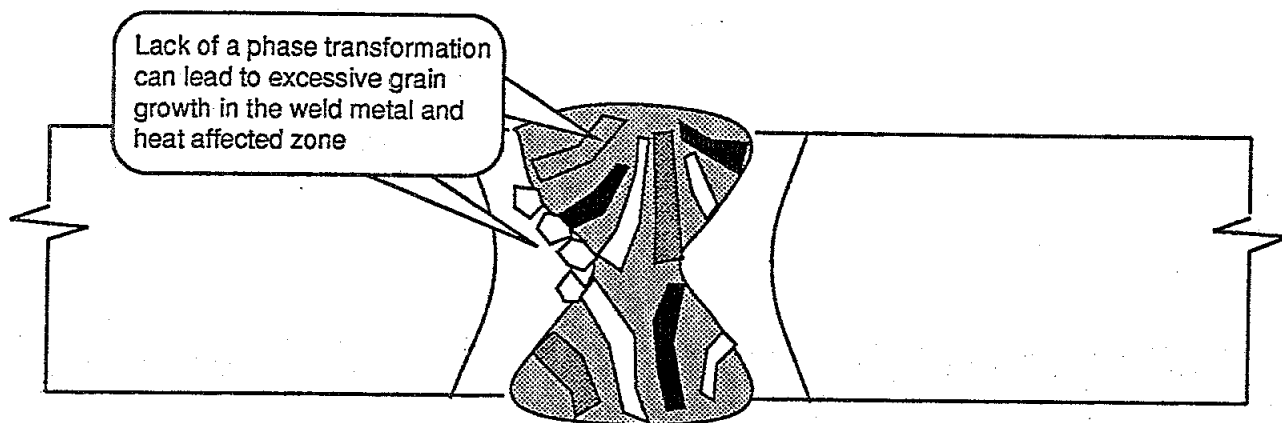
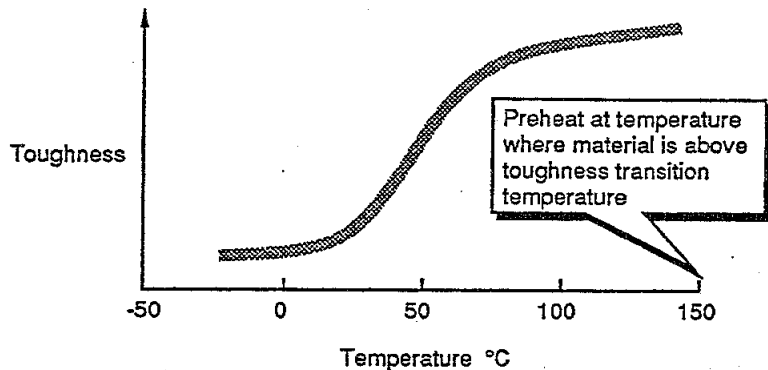


Figure 46. High heat input in welding can cause excessive grain growth in ferritic stainless steels because there is no phase transformation to austenite on heating. This also means that grains cannot be refined by a subsequent post-weld heat treatment.

Figure 47. Preheat temperatures for welding ferritic stainless steels should be above the toughness transition to reduce risk of cracking.



Preheating

by preheating for welding. As we illustrate in Fig. 47 this has the effect of raising the temperature of the steel above its ductile-to-brittle transition temperature, removing hydrogen and reducing residual stresses. Typically preheat temperatures of about 150°C are employed, but high interpass temperatures should be avoided because of their contribution to grain growth.

Contamination

Many of the ferritic stainless steels can be joined with matching filler metals although there may be limitations on availability. When welding the low interstitial grades low levels of nitrogen and carbon must be maintained in the weld metal, and inert gas shielded processes such as GTAW are recommended. Where shielded metal arc welding must be used austenitic electrodes have proven a useful alternative in some applications. Welding ferritic steels requires careful control of procedures to avoid contamination by oxygen and particularly by the interstitials carbon, nitrogen, and hydrogen (Fig. 48). Even small quantities of interstitials can greatly embrittle the weld metal and heat affected zone. Some of the practical steps that can be taken to avoid contamination are discussed in a later section.

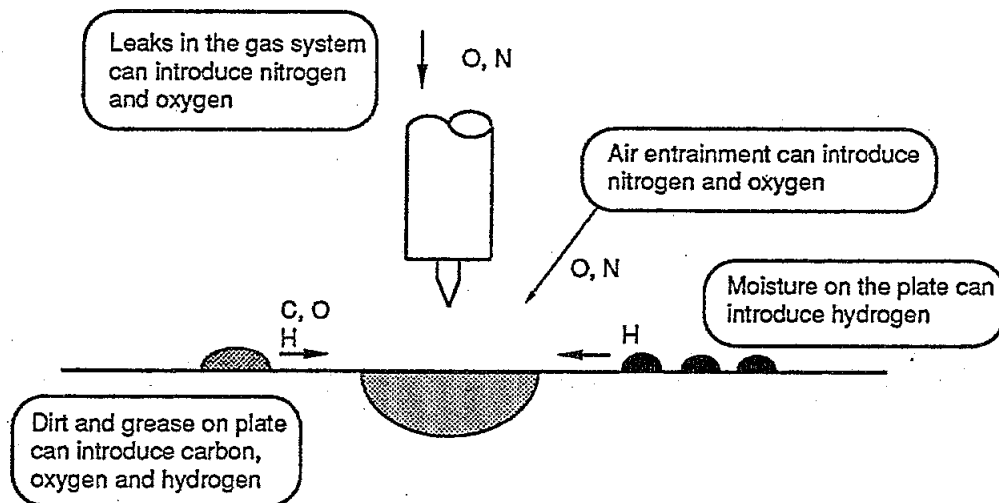


Figure 48. Possible sources of contamination in welding ferritic stainless steels.

WELDING DUPLEX STAINLESS STEELS

Austenite/ferrite
content

Duplex stainless steels rely on a balance of austenite and ferrite in the microstructure to provide a unique combination of properties. The optimum phase balance is normally considered to be about 50:50. Numerous problems can arise when the austenite:ferrite ratio is not correct. For example, relatively little austenite can lead to poor toughness and loss of general corrosion resistance while excessive austenite will lower the strength and can impair stress corrosion cracking resistance.

During solidification a duplex steel will initially solidify as ferrite. The ferrite to austenite transformation subsequently occurs in the solid state at temperatures in the range of 1100°- 1300°C. In wrought material this effect is achieved and controlled by appropriate heat treatment. In the case of welding, however, fast cooling rates can suppress the ferrite to austenite transformation in the weld metal such that it can contain significantly higher ferrite contents than the base material. Stop-starts are particularly susceptible to this effect in the HAZ. Precipitates such as carbides are also a factor which can influence properties during the welding of duplex stainless steels.

