

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

PART OF THE GCIL CERTIFICATE PROGRAMS

GOODERHAM | **CENTRE**
FOR INDUSTRIAL LEARNING

MODULE 23

**WELDING METALLURGY
OF NON-FERROUS METALS
AND CAST IRON**

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MODULE 23

WELDING METALLURGY OF NON-FERROUS METALS AND CAST IRON

Introduction

Although not welded in the same quantities as steel, the non-ferrous metals play an important role in modern engineering, and an understanding of their welding behaviour is essential for the practising welding engineer. To specify a successful procedure for welding a non-ferrous metal you must understand the problems likely to be encountered and the practical controls that can be implemented to avoid them. You will find practical procedures are often significantly different from those for welding steel.

The objective of this module is to provide you with a comprehension of the way in which the properties of non-ferrous alloys and cast iron affect their welding behaviour enabling you to specify appropriate welding procedures. It is not the intent in this module to describe the metallurgy and welding of all non-ferrous metals or provide prescriptions for welding them but rather to discuss the basic principles involved that affect the selection of welding procedures. Thus we will discuss in detail only a limited number of the more common metals. You should, however, be able to extend the general concepts learned to other metals providing the basis on which to devise a welding procedure identifying those parameters requiring careful control in practice.

Aluminum—perhaps the most important in the group of non-ferrous metals—is not discussed in this module since it is thoroughly covered separately in other modules.

Objectives

After successful completion of this module you will be able to:

- List the major properties of non-ferrous metals and cast irons that affect welding.
- Identify the major problems encountered in welding.
- Determine the main elements of a welding procedure for successfully joining non-ferrous metals and cast irons.

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

Table 1. Common non-ferrous metals.

Metal	Crystal structure	Atomic spacing mm x 10 ⁻⁷	Melting point °C	°F
Lead	fcc	3.499	327	(621)
Zinc	hcp	2.664	419	(786)
Magnesium	hcp	3.196	650	(1202)
Aluminum	fcc	2.862	660	(1220)
Copper	fcc	2.556	1083	(1981)
Nickel	fcc	2.491	1453	(2647)
Titanium	hcp < 900°C	2.89	1668	(3034)
	(1652°F)	2.89		
	bcc > 900°C			
	(1652°F)			

Non-ferrous metals

All metals and alloys in which iron is not the major component are termed non-ferrous. A partial list of non-ferrous metals showing their crystal structure and melting point is given in Table 1. The properties of these metals vary considerably and usually one or two specific properties determine their field of application. For example, the high electrical conductivity of copper and aluminum makes them suitable for electrical conductors in power transmission systems while the chemical properties of nickel allow its use in food processing and chemical plant.

Density

The light weight coupled with fairly high strength of aluminum and magnesium alloys is the reason these materials are used extensively in aircraft, passenger rail cars, ships and other transportation vehicles. The strength-to-weight ratio of some alloys is listed in Table 2.

Table 2. Strength-to-weight characteristics of non-ferrous metals compared to steel.

Alloy	Modulus of elasticity		Density		Strength-to-weight ratio relative to steel
	GPa	(x10 ³ ksi)	Mg/m ³	(lb/ft ³)	
High strength low alloy structural steel	200	(29.0)	7.83	(489)	1
Magnesium alloy	45	(6.5)	1.78	(111)	3
Aluminum alloy (e.g. 7004)	69	(10.0)	2.77	(173)	3
Titanium alloy (heat treated $\alpha\beta$ alloy)	102	(14.8)	4.85	(303)	5.5

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

Corrosion resistance

Some of the highly reactive metals such as titanium form coherent oxide layers on the surface and render them very corrosion resistant. These materials find use in chemical plant and some high temperature applications. In Table 3 we list some of the major uses of non-ferrous metals and the key properties that determine their suitability.

Table 3. Typical applications for some non-ferrous metals.

Metal	Typical applications	Main property
Aluminum	Aircraft, aerospace vehicles Boats, trains, tank cars Cryogenic vessels Chemical plant Electrical conductors, bus bars Beverage cans	Low density Low temperature toughness Corrosion resistance Electrical conductivity Ductility
Copper	Electrical products Tubing Valves, fittings Chemical plant	Electrical conductivity Ductility, corrosion resistance Corrosion resistance Corrosion resistance
Magnesium	Printing equipment Conveyors Ladders Aerospace	Low density
Nickel	Food equipment Chemical plant High temperature equipment	Corrosion resistance High temperature strength
Titanium	Aerospace Chemical plant	Low density Corrosion resistance

Chemical properties affecting welding

The affinity for oxygen is one of the most important characteristics of a metal in determining its behaviour during fusion welding. This property dictates the type of shielding to be used and therefore the range of welding processes that can be employed. The affinity for oxygen can be measured by the free energy of formation of the oxide and some values are listed in Table 4. For metals with a low free energy of oxide formation little shielding from the air is needed and oxides are not likely to cause a problem. Lead, for example, can be welded by pouring liquid lead into the joint without external shielding.

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

Metal	Approximate free energy of oxide formation at 20 °C ΔG° (kcal)
Copper	-70
Lead	-90
Nickel	-105
Iron	-120
Zinc	-155
Titanium	-210
Aluminum	-240
Magnesium	-275

Table 4. Free energy of formation of some non-ferrous metal oxides. A large negative free energy shows a strong affinity for oxygen. This property has a major influence on the type of shielding required during welding and the processes that can be used.

Refractory oxides

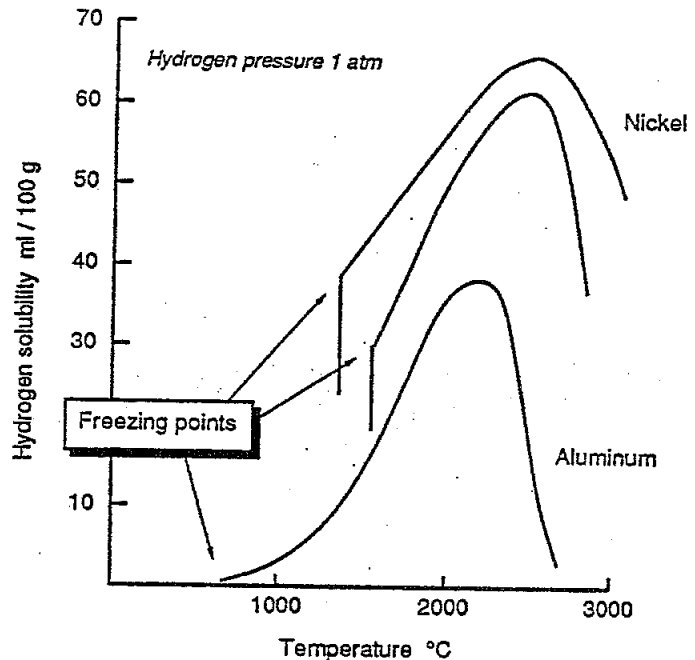
Metals such as titanium and chromium have large values of free energy of formation indicating a stable oxide and a strong tendency to form the oxide when heated. For these metals a refractory oxide is formed that does not melt at the temperature of welding, and unless removed or prevented from forming this oxide can result in improper fusion, weld defects, and poor ductility. Some oxides can be removed by fluxing where the addition of fluxes dissolves the oxide forming a liquid slag which floats out leaving a clean weld pool. In some cases the fluxes themselves may be detrimental to the performance of the metal if not completely removed after welding. The presence of fluoride fluxes left on aluminum, for example, may cause severe corrosion in some applications.

Weld pool shielding

For metals forming stable refractory oxides (titanium for example) it is better to prevent their formation by effective shielding during welding. This may restrict welding to the inert gas shielded processes or vacuum methods such as electron beam. Even in the conventional inert gas shielded processes such as gas tungsten arc and gas metal arc welding the shielding system is not perfect. There are still many opportunities for air to gain access to the weld pool, and for highly reactive metals additional special techniques are needed. Some of the techniques you should consider for ensuring adequate shielding when using GTAW or GMAW are:

- Pre-purging to remove any air from the system before start-up
- Specially designed shielding nozzles or larger size gas cup
- Prevention of air entrainment and leaks
- Trailing shields
- Shielding filler metal when added separately
- Reverse side shielding
- Special gas boxes or welding chambers.

Figure 1. Solubility of hydrogen in liquid metals. As liquid cools it will tend to reject hydrogen. Note that aluminum has a very low solubility for hydrogen at the freezing point but a substantial solubility at higher temperatures. Thus hydrogen is a prime cause of porosity in aluminum welds.



A consideration of these items should result in specific requirements being written into the welding procedure and the provision of suitable equipment. In many cases equipment such as gas shields must be custom made for each application.

Solubility of gases

In addition to chemical reactions between gases and the molten metal, gases from the atmosphere may dissolve in the weld pool and become a potential source of porosity. An indication of the potential for porosity can be gained from a study of the ratio of the maximum solubility of the gas in the liquid metal to that at the freezing point. Fig. 1 shows the solubility of hydrogen in three metals. We observe the highest solubility ratio for hydrogen in aluminum and this gas presents a high risk of porosity. Similarly the solubility ratio for nitrogen in nickel is very high and this gas is a major contributor to porosity in nickel welds.

Sources of gases

Identification of the gas that could present a potential problem in welding is the first step in devising appropriate procedures to exclude the gas from the weld pool. For example, if nitrogen is the offending gas, the major source is likely to be the air. Attention must be directed to gas shielding, leaks, air entrainment, back shielding or other ways in which air could gain access to the weld pool (Fig. 2). If hydrogen is the offending gas pay attention to all sources of hydrogen, such as moisture, dampness on the work piece, moisture in consumables, condensation in welding equipment (especially if water cooled), dirt, grease, paint, and solvents.

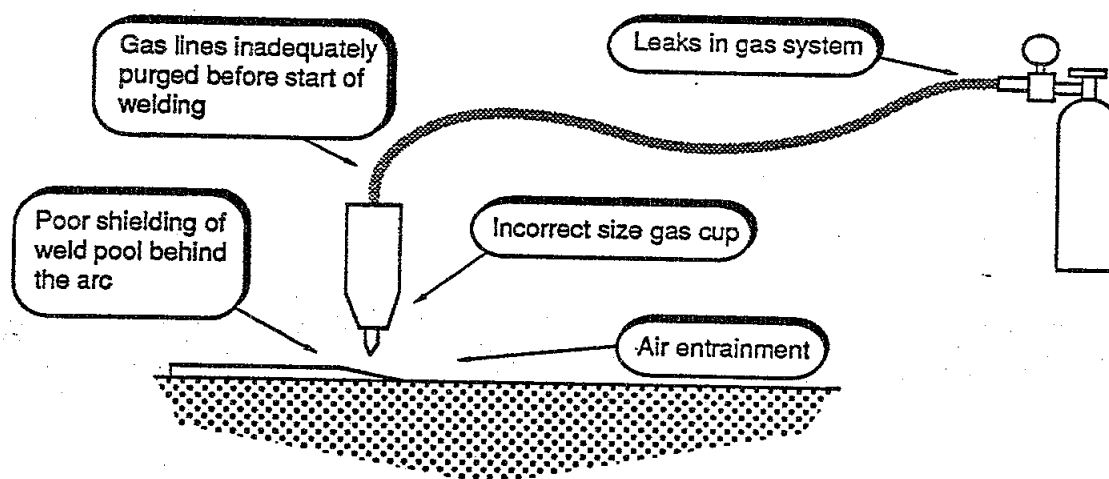


Figure 2. Some potential sources of air contamination in inert gas shielded welding.

Melting temperatures

The melting point of the metal (Fig. 3) obviously has an important influence on its ability to be fusion welded and is a first consideration in selecting a suitable process. Prior to the development of acetylene and the electric arc in the 19th century very few metals could be fusion welded because the heat sources available could not reach the melting temperatures. Iron, for example, was commonly joined by forge welding requiring the pieces to be hammered together at high temperature, but no melting was involved. Today, a wide range of heat sources exist enabling all the commonly used metals to be fusion welded. Even high melting point metals, such as molybdenum and tungsten, can be welded by the GTAW process, but electron beam with its high energy density is more efficient.

lead	327°C
zinc	419°C
magnesium	650°C
aluminum	660°C
copper	1083°C
nickel	1453°C
iron	1536°C
titanium	1668°C

Figure 3. Melting temperatures of common metals, °C.

Boiling point

Alloys containing metals with low *boiling* points may present special problems when using arc welding. The temperature of the arc and the weld pool may be high enough to cause significant evaporation of the element changing the resulting weld chemistry or even causing porosity in the weld. This is very possible with zinc which boils at only 906°C. Brass, for example, which contains zinc may suffer porosity problems when welded because of zinc boiling. An additional problem with evaporation that demands serious attention is the toxicity of the element. If the evaporating element is toxic or harmful in any way then special precautions are required to ensure that the welder is not exposed to the fumes. Again, zinc is a good example.

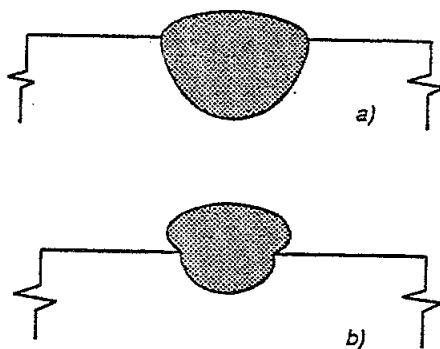


Figure 4. A metal with low thermal conductivity (a) will produce a weld with a large amount of fused base metal and little added filler. A metal with high thermal conductivity (b) will produce a small amount of melted base metal and a large amount of added filler metal.

Thermal conductivity

More important than the melting point of the metal is the thermal conductivity since this determines the rate at which heat is conducted away from the joint, and hence establishes the melting efficiency of the process. For high conductivity metals like copper the efficiency is very low, and considerably more heat is required to make the weld than would be needed to just melt the weld pool itself. In consumable electrode welding this means it is difficult to melt the base metal while at the same time the electrode is melting easily and supplying large amounts of filler metal (Fig. 4). The result can be a tendency to produce cold welds, cold laps, incomplete fusion, incomplete penetration, humpy beads or other types of fusion defects. To avoid this, high conductivity metals may require preheat to ease fusion of the base metal, large groove angles and wide gaps to accommodate the filler metal, and possibly higher welding currents and speeds to increase the melting efficiency.

iron	11.8
nickel	13.3
copper	16.5
aluminum	23.6
magnesium	27.1
lead	29.3
zinc	39.7

Figure 5. Coefficients of thermal expansion for several metals, per °C × 10⁻⁶.

lead	3.5%
zinc	4.2%
magnesium	4.2%
copper	4.2%
aluminum	6.0%

Figure 6. Percentage volume change on melting.

Thermal expansion

Effects of alloys

Hot cracking

Non-ferrous metals often have a coefficient of thermal expansion considerably higher than that of steel, as Fig. 5 shows. This increases the potential for distortion and high residual stresses. They may also undergo a greater volume change on solidification which raises the susceptibility to cracking. This is a significant factor in aluminum as you can judge from Fig. 6.

No general rules can be provided for predicting the welding behaviour resulting from the design of a specific alloy, but several possible problems may be anticipated by studying the composition or the strengthening method. Many non-ferrous alloys derive strength from work hardening, and the heat of welding may cause a loss of strength in the heat affected zone as the result of recovery and recrystallization. Careful attention to heat input may be called for to ensure that the weld has an acceptable strength, but in some cases the loss may be so severe that the alloy must be regarded as unweldable.

A study of the phase diagrams of the metal and the principal alloying elements is useful in identifying potential hot cracking problems. Those alloys with wide solidification ranges, as illustrated in Fig. 7, may be highly susceptible to hot cracking, and again in extreme cases the alloy may be deemed unweldable.