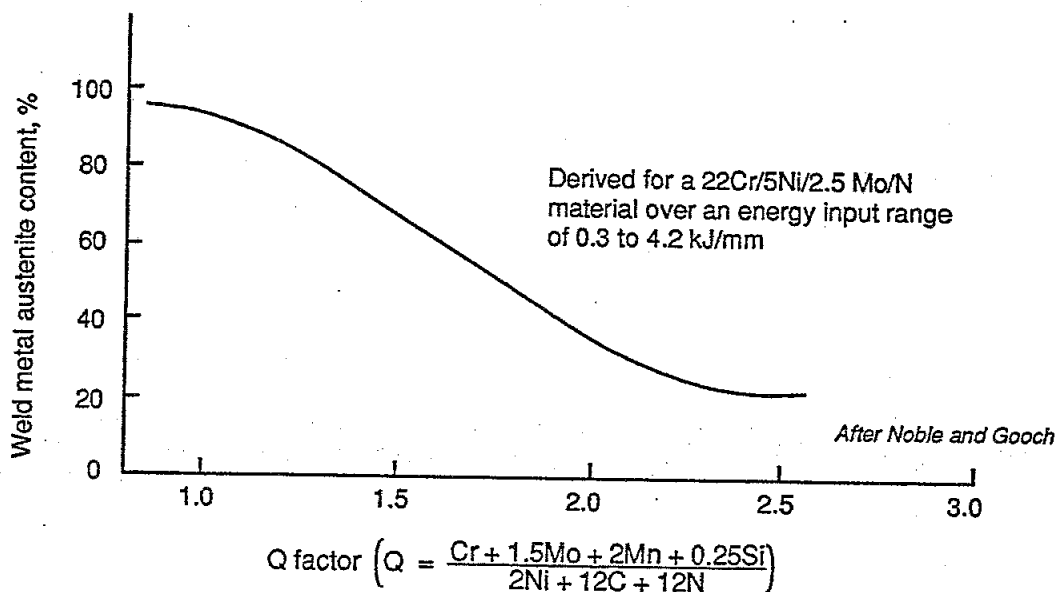


Figure 49. Q factor v. weld metal austenite content.

Composition also plays an important role in the transformation process and compositional factors have been derived for particular steels as shown in Fig. 49.

Matching filler metals are often used for duplex stainless steels but with somewhat higher nickel content to provide an optimum austenite content. The role of nickel is evident for the "Q" factor in Fig. 49.

HAZ properties

In the HAZ the effect of peak temperature and cooling rate on ferrite content and impact toughness is shown in Fig. 50. Hence it can be seen that the welding of duplex stainless steels is more demanding than that required for standard austenite grades. This arises from the difficulty in balancing the ferrite:austenite ratio in the welded joint and from the precipitation of intermetallics during welding, cooling, and reheating. Improper welding can lead to loss of corrosion resistance and mechanical strength. Procedure testing and control of welding operations through detailed procedure specifications are essential to ensure that the properties of welded joints are maintained.

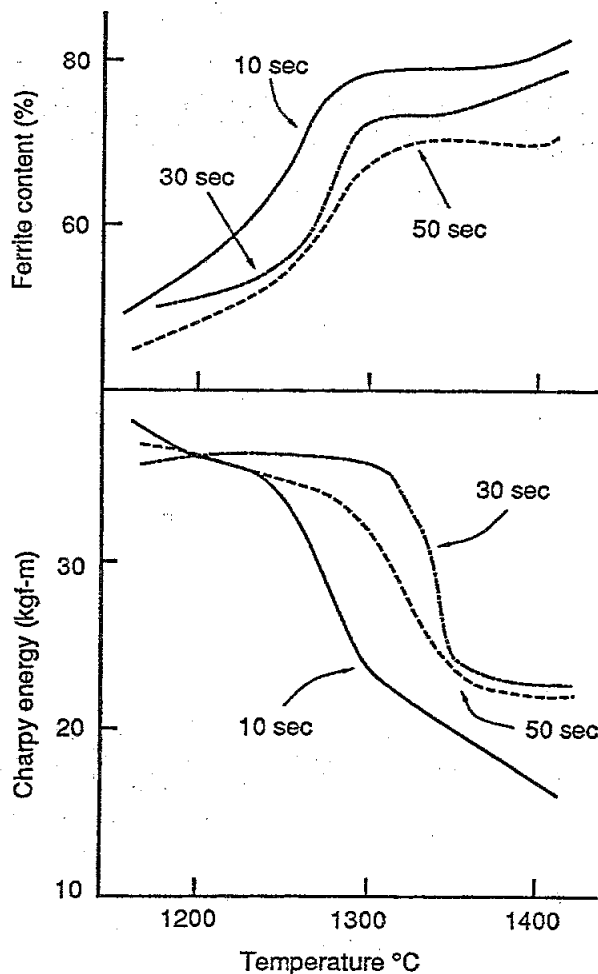


Figure 50. Effect of peak temperature and cooling rate between 800°-500°C on ferrite content and impact toughness values in thermally cycled duplex stainless steel. After Ogawa.

WELDING PRECIPITATION HARDENING STAINLESS STEELS

Effects of heating

The precipitation hardening stainless steels rely for their strength on a heat treatment that results in precipitation of small particles in the matrix. The first observation we make in discussing the welding of these steels is that the heat from welding will upset the effects of the initial heat treatment. Close to the fusion boundary is a solution treated region in which precipitates are re-dissolved, and further away there exists an overaged region (Fig. 51). The consequence of this is that to achieve matching, full strength, the weld must undergo the complete heat treatment after welding, involving solution treatment and aging. If the weld is subject to full post-weld heat treatment the original condition of the material is not significant but is normally annealed.

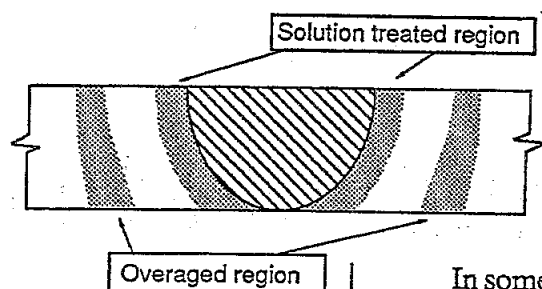


Figure 51. Regions of the HAZ where the strength may drop. Close to the fusion boundary precipitates are dissolved. In the region further away strength may drop due to overaging.

In some cases where full matching strength is not required or full heat treatment not possible, a post-weld aging only is applied. For this treatment the material must be in the solution treated condition for welding.