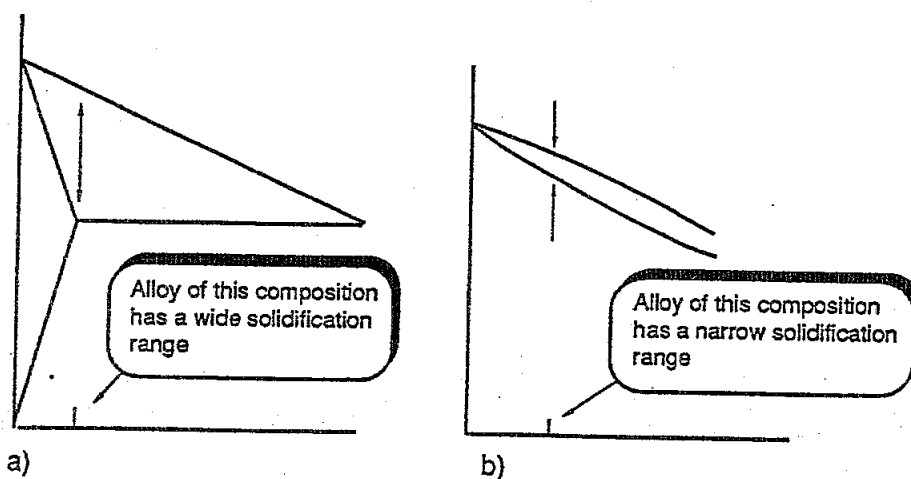


Figure 7. Phase diagrams indicate the width of the solidification range which has a major effect on the susceptibility of alloys to hot cracking during welding.

Precipitation hardened alloys

Precipitation hardening is a common strengthening method in non-ferrous alloys. A careful heat treatment is required to achieve the desired properties, and when welded the heat from welding may undo the effects of this heat treatment. It may be necessary to postweld heat treat the completed joint to restore adequate properties. Heat treatments may involve complete solution treating and aging, or sometimes just a postweld aging is sufficient.

We see from the foregoing section that a considerable amount of information can be obtained by studying the basic physical and chemical properties of an alloy and its metallurgical design. This can greatly assist the welding engineer in anticipating the problems likely to be encountered in welding thus providing a sound basis for process selection, equipment choice, inspection and welding procedure details.

Applications

NICKEL AND NICKEL ALLOYS

Nickel has a face-centred cubic structure over the complete range of temperature up to the melting point (Fig. 8). This structure makes nickel ductile. The special properties that make nickel useful as an engineering material are its corrosion resistance and its excellent high temperature properties when appropriately alloyed. It is used in food processing equipment, chemical vessels, and in a wide range of special alloys. In its commercially pure form it is often employed as a clad metal in caustic containers where the excellent corrosion properties of the nickel are combined with the structural and economic advantages of steel.

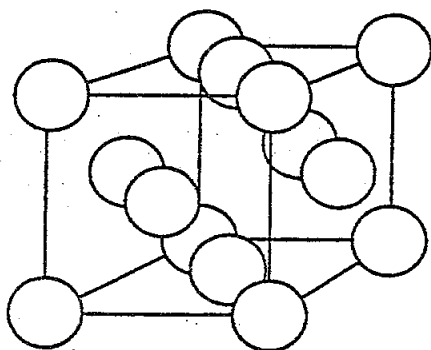


Figure 8. Nickel has a face-centred cubic structure with a closest atomic spacing of 2.491 Å.

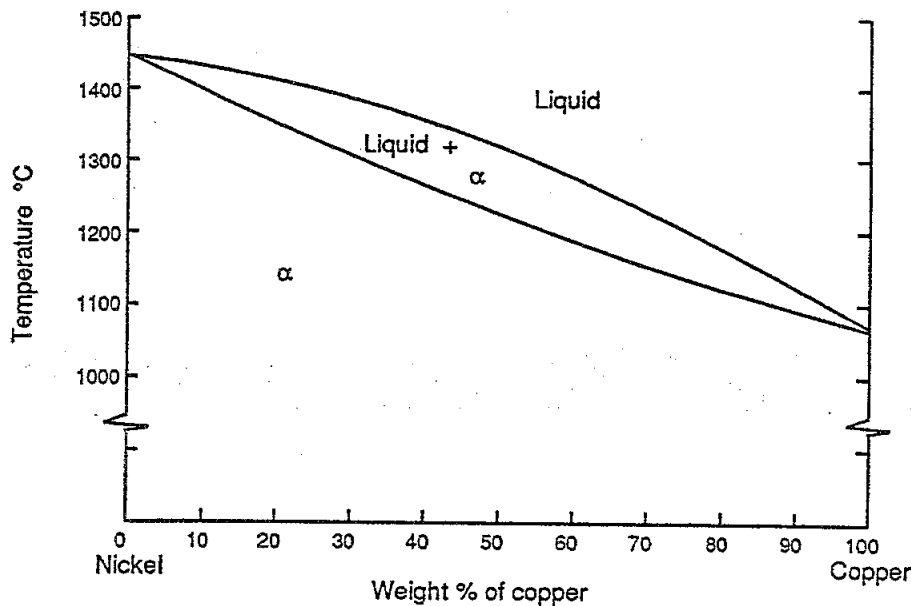


Figure 9. Phase diagram for the copper-nickel system. Note the complete range of solid solubility.

Nickel alloys

A wide range of alloys based on nickel are available and derive their strength from solid solution hardening, precipitation hardening or dispersion hardening. We will discuss only a few to illustrate the various ways in which the design of the alloy affects welding behaviour. Many of these alloys are known by their commercial proprietary names and we will use these here.

Copper and nickel have complete solid solubility as you can see from the phase diagram shown in Fig. 9. The chief commercial copper/nickel alloys are the Monels with 30-45% copper. Monel K has 3% aluminum added which makes it age hardening.

Chromium is added to nickel principally to enhance the high temperature properties improving the resistance to oxidation. Some of the chromium/nickel alloys have additional elements that provide precipitation hardening. Chromium is the principal alloying element in the Inconel series of alloys with some of them adding iron as a third element.

Molybdenum is the major alloy in the Hastelloy series, and these alloys are used primarily for their corrosion resistance. Some of them also have additions of iron and cobalt.

Precipitation hardening is usually achieved through aluminum additions although in several alloys part of the aluminum is replaced by titanium or niobium (columbium).

In Table 5 we give a summary of some of the major nickel alloys.

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

Table 5. Designation and composition of major nickel alloys.

Common designation	UNS number	Nominal composition weight %												
		Ni	Cr	Fe	Cu	C	Mn	Si	Mo	Ti	Al	Nb(Cb)	Co	Other
Monel 400	N04400	66.5		1.2	31.5	0.2	1	0.2						
Monel 404	N04404	54.5		0.2	44	0.08	0.05	0.05			0.03			
Nichrome	N06004	57	16	25		0.1	1	1						
Inconel 600	N06600	76	15.5	8	0.2	0.08	0.5	0.2						
Inconel 601	N06601	60.5	23	14		0.05	0.5	0.2						
Inconel 625	N06625	61	21.5	2.5		0.05	0.2	0.2	9	0.2	0.2	3.6		
Carpenter 20Cb-3	N08020	36	20	36	3.5	0.04	1	0.5	2.5			0.5		
Incoloy 800	N08800	32.5	21	46		0.05	0.8	0.5		0.4	0.4			0.02 Mg
Hastelloy B	N10001	61	1	5		0.05	1	1	28				2.5	
Hastelloy C	N10002	54	15.5	5		0.08	1	1	16				2.5	4.0 W
Hastelloy X	N06002	47	22	18		0.10	1	1	9				1.5	0.6 W
Nimonic 75	...	75	19.5	2.5	0.25	0.12				0.4	0.15			
Precipitation hardening alloys														
Monel K-500	N05500	66.5		1	29.5	0.10	0.08	0.2		0.6	2.7			
Waspaloy	N07001	58	19.5						4	3	1.3		13.5	0.006 B 0.06 Zr
René 41	N07041	55	19	1		0.10	0.05	0.1	10	3	1.5		10	0.005 B
Nimonic 80A	N07080	76	19.5			0.06	0.3	0.3		2.4	1.6			0.006 B 0.06 Zr
Nimonic 90	N07090	59	19.5			0.07	0.3	0.3		2.5	1.5		16.5	0.003 B 0.06 Zr
Udimet 500	N07500	54	18			0.08	0.5	0.5	4	2.9	2.9		18.5	0.006 B 0.05 Zr
IN 100	N13100	60	10			0.18			3	4.7	5.5		15	0.014 B 0.06 Zr 1.0 V

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

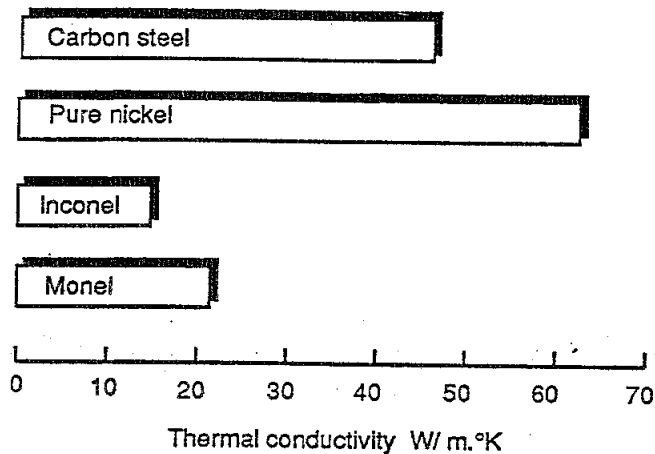


Figure 10. Thermal conductivity of some nickel alloys compared with that for steel.