The martensitic and semi-austenitic types are relatively easy to weld and despite the formation of martensite the very low carbon levels in these alloys prevents hydrogen cracking. Preheat is not required. The austenitic types, however, are difficult to weld because of hot cracking in the heat affected zone. They are often welded using nickel based filler metals.

Electrodes

For full strength a filler metal matching the base metal in composition is specified and this may determine the type of welding process that can be used. A variety of precipitation hardening agents are employed including copper, niobium (columbium), titanium, and aluminum. Those that are highly oxidizable, such as titanium and aluminum, cannot be used in covered electrodes and inert gas shielded processes, GTAW and GMAW, must be employed. Even with GMAW the use of argon with 2% oxygen for arc stability and improved wetting may cause a loss of titanium or aluminum during transfer to the weld pool.

PROCEDURES FOR WELDING STAINLESS STEEL

Shielding

There are a number of factors we need to consider when selecting a welding process for stainless steels. First, we recall that chromium is highly reactive with oxygen forming a refractory oxide that can be difficult to remove. Good shielding of the molten weld pool is essential to limit contamination by oxygen, and for many applications inert gas shielded processes are preferred. Even when shielded metal arc welding is used, additional protection from an inert gas may be desirable in some applications. When welding from one side, protection of the reverse side by gas shielding is recommended practice, as Fig. 52 illustrates.

GTAW and GMAW with argon or helium/argon mixtures have the advantage that reactive elements such as aluminum and titanium are transferred across the arc without significant losses which makes these processes attractive for alloys of the 321 type.

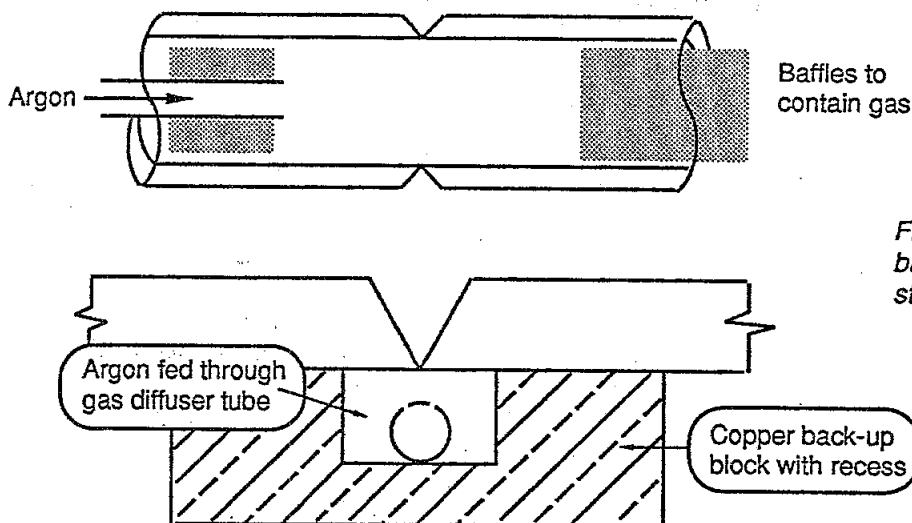


Figure 52. Typical methods for back shielding when welding stainless steel from one side.

When CO_2 is added to argon base shielding gas for the GMAW process, carbon pickup in the weld metal can occur as shown in Fig. 53. Caution should be exercised when welding the low carbon grades. Depending on the carbon content of the filler metal, CO_2 in the shielding gas can increase the weld metal carbon level beyond 0.03%.

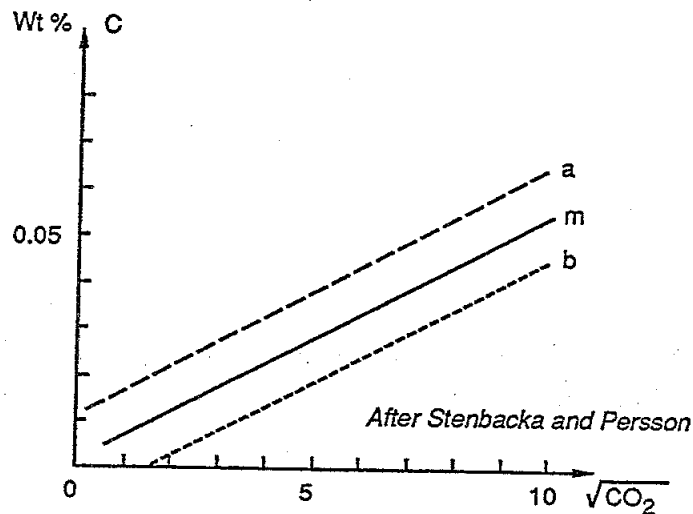


Figure 53. Carbon pickup as a function of the CO_2 content in argon for gas metal arc welding (ELC weld metal). The data in the figure are values taken from different sources. The line *m* represents an experimental calculated relationship, while lines *a* and *b* represent the scatter limits for 95% probability.

Chromium recovery

Flux shielded processes such as SAW and SMAW can be used for many types of stainless steels. Fluorides are often present in the fluxes to assist in fluxing away chromium oxide formed from air contamination, and the slag residue must be cleaned thoroughly to avoid it promoting corrosion in service. Conventional fluxes for carbon steels should not be used on stainless steels, special fluxes having been developed. Fluxes are designed to give low oxygen but there is inevitably some loss of chromium during transfer from the electrode to the weld pool. Electrode compositions are modified to correct for this, and some submerged arc fluxes of the bonded or agglomerated type will contribute make-up chromium from the flux (Table 11).

Table 11. Typical data showing the effect of welding conditions on the transfer of chromium in an alloy flux designed for stainless steel welding. Make-up chromium is contributed from the flux to balance the losses due to oxidation. The amount transferred from the flux is sensitive to the welding parameters which must be carefully controlled when using these types of fluxes.

	Current	Voltage	%Chromium	
Wire			19.0	12.0
Deposit	580	29	18.5	12.15
	580	26	18.15	11.8
	650	29	18.1	11.8

SMAW electrodes

Flux coverings on SMAW electrodes are generally of two types: lime or titania. Table 12 describes the various classifications in AWS A5.4-92 "Specification for Stainless Steel Electrodes for Shielded Metal Arc Welding."

Table 12. AWS Specification for Stainless Steel Electrodes for Shielding Metal Arc Welding.