Basic considerations in welding

The thermal conductivity of nickel is higher than that of carbon and alloy steels (Fig. 10), and this contributes to the greater difficulty of achieving good fusion between parent metal and added weld metal. To minimize potential fusion problems joints should be designed with wide angles to provide space for the filler metal and allow good fusion of the base metal. Most of the major welding processes are suitable for welding nickel and nickel alloys. Both gas shielded and flux shielded arc welding processes are employed, and the relatively high electrical resistance (Fig. 11) allows these materials to be welded by resistance welding methods. Some alloys, however, may require special processes. In particular the precipitation hardened alloys can generally only be satisfactorily welded with the GTAW process.

Heat input is normally limited in welding nickel and its alloys in order to reduce the risk of hot cracking, minimize grain growth, and retain corrosion resistance. This may limit the processes suitable, many alloys being preferably welded with GTAW only. Heat input is also minimized by employing stringer bead techniques rather than wide weaving. When submerged arc welding is employed fluxes specially designed for nickel alloys must be used, those for carbon steel or stainless steel being unsuitable.

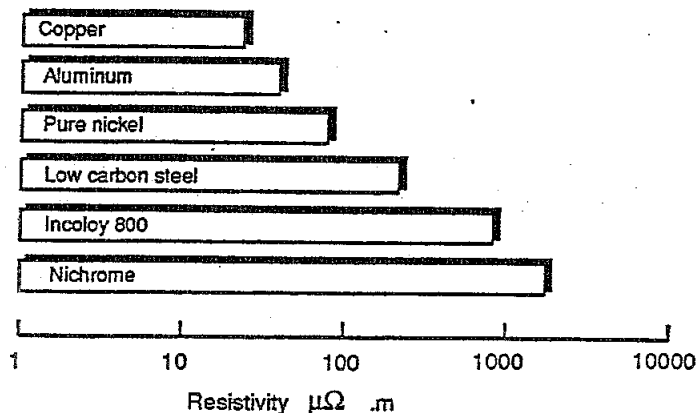


Figure 11. Electrical resistivity of some nickel alloys compared with other metals.

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

Table 6. Some examples of the composition of electrodes for welding nickel and nickel alloys. Note the use of titanium to control nitrogen and reduce porosity.

Electrode	Nominal composition									
	C	Mn	Si	Fe	Ni+Co	Cr	Cu	Mo	Ti	Other
ERNi-1	0.15	1.0	0.75	1.0	93.0#		0.25		2.0-3.5	1.5 Al
ERNiCu-7	0.15	4.0	1.25	2.5	62.0-69.0		rem		1.5-3.0	1.25 Al
ERNiFeCr-1	0.05	1.0	0.5	22.0#	38.0-46.0	19.5-23.5	1.5-3.0	2.5-3.5	0.6-1.2	0.2 Al
ERNiCrFe-6	0.08	2.3	0.1	6.6	71.0	16.4	0.04		3.2	
ERNiCr-3	0.10	2.5-3.5	0.5	3.0	67.0#	18.0-22.0	0.5		0.75	2.0-3.0 Nb (Cb)
ERNiCrFe-5	0.08	0.10	0.35	6.0-10.0	70.0#	14.0-17.0	0.5			1.5-3.0 Nb (Cb)
ERNiMo-1	0.08	1.0	1.0	4.0-7.0	rem	1.0	0.5	26.0-30.0		
ERNiCrMo-3	0.01	0.5	0.5	5.00	58.0#	20.0-23.0	0.5	8.0-10.0	0.4	3.15-4.15 Nb (Cb)
ERNiCrMo-4	0.02	1.0	0.08	4.0-7.0	rem	14.5-16.5	0.5	15.0-17.0		3.0-4.5 W
ERNiCrMo-9	0.015	1.0	1.0	18.0-21.0	rem	21.0-23.5	1.5-2.5	6.0-8.0		1.5W

min For details refer to AWS A5.14 "Specification for Nickel and Nickel Alloy Bare Welding Rods and Electrodes"

Porosity

The drop in solubility of nitrogen in cooling liquid nickel is high and presents a significant risk of porosity if nitrogen is allowed to dissolve in the weld pool. Porosity due to nitrogen is one of the chief problems in welding pure nickel and some of the nickel alloys, and special attention to details of the welding procedure that affect nitrogen pickup is required. To alleviate the problems of nitrogen and to provide some deoxidizing capability, electrodes for nickel and nickel alloys contain titanium or other strong nitride and oxide formers (Table 6). This allows the shielded metal arc process to be used, but it is still necessary to employ a very short arc technique since a long arc will tend to encourage nitrogen pickup.

Gas shielding

Gas shielding in the GTAW process is critical when joining nickel or its alloys. Reverse side shielding is necessary, and the correct gas cup size and torch angle is important to avoid air entrainment (Figs. 12 and 13). If filler metal is added by hand the tip of the rod must always be held in the gas shield of the arc and not periodically

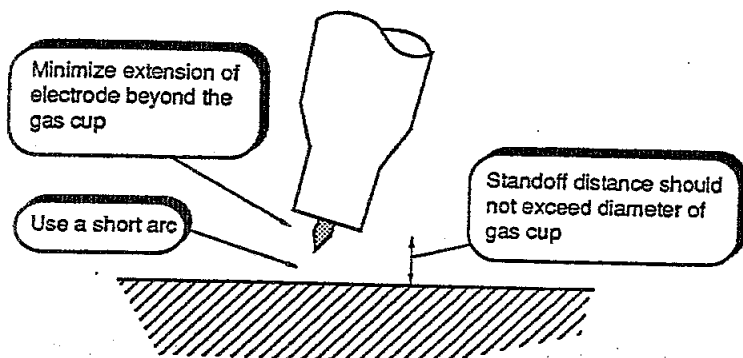


Figure 12. Technique in GTAW is important in minimizing porosity.

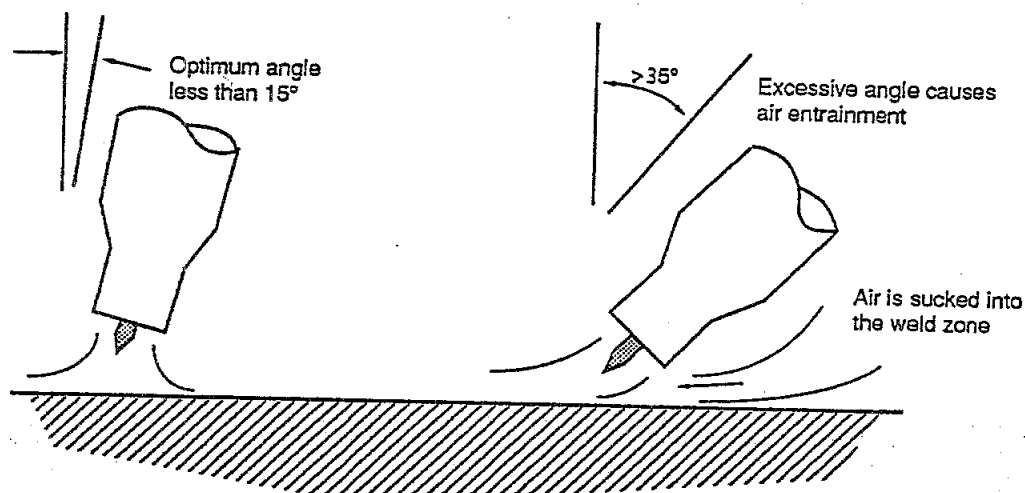


Figure 13. Electrode angle must be controlled to avoid air entrainment.

Technique

removed. A "dabbing" technique, not uncommon in welding some metals, can cause contamination of the pool and porosity because of pickup of nitrogen and oxygen when the hot tip of the rod moves out of the gas shield into the air (Fig. 14). It is better with GTAW to mechanize the wire feed so that supply of the wire is not dependent on the operator's technique.

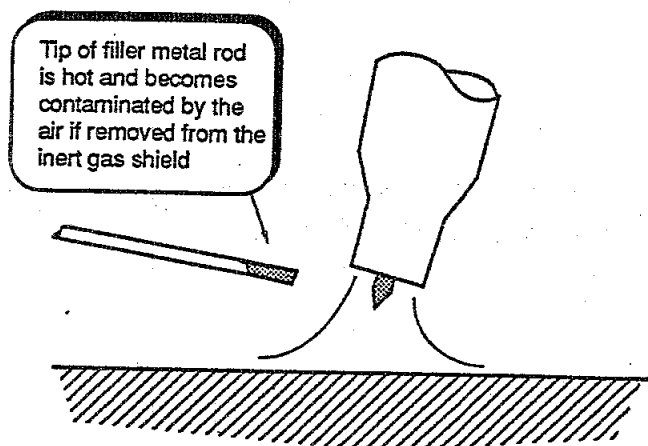


Figure 14. Tip of filler rod must be held in the shielding gas at all times to avoid contamination.

Joint geometry

Because titanium is provided in the filler metal to control porosity it is important that an adequate amount of filler is added to the weld. This may mean that a joint has to be prepared with a wide V groove to accommodate the filler even if the weld could otherwise be made without a preparation. Even in GTAW of thin sections filler metal must be added (Fig. 15). In general the weld should be at least 50% filler metal. This is another good reason to use a mechanized wire feed for GTAW because the amount of filler can be carefully controlled.

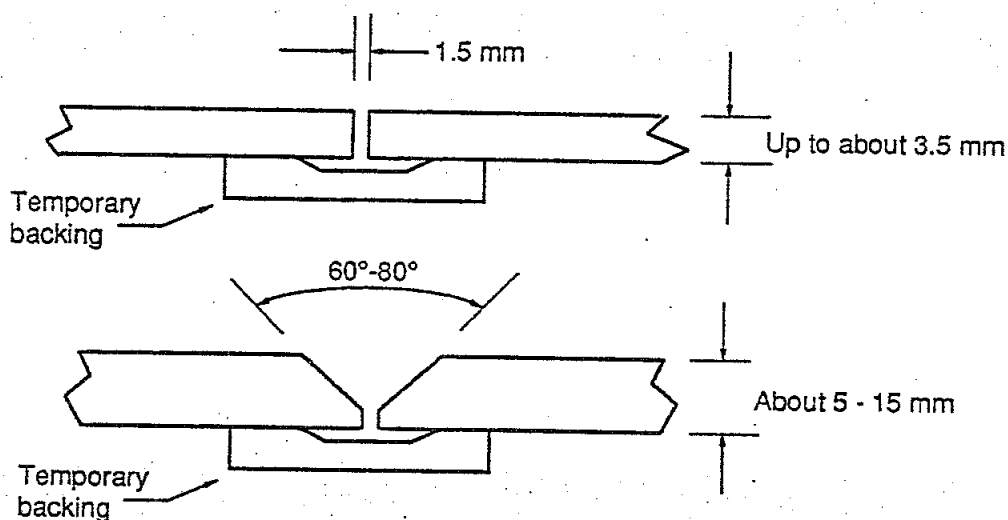
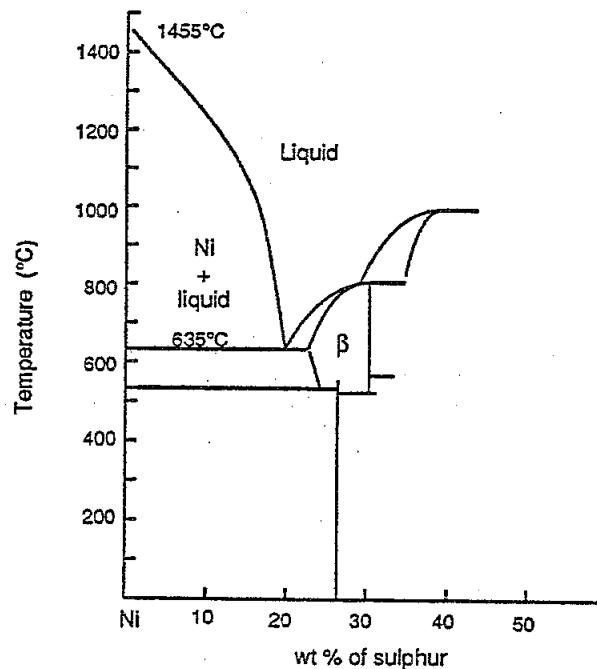


Figure 15. Typical joint preparations for welding nickel. Even with thin material filler metal is necessary.

Hot cracking

Nickel and many of its alloys are prone to hot cracking in the weld metal due to sulphur and other impurities. The nickel-sulphur phase diagram (Fig. 16) shows a low melting point eutectic which can be the cause of liquid films remaining on grain boundaries after solidification if sulphur is present. The detrimental effects of sulphur can be offset by the presence of manganese and magnesium which are strong sulphide formers preventing the nickel sulphide films from occurring. With some alloys a limitation on heat input may be required to prevent the formation of hot cracks in the weld metal. Cracking resulting from sulphur contamination is also possible in the heat affected zone. Prevention of contamination is essential in welding nickel and nickel alloys and this requires careful attention to cleaning, removal of grease and dirt, use of stainless steel brushes and avoiding any type of foreign material in the weld zone.

Figure 16. Part of the nickel-sulphur phase diagram. Note the lack of solubility of sulphur in the solid nickel and the low temperature, 635°C of the eutectic.



Strain age cracking

A second form of cracking that occurs in precipitation hardened alloys is strain age cracking. If high residual stresses are present, for example from welding, then these may cause cracks to initiate when the material is subject to a heat treatment that produces precipitation hardening. The increase in tensile strength is accompanied by a reduction in ductility creating an opportunity for cracks to form if high stresses are present (Fig. 17). The most susceptible alloys are those high in aluminum or titanium. Niobium (columbium) slows down the rate of aging and reduces the susceptibility to this kind of problem. The phenomenon may occur during any heat treatment that creates the critical combination of time and temperature and may be an aging treatment, annealing, or post weld stress relieving. Control of the problem often rests with controlling the magnitude of the residual stresses by attention to weld sequence, heat treating component parts before final welding, and intermediate stress relief treatments. There are other methods that have been developed for specific alloys.

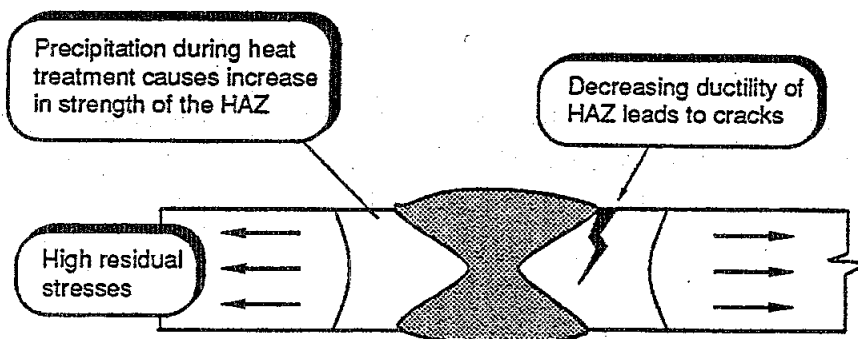


Figure 17. Illustration of the cause of strain age cracking that can occur in some nickel alloys.

Clad plate

Nickel is frequently used as a cladding metal over carbon steel. When welded special joint preparation and welding sequence is needed to minimize dilution of one metal into the other. Although nickel can tolerate quite high levels of iron a high iron content may not be suitable for the intended application, and it is not uncommon to have a maximum iron content in the nickel surface layers specified. Sufficient layers of nickel must therefore be deposited to ensure an acceptably low dilution, and the joint design shown in Fig. 18 facilitates this.