AWS Classification	Electrode Coating	Current Type	Welding Position	Operating Characteristics
EXXX(X)-15	Lime	DC	All	Excellent metallurgical properties
EXXX(X)-16	Titania	DC or AC	All	Good bead profile
EXXX(X)-17	Titania/Silica	DC or AC	All	Fine spray arc with very smooth bead profile
EXXX(X)-25	Lime	DC	Horizontal Flat	Similar to -15 but core wire may be mild steel
EXXX(X)-26	Titania	DC or AC	Horizontal Flat	Similar to -16 but core wire may be mild steel

Cleaning

Of paramount importance in welding all types of stainless steels is the need for cleaning prior to and after welding. The unique corrosion properties of the steel may be destroyed by the presence of contaminants picked up on the surface during welding operations. Chlorides and other members of the halogen family contribute to stress corrosion cracking and should be avoided. Fluids, such as degreasing agents, machining and cutting fluids should be halogen free.

Carbon contamination requires careful control, particularly when welding the low carbon and ferritic steels, and among the necessary precautions are:

- Use stainless steel cleaning brushes
- Use tools reserved for stainless steel
- Use aluminum oxide grinding wheels reserved only for stainless steel
- Carefully clean off grease and dirt before welding
- Do not use electrodes with cellulose in the covering
- Do not use 100% CO₂ for shielding

Welding Metallurgy of Stainless Steels

Joint preparation

Conventional flame cutting with oxy-acetylene cannot be used with stainless steels. Oxy-acetylene flame cutting of steel works not by melting the metal but by oxidizing it. The resulting oxide melts and is removed. The oxidation of iron is retarded by the presence of chromium in stainless steels which tends to form a solid, high melting point oxide. For thermal cutting, either powder cutting or plasma is needed. In the powder process an iron-rich powder is introduced into the oxygen stream which accelerates the oxidation reaction facilitating the cut. Thermally cut weld preparations require machining or grinding to provide an acceptably clean surface for welding.

The thermal characteristics of austenitic stainless steels permit a narrower groove angle to be used without increasing the risk of incomplete fusion consistent with proper access. It is common practice in thick sections to machine a U or J groove preparation thus minimizing the amount of filler metal required. Some typical preparations are shown in Figs. 54, 55 and 56. If backing or inserts are used they must be of the same alloy as the base metal.

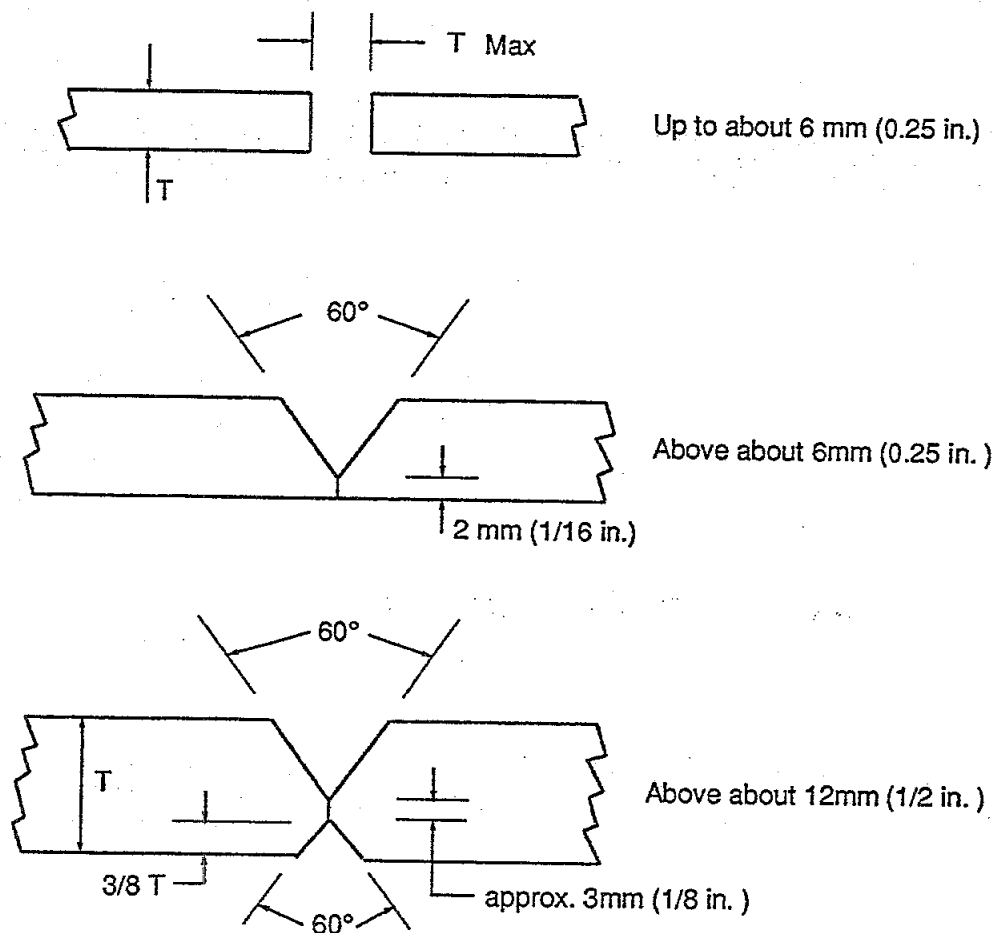


Figure 54. Typical joint preparations for GTAW in stainless steel.

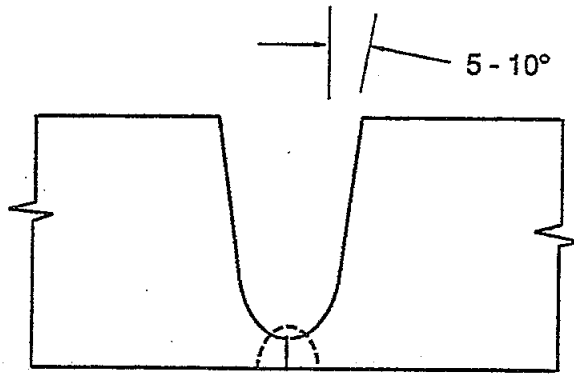
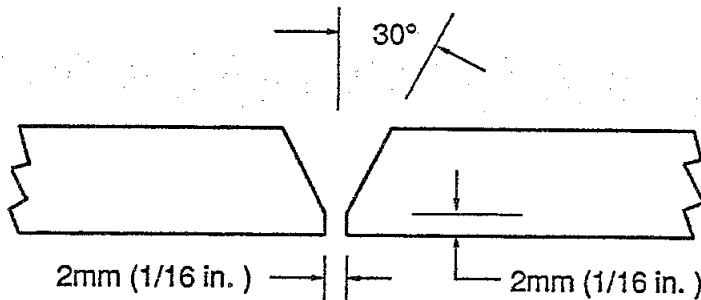


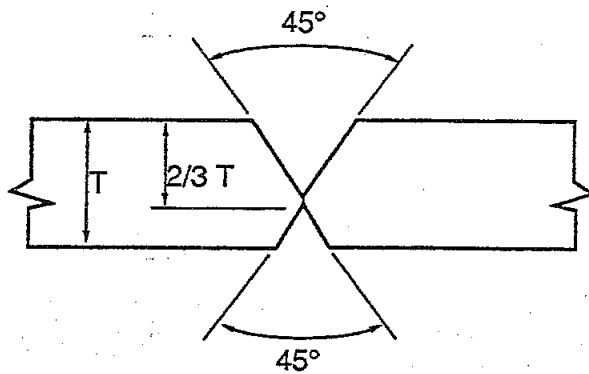
Figure 55. Typical joint preparation for SAW of thick sections.