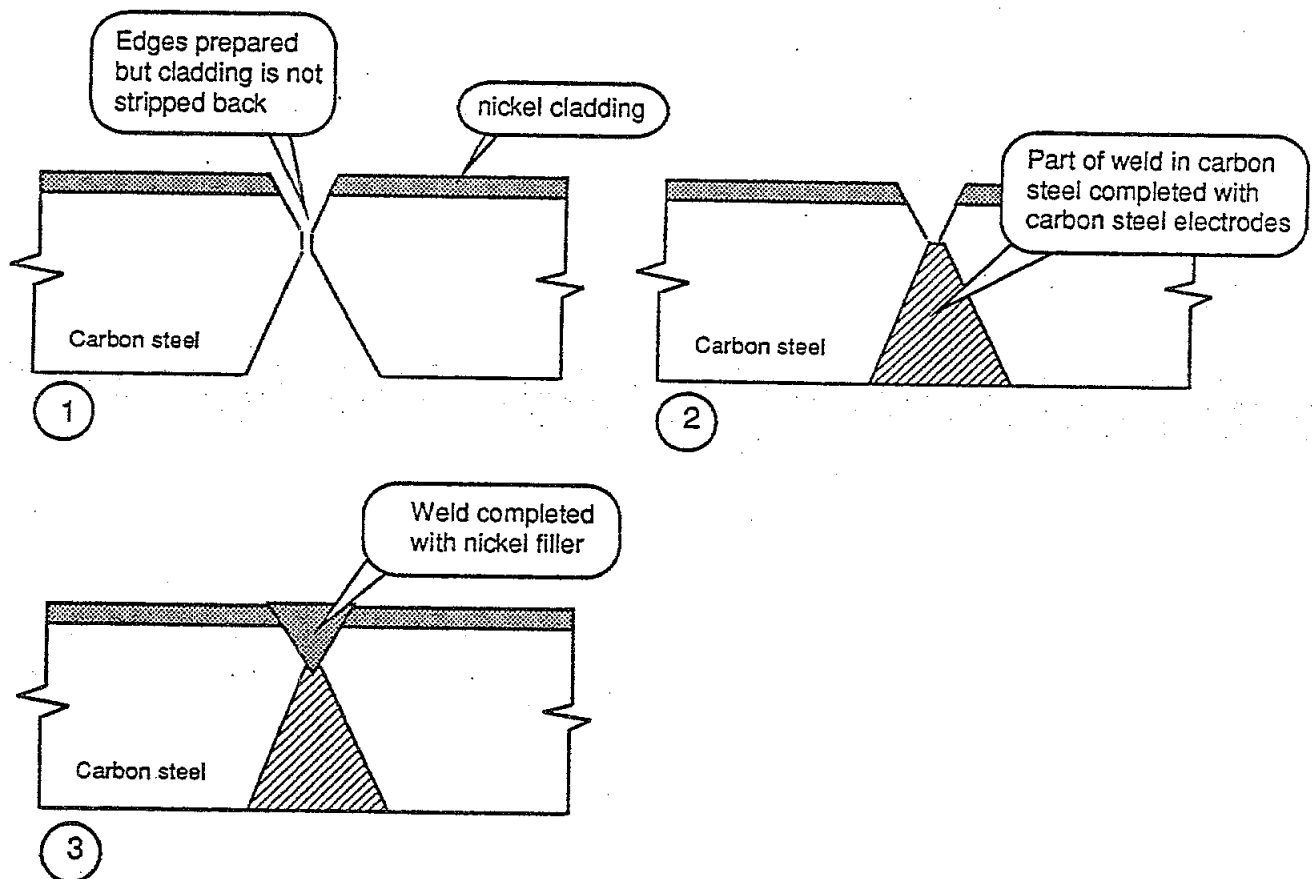


Figure 18. Typical method for welding nickel clad plate that minimizes iron content of final layer.

COPPER AND COPPER ALLOYS

Properties

Copper is a ductile metal, a property it acquires from its face-centred cubic structure (Fig. 19). It has a relatively low melting point but very high thermal and electrical conductivity which has important implications in welding. It is used primarily for its electrical and thermal properties and its excellent corrosion resistance in certain environments, particularly sea water.

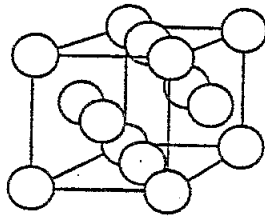


Figure 19. Copper has a face-centred cubic structure with a closest atomic spacing of $2.556\text{\AA}$.

Alloys

Copper forms solid solutions with a wide range of elements usually producing alloys that are single phase over the entire temperature range up to the melting point. The most important are:

- Brass: Copper and zinc.
- Bronze: Copper and tin.
- Silicon bronze: Copper and silicon.
- Aluminum bronze: Copper and aluminum
- Copper-beryllium
- Copper-nickel.

The copper-zinc phase diagram is shown in Fig. 20. Up to about 35% zinc a single phase solid solution, termed α or yellow brass, is

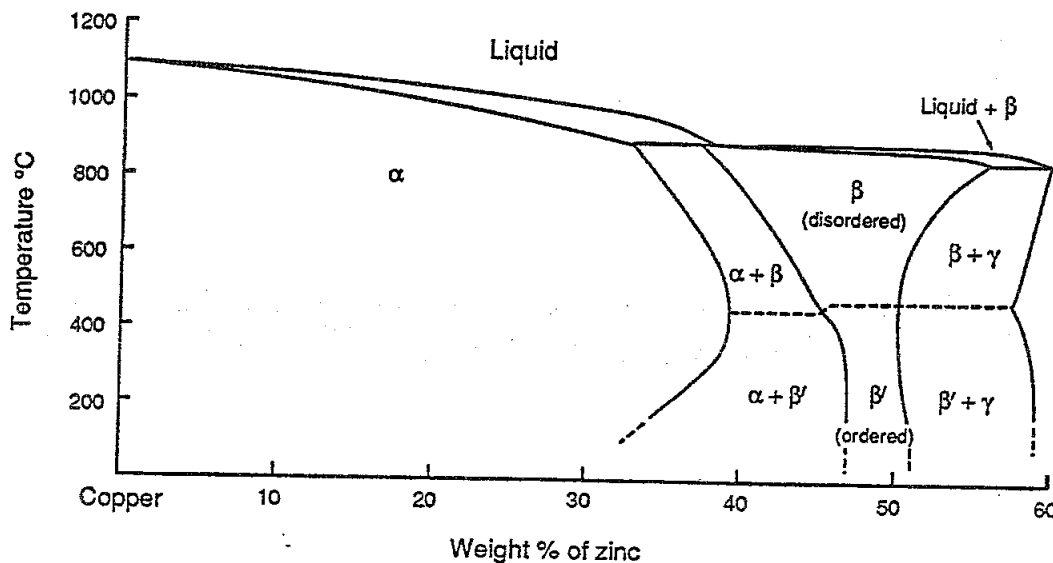
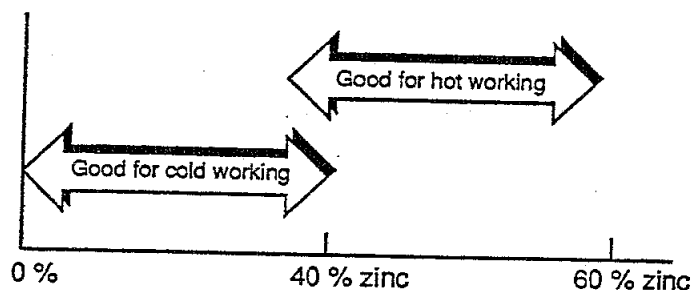


Figure 20. Part of the phase diagram for copper-zinc.

Figure 21. Range of zinc contents for good hot and cold working properties in brass.