Up to about 5 mm (3/16 in.)



From about 6 to 19 mm (1/4 to 3/4 in.)



Over 19 mm (3/4 in.)

Figure 56. Typical joint preparations for GMAW of stainless steel.

Dissimilar metals

Although machined preparations allow for excellent fit-up, distortion during welding of stainless steels is higher than for carbon steels. When welding thin sections, typically less than 6 mm (1/4 in.), good clamping and fixturing is required.

Frequently the welding engineer must specify a procedure for welding dissimilar metals. Joints between stainless steel and carbon or other steel occur frequently in chemical and power plants, particularly in piping where different materials are selected for various temperature regimes.

Buttering

A number of special techniques have been developed for welding dissimilar metals, in particular austenitic steels to carbon steel. The first consideration is selecting the electrode which must have adequate alloy elements present to handle the effects of dilution and still yield an acceptable metallurgical structure. As discussed earlier, in many cases a 309 is suitable for welding onto carbon steel, but care must be exercised to limit the degree of dilution. A common procedure is to butter the carbon steel with 309 first to form a layer of austenitic weld metal then complete the weld as a conventional stainless steel weld (Fig. 57). The buttered carbon steel may need to

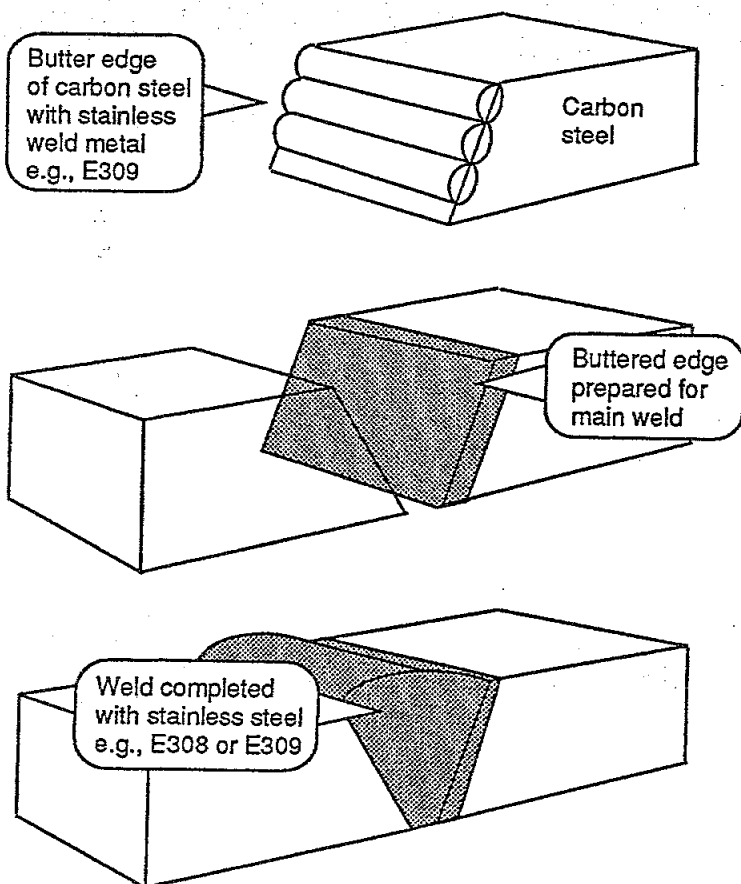


Figure 57. Typical method of making a dissimilar metal (carbon steel to stainless steel) joint.

Thermal stresses

be stress relieved (tempered) prior to completing the joint. In this way the carbon steel can be stress relieved without exposing the stainless steel to a heat treatment that might sensitize it.

A further important consideration in selecting a procedure for a dissimilar metal joint is the effect of differences in the physical properties. If the properties, particularly the coefficient of thermal expansion, are greatly different, stresses can be built up in the weld. This is very likely when the joint must enter high temperature service. High stresses can lead to cracking and failure of the joint.

In some cases it is possible to select a weld metal that has properties that minimize the build-up of stress. Often weld metal with a coefficient of expansion midway between the two metals is specified. No clear rules can be given because it depends on the alloys being welded, service conditions and other constraints, and the welding engineer must address each case on its own merits.

Welding clad steel

It is common practice when designing thick walled vessels to specify clad steel rather than solid stainless steel. The thin layer of stainless cladding provides the necessary corrosion resistance while the thick carbon steel provides the mechanical strength. The overall cost can be considerably less. Special techniques, however, are required in welding clad steels.

The technique must be designed to ensure freedom from weld defects, correct metallurgical structure, and correct composition of the final clad layers that are exposed to the corrosive environment. Special restrictions may be placed on the composition of the exposed layers such as a maximum carbon content, and detailed attention to dilution effects is required. If, for example, we require less than 0.03% carbon in the clad layer, and the base steel has 0.2% carbon, then several buffer layers are needed between the carbon steel and the exposed layer to obtain an adequately low carbon level.

Basic methods

There are three basic methods employed for welding clad steel:

- 1) Peel back the cladding, complete the joint as though it were a carbon steel then overlay the peeled back region with stainless.
- 2) Complete part of the joint from the carbon steel side using carbon steel electrodes then finish from the clad side using stainless.
- 3) Use stainless weld metal throughout the joint.

The sequences employed in these three methods are illustrated in Figs. 58, 59 and 60. All the methods involve depositing stainless steel weld metal onto carbon steel and the principles discussed earlier apply. The stainless steel filler metal must have adequate chromium and nickel to prevent the formation of martensite after dilution with the carbon steel. Method 3 uses the most stainless steel filler metal and would only be economical in thin sections.