Brass

formed. Over this range the ductility and strength of the alloy increase allowing it to be readily formed by cold working. The hot working characteristics, however, deteriorate, particularly in the presence of minor impurities like lead. Above 40% zinc a second phase β appears. This is hard and strong, reducing the ductility and cold working properties of the brass. Fig. 21 summarizes the effect of zinc content on the hot and cold working properties. The β phase is, on the other

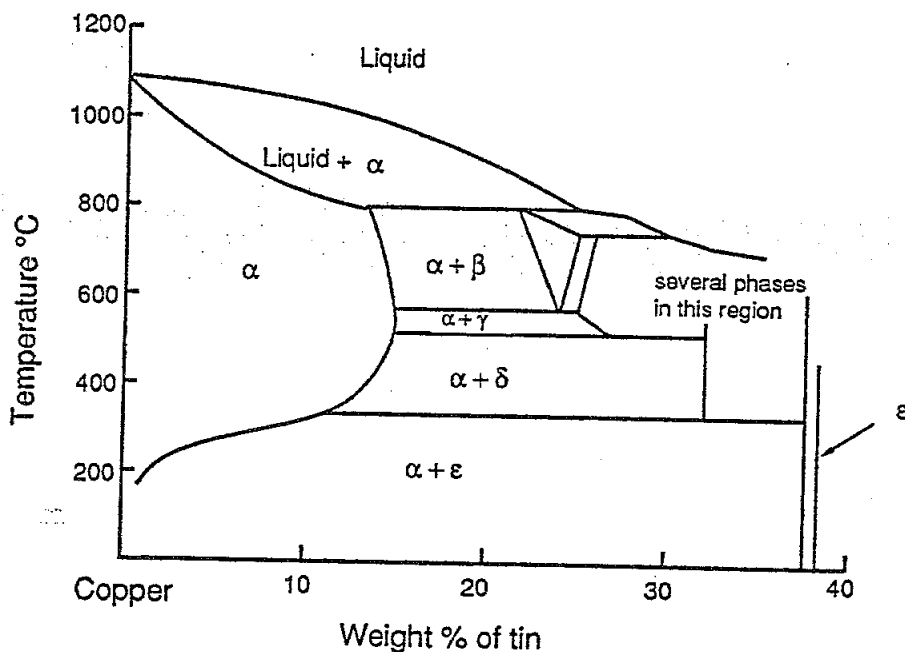


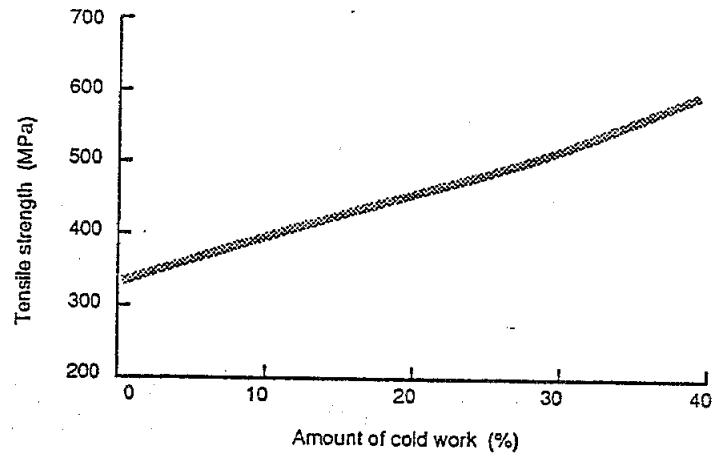
Figure 22. Part of the phase diagram for the copper-tin system.

hand, quite ductile at elevated temperatures, improving the hot working behaviour. Brasses with 40 to 60% zinc are popularly known as 60-40 brass, α - β brass or Muntz Metal.

Bronze

Alloys of copper and tin are known as bronze or, more often, phosphor bronze, since phosphorus, in amounts 0.03 to 0.04%, is usually added for deoxidation. A study of the rather complex phase diagram of copper and tin shown in Fig. 22 would suggest that alloys containing 1 to 10% tin would be two phase. In practice, however, the equilibrium conditions represented by the phase diagram are not obtained, and bronzes less than 10% tin are single phase. The strength

Figure 23. Typical increase in strength due to work hardening of a Cu-Zn-Sn alloy.



of the alloy can be increased substantially by cold working (Fig. 23). When tin levels reach 10% a second phase appears in the form of a eutectoid, increasing the strength but reducing the ductility. These alloys are often used in the cast condition.

Aluminum bronze

Aluminum alloys of copper (popularly called aluminum bronzes) contain 4 to 15% aluminum. Up to 8% they are single phase (see Fig. 24), and above this they are two phase, these phases appearing as the result of either a martensitic type reaction or a eutectoid reaction. Slow cooling produces a hard, brittle eutectoid whereas quenching from 750°-800°C forms a martensite which can be tempered at 350°-550°C. The single phase alloys can be work hardened to increase their strength.

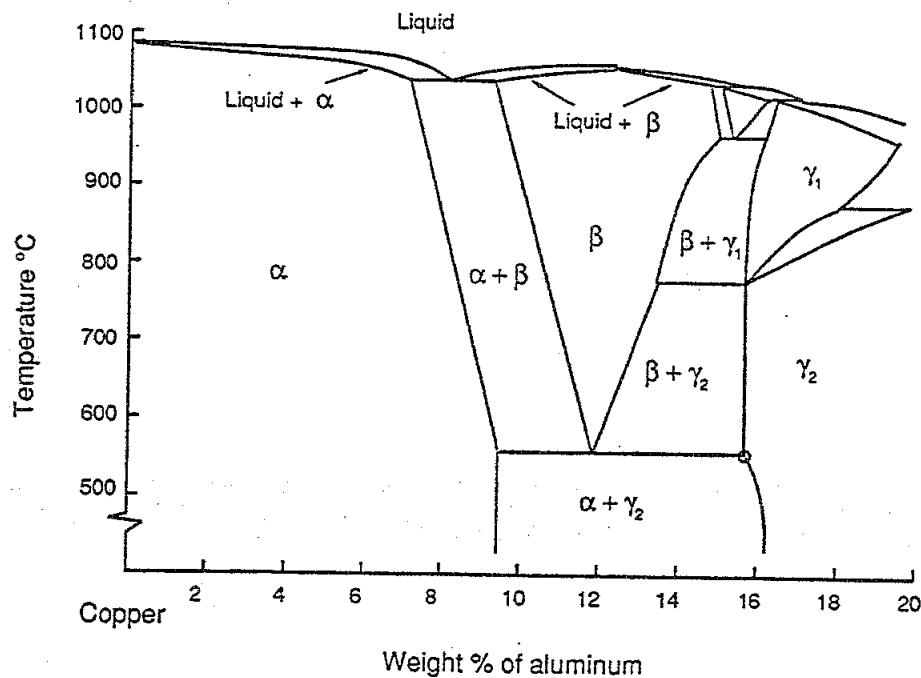
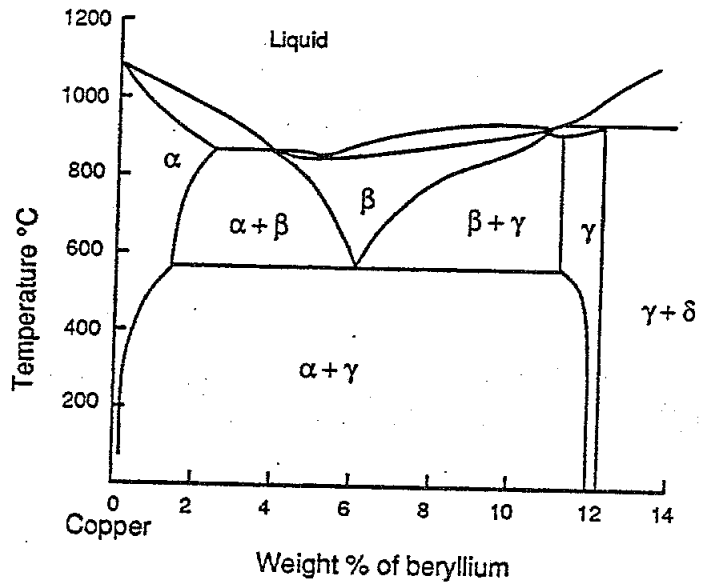


Figure 24. Part of the phase diagram for the copper-aluminum system.

Figure 25. Part of the phase diagram for the copper-beryllium system. Note the increasing solubility of beryllium with increasing temperature (α phase) which is favourable for precipitation hardening.



Copper-beryllium

Beryllium is used in copper as a precipitation hardening alloy element. The phase diagram in Fig. 25 shows solubility at room temperature to be only 0.3% whereas it is 2% at 900°C. This change in solubility is favourable for precipitation hardening, and alloys with 1.5-2.5% beryllium can be heat treated to produce extremely high tensile strength and hardness. The heat treatment illustrated in Fig. 26 comprises quenching from about 900°C to form a supersaturated solid solution followed by aging at 275°-325°C to promote precipitation of the second phase.