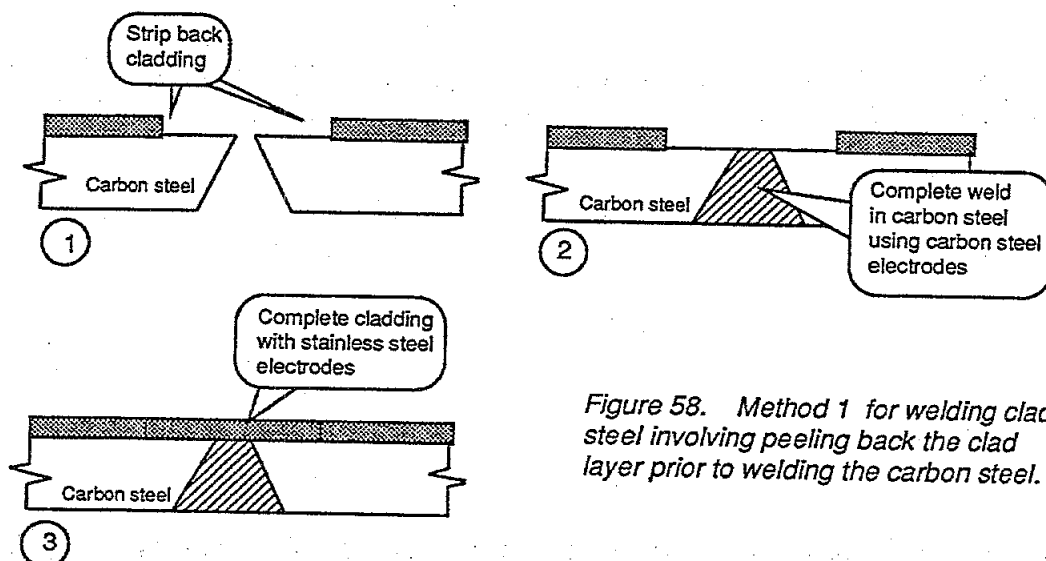


Figure 58. Method 1 for welding clad steel involving peeling back the clad layer prior to welding the carbon steel.

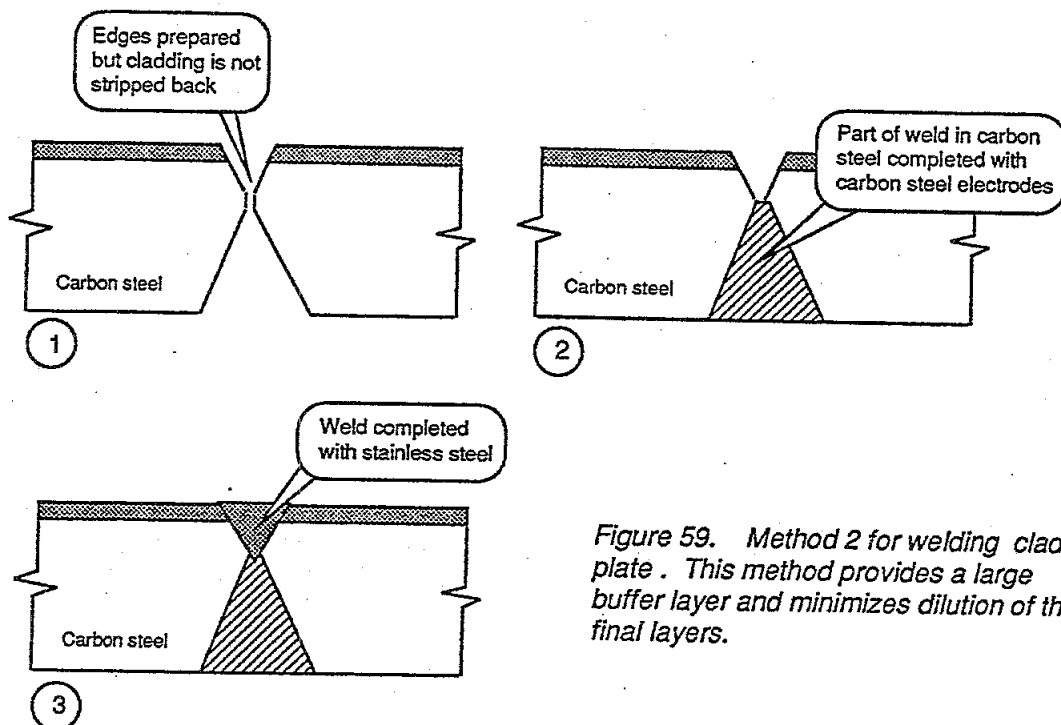


Figure 59. Method 2 for welding clad plate. This method provides a large buffer layer and minimizes dilution of the final layers.

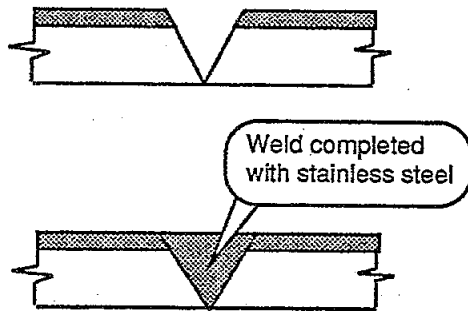


Figure 60. Method 3 for welding clad plate, suitable only for thin material.

Methods 2 and 3 allow more buffer layers of stainless steel between the carbon steel and the final layers, and these techniques may be preferred when very low carbon is specified. Method 2 uses the least amount of stainless steel filler metal and is the most economical, but there is a greater risk of the first pass of the carbon steel weld melting through and picking up alloys from the cladding. If this happens cracking is very likely, and the offending pass must be completely removed before re-welding. When using method 1 or 2 in thick sections a stress relief is sometimes specified after the carbon steel weld is completed to reduce the risk of cracking when depositing the stainless weld metal.

Summary

Most of the problems in welding stainless steels arise from basic errors: incorrect choice of electrodes, for example. Correctly specifying a stainless steel welding procedure requires a good comprehension of the underlying metallurgical principles which has been the topic of this module. We have discussed the effects of nickel and chromium on metallurgical structure, and shown how some elements promote austenite while others favour ferrite. We described the Schaeffler, DeLong and WRC diagrams which predict weld metal structure. It was described how these diagrams could be used to select the correct composition of an electrode to provide, for example, adequate δ ferrite to avoid hot cracking. We discussed sensitization, stress corrosion cracking, and the consequences of chromium oxidation. The main features of welding procedures for austenitic, ferritic, and martensitic steels, and dissimilar metal joints were introduced.

Having successfully completed this module you will be able to recognize potential metallurgical problems in welding stainless steels and select the main features of a welding procedure to successfully weld them. It is recommended, however, that you consult the supplier and other resources for exact details for welding specific alloys.

Additional Resources

Below is a short list of additional sources of information that may help you in your study of the Welding Metallurgy of Stainless Steels.

1. Welding aspects are covered in:

- *Welding Handbook*, Seventh Edition, Vol. 4
American Welding Society, 550 N.W. LeJeune Road,
Miami, FL 33126, U.S.A.
- *Metals Handbook*, Tenth Edition, Vol. 6
American Society for Metals, Metals Park, Ohio 44073,
U.S.A.
- *Welding of Stainless Steels and other Joining Methods*
1979 American Iron and Steel Institute, 1000 16th Street
N.W. Washington, DC., U.S.A.

2. There is an extensive literature covering cracking and ferrite in stainless steel weld metals. This was the topic of the 1974 Adams Lecture:

- *Ferrite in Austenitic Stainless Steel Weld Metal*,
by W. T. DeLong, Welding Journal Research Supplement,
July 1974 pp 273-s to 286-s.

Diagrams for predicting stainless steel weld metal structure have been reviewed by Olsen:

- *Prediction of Austenitic Weld Metal Microstructure and Properties*, D. L. Olsen, Welding Journal Research Supplement, October 1985 pp 281-s to 295-s.

3. For information on welding specific alloys you should contact the various suppliers.

Welding Metallurgy of Stainless Steels

GUIDES AND EXERCISES

MODULE 22

WELDING METALLURGY OF STAINLESS STEELS

WELDING METALLURGY OF STAINLESS STEELS

MODULE 22

Guides & Exercises

To obtain maximum benefit from this module we suggest that you follow this guide and complete the exercises as indicated. It is important that you work through the text methodically, studying each section thoroughly before moving on. The exercises are designed to give you an indication of whether you have learned the material and can move on or whether you need to go back and study the section again.

Do the exercises honestly. They will not help you unless you take them seriously. If you get a question wrong go back through the text until you understand where you have gone wrong and know the correct answer.

The length of time required to complete the module will vary from student to student. Find your own pace. Do not rush. Remember you are trying to learn something, not win a race.

Some people like to underline sections when they read a text. We suggest that you use caution if you do this. What you think is important first time you read it may be different after reading it three times. We suggest you read a section three times thoroughly before highlighting anything.

The last exercise is designed to give you an indication of whether you are ready to take the closed-book exams. The exercise questions are of a similar standard to the official exams. Do not take the exam until you feel you are ready, and you may wish to study several Modules before taking the exams on each. The details of the examination procedures are on a separate sheet.

If you have any difficulties with this Module do not hesitate to ask for help. You may find you learn more by attending seminars, and you should also contact your local WIC Chapter to see if they can be of assistance. Remember, if you fail the examination you can always try again later.

MODULE 22

Guide 1

Carefully read pages 1 to 7 and answer the following questions:

1. Complete the following:
 - a) Chromium stabilizes the _____ form of iron
 - b) Nickel stabilizes the _____ form of iron
2. If a straight chromium steel of 18% Cr and < 0.1% C is heated to 1000°C will it transform to austenite or remain as ferrite?
3. What is the predominant structure of an 18% Cr, 8% Ni steel at room temperature?
4. The chromium content of a stainless steel is 20%. Is it likely this is a martensitic grade?
5. What does the letter L signify in the designation 316L?
 - a) low chromium
 - b) longitudinal specimen
 - c) low carbon (maximum 0.03%)

Check your answers for accuracy. If any of your answers are wrong re-study the guide subject matter in the text until you understand it.

Welding Metallurgy of Stainless Steels

MODULE 22

Guide 2

Carefully read pages 8 to 17 and answer the following questions:

1. A 14% Cr martensitic steel heated to 1000°C and air cooled produces—
 - a) ferrite
 - b) austenite
 - c) martensite
2. Determine the minimum specified titanium content of a type 409 ferritic stainless steel with 0.05% carbon.
3. Does an austenitic stainless steel have a greater or lesser work hardening rate than carbon steel?
4. A carbon steel component operates satisfactorily at 500°C under a stress of 50MPa. If 304 stainless were substituted, up to what level could the temperature be raised?
5. True or false?
"100% CO₂ is not generally used for GMAW of stainless steels"

Check your answers for accuracy. If any of your answers are wrong re-study the guide subject matter in the text until you understand it.

MODULE 22

Guide 3

Carefully read pages 18 to 24 and answer the following questions:

1. The loss of corrosion resistance due to carbide formation and chromium depletion is known as—
 - a) sigma formation
 - b) sensitization
 - c) stabilization
2. What maximum carbon level is usually specified to ensure freedom from sensitization during welding?
 - a) 0.03%
 - b) 0.003%
 - c) 0.3%
3. The presence of residual delta ferrite in the weld metal indicates that primary solidification was—
 - a) ferrite
 - b) austenite
4. A method of controlling weld metal fissuring is—
 - a) to always use a stabilized weld metal
 - b) to ensure primary solidification is austenite
 - c) to ensure there is a small amount of residual delta ferrite in the weld metal

Check your answers for accuracy. If any of your answers are wrong re-study the guide subject matter in the text until you understand it.

MODULE 22

Guide 4

Carefully read pages 25 to 33 and answer the following questions:

1. For the following weld metal (E312) draw a box on the Schaeffler diagram showing the possible range of structures:

8–10.5%Ni; 28–32%Cr; 0.15%C max; 0.5–2.5%Mn; 0.9%Si max; 0.75%Mo max.
2. Use the DeLong diagram to estimate the ferrite number of a weld metal with composition: 13.3%Ni; 20.1%Cr; 0.03%C; 0.6%Si; 1%Mn; 0.01%N.
3. A stainless steel deposit is made on mild steel (0.2%C, 1%Mn) with 50% dilution. What should the Ni and Cr equivalents of the electrode be to avoid formation of martensite in the deposit?

Check your answers for accuracy. If any of your answers are wrong re-study the guide subject matter in the text until you understand it.

MODULE 22

Guide 5

Carefully read pages 34 to 44 and answer the following questions:

1. True or false:
"Welds in austenitic stainless steels are always preheated to prevent hydrogen induced cracking"
2. When a two layer overlay of stainless on carbon steel is made it is common practice to use E308 for the second layer and E _____ for the first layer.
3. Weld metal containing large amounts of ferrite and exposed to high temperature service may:
 - a) suffer embrittlement due to sigma formation
 - b) have improved ductility due to ferrite growth
 - c) become air hardening
4. Preheat is usually required for welding martensitic stainless steels:
 - a) to prevent cracking
 - b) to soften the HAZ
 - c) to promote ferrite
5. Why would 650°C be a better temperature to specify for a PWHT of a welded martensitic stainless steel than 550°C?
6. True or false:
"Ferritic stainless steels are very tolerant of contamination during welding because of their very high ductility"

Check your answers for accuracy. If any of your answers are wrong re-study the guide subject matter in the text until you understand it.

MODULE 22

Guide 6

Carefully read pages 45 to 54 and answer the following questions:

1. Which of the following electrode classifications might be stainless steel electrodes?
 - a) EXXX-27
 - b) EXXX-15
 - c) EXXX-10
 - d) EXXX-16
2. True or false?

"Conventional flame cutting with oxy-acetylene cannot be used with stainless steels"
3. Which of the following actions might reduce the risk of carbon contamination in welding stainless steels?
 - a) use aluminum oxide grinding wheels reserved for stainless steel
 - b) use cellulosic type electrodes
 - c) carefully clean off grease and dirt before welding
 - d) use stainless steel cleaning brushes
 - e) use CO₂ for back shielding the weld
4. If a buttering technique is used to weld 304 stainless to mild steel what should be used for the butter layer?
 - a) E48018 (mild steel)
 - b) E308
 - c) E309
5. If a clad plate is welded using method 2 of Fig. 59 estimate the approximate number of layers of stainless weld metal needed to meet a specified maximum carbon of 0.03% in the final layer. Assume the electrode has 0.02% C, the carbon steel has 0.2% C, and dilution for each pass is 30%.

Check your answers for accuracy. If any of your answers are wrong re-study the guide subject matter in the text until you understand it.

MODULE 22

ANSWERS

Guide 1

1. a) bcc b) fcc
2. remain as ferrite
3. austenite
4. no
5. c)

Guide 2

1. c)
2. 0.3% Ti
3. greater
4. 600°C
5. true

Guide 3

1. b)
2. a)
3. a)
4. c)

Guide 4

2. 5 FN
3. 18 Ni equivalent; 35 Cr equivalent.

Guide 5

1. false
2. E309
3. a)
4. a)
5. to avoid temper embrittlement
6. false

Guide 6

1. b) and d)
2. true
3. a), c), d)
4. c)
5. three

Welding Metallurgy of Stainless Steels

MODULE 22

TEST

This test is designed to determine whether you are ready to attempt the formal examination.

Complete the ANSWER SHEET and compare the results with the TEST KEY. If you score less than 70% we suggest you re-study the material.

1. The presence of chromium in iron stabilizes which crystal structure?
 - (a) hcp
 - (b) cementite
 - (c) fcc
 - (d) austenite
 - (e) bcc

2. A straight chromium steel with <0.1% carbon and 18% chromium when heated to 1000°C will—
 - (a) remain ferritic
 - (b) form martensite
 - (c) transform to austenite
 - (d) cause grain refinement
 - (e) precipitate sigma phase

3. Stabilized austenitic stainless steels such as 347 do not become sensitized in welding because—
 - (a) they have very low carbon that avoids carbide precipitation
 - (b) they contain elements such as niobium (columbium) that tie up the carbon
 - (c) they have higher than average chromium
 - (d) they have a small percentage of ferrite present
 - (e) they are always supplied in the solution annealed condition

4. If a plate of austenitic stainless steel is cold formed it experiences—
 - (a) zero work hardening
 - (b) discontinuous yielding
 - (c) grain growth
 - (d) strain aging
 - (e) a greater spring-back than a comparable plate of carbon steel

5. Weld decay is caused by—
 - (a) excessive grain growth in the HAZ
 - (b) chromium depletion at the grain boundaries due to carbide precipitation
 - (c) loss of chromium during transfer in the arc
 - (d) precipitation of niobium (columbium) carbide at the grain boundaries
 - (e) insufficient ferrite

MODULE 22

TEST continued

6. There is an increased risk of weld metal fissuring when—
 - (a) the steel is not stabilized
 - (b) no preheat is applied
 - (c) the ferrite content is too high
 - (d) the primary solid to form on solidification is austenite
 - (e) chromium depletion occurs on solidification
7. On the DeLong diagram the amount of ferrite is indicated by—
 - (a) the percent ferrite
 - (b) the nickel equivalent
 - (c) the ferrite number
 - (d) the chromium equivalent
 - (e) it is not indicated on the DeLong diagram
8. Which of the following is likely to result in cracking due to martensite formation?
 - (a) E309 deposited over E308 weld metal
 - (b) E309 deposited over 304 stainless steel plate
 - (c) E308 deposited over E309 weld metal
 - (d) E48018 (mild steel) weld metal deposited over E308 weld metal
 - (e) E309 deposited over E48018 weld metal
9. Which of the following processes would not be recommended for welding type 304 stainless steel?
 - (a) GTAW with argon shielding
 - (b) SMAW with EXX-15 electrodes
 - (c) GTAW with helium shielding
 - (d) GMAW with CO₂ shielding
 - (e) GMAW with argon-5% O₂
10. An unstabilized stainless steel with 0.15% carbon has been welded. What heat treatment could be applied to prevent weld decay in service?
 - (a) stress relief at 650°C followed by a furnace cool
 - (b) stress relief at 650°C followed by a quench
 - (c) solution treatment at 1100°C followed by a furnace cool
 - (d) austenitize at 910°C followed by a furnace cool
 - (e) solution treatment at 1100°C followed by a rapid cool

Welding Metallurgy of Stainless Steels

Canadian Welding Bureau Answer Sheet - Module 22

Complete the "Answer Sheet" and compare the results with the "Test Key". If you have a pass mark less than 70%, you are advised to re-study the material.

Please circle only ONE letter corresponding to the answer you think is most correct.

QUESTION	ANSWERS				
1	a	b	c	d	e
2	a	b	c	d	e
3	a	b	c	d	e
4	a	b	c	d	e
5	a	b	c	d	e
6	a	b	c	d	e
7	a	b	c	d	e
8	a	b	c	d	e
9	a	b	c	d	e
10	a	b	c	d	e

The answer key below is provided for your use in the event that you wish to retest yourself.

QUESTION	ANSWERS				
1	a	b	c	d	e
2	a	b	c	d	e
3	a	b	c	d	e
4	a	b	c	d	e
5	a	b	c	d	e
6	a	b	c	d	e
7	a	b	c	d	e
8	a	b	c	d	e
9	a	b	c	d	e
10	a	b	c	d	e

Canadian Welding Bureau
Test Key - Module 22

Compare your answer sheet to this key.

QUESTION	ANSWERS				
1	a	b	c	d	☒ e
2	☒ a	b	c	d	e
3	a	☒ b	c	d	e
4	a	b	c	d	☒ e
5	a	☒ b	c	d	e
6	a	b	c	☒ d	e
7	a	b	☒ c	d	e
8	a	b	c	☒ d	e
9	a	b	c	☒ d	e
10	a	b	c	d	☒ e

Welding Metallurgy of Stainless Steels