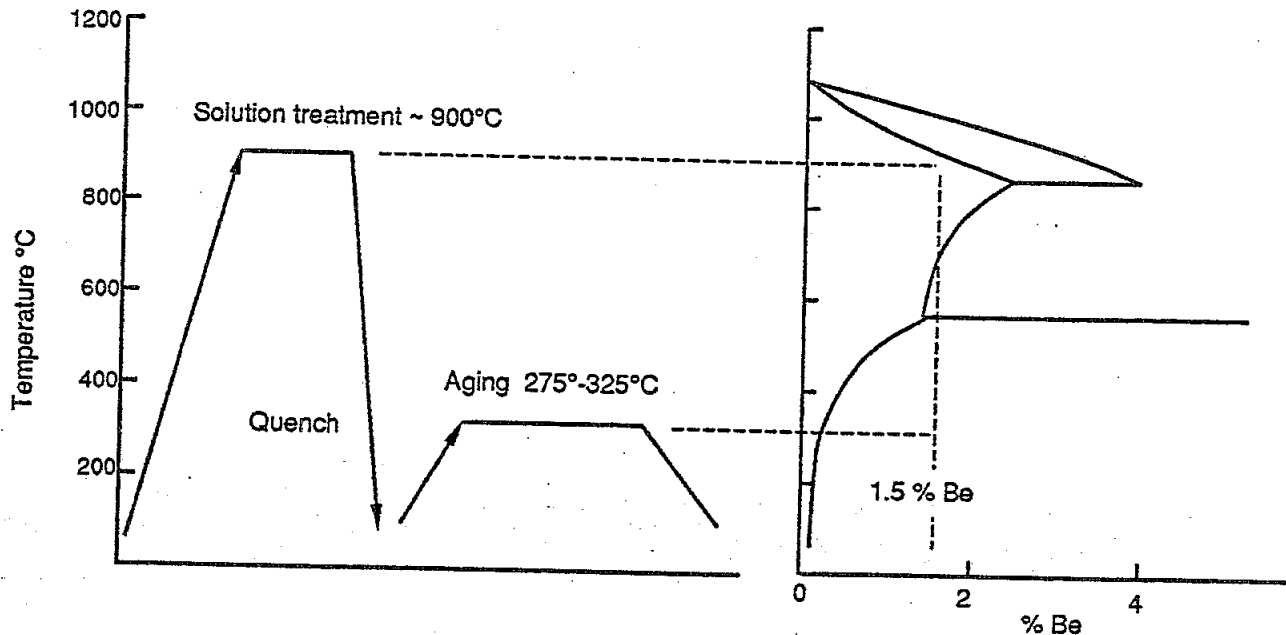


Figure 26. Diagram showing the heat treatment to obtain precipitation hardening in a Cu-1.5% Be alloy.

Alloy	Electrical conductivity % IACS*
Oxygen free copper	101
Commercial bronze 90%	44
Red brass 85%	37
Cartridge brass 70%	28
Manganese bronze A	24
Beryllium copper	22
Phosphor bronze 5% A	15
Aluminum bronze D	14
Phosphor bronze 10% D	11
Copper-nickel 10%	9
High silicon bronze A	7
Nickel silver 65-15	6
Copper-nickel 30%	4.6

* % relative to annealed copper

Table 7. Electrical conductivity of several copper alloys.

Basic considerations in welding

The most obvious feature of copper and its alloys that has an effect on its welding behaviour is the high thermal conductivity. The rapid conduction of heat away from the weld zone makes it harder to achieve good fusion. The preferred welding processes are GMAW and GTAW since these provide a highly concentrated source of heat. Oxy-acetylene can be used but is slow and inefficient. The high electrical conductivity of copper precludes the use of resistance welding except for those alloys with conductivity less than about 30% of that for pure copper. Electrical conductivities of several alloys are listed in Table 7 where it is seen that the values cover a very wide range.

In all but the thinnest sections, copper must be preheated to facilitate melting the parent metal and provide good fusion. Preheat temperatures necessary depend on the type of welding process, welding conditions, and shielding gas. As an approximate guide, Fig. 27 presents some typical values for copper. For copper alloys the preheat levels naturally depend on the alloy composition, and lower temperatures than for copper are needed. With GMAW and GTAW the shielding gas plays a prominent role with helium offering an advantage over argon in terms of required preheat and degree of penetration. Fig. 28 illustrates the effect of shielding gas on the size of the fusion area of welds in copper.

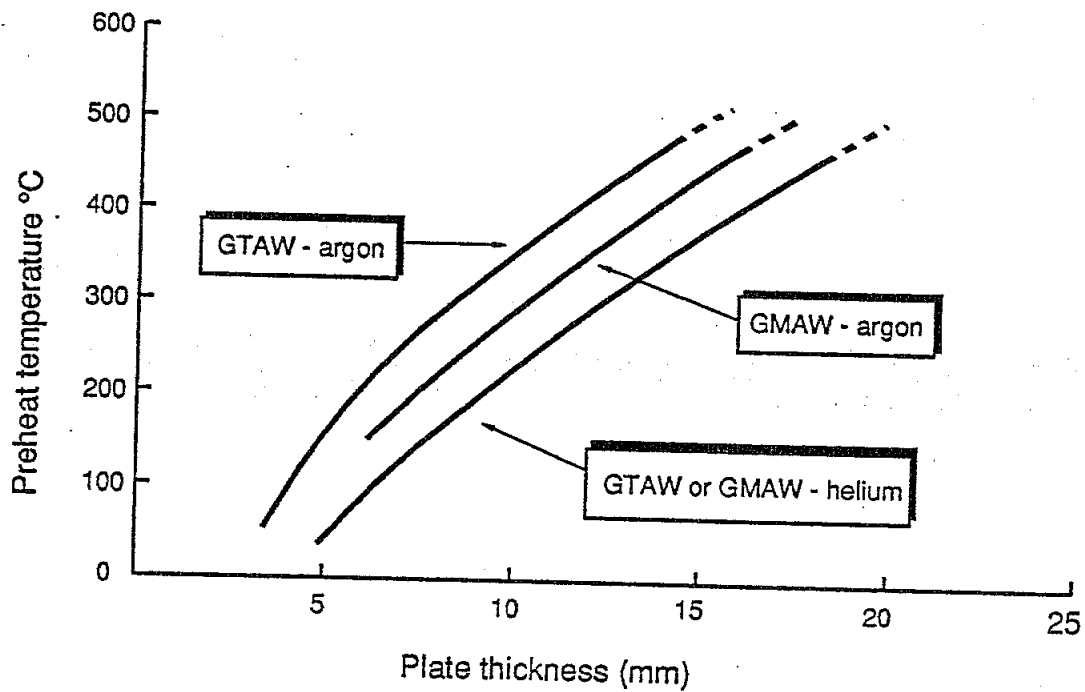


Figure 27. Typical preheat levels for welding copper.

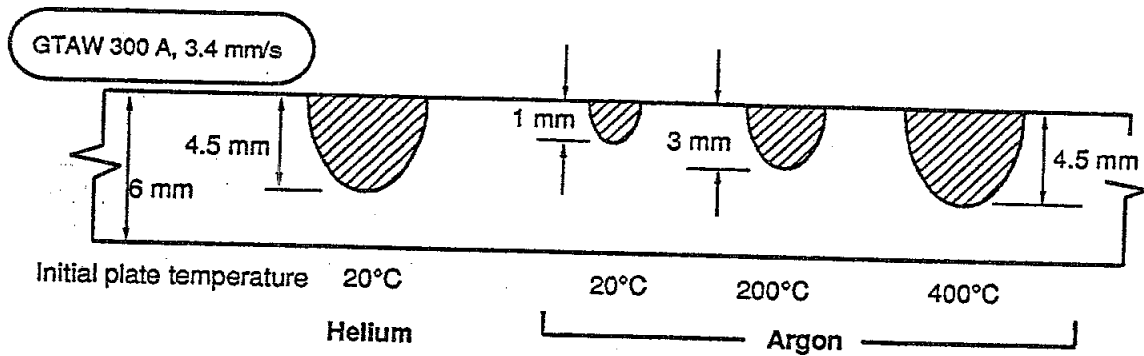


Figure 28. Illustration of the effect of preheat and shielding gas on penetration in welds on copper.

Joint geometry

Coupled with the need for high preheats is the requirement for wide groove angles when welding thick plates. The wide groove angle facilitates good fusion and provides a space for the added filler metal. Some typical joint designs for copper and copper alloys are shown in Fig. 29.

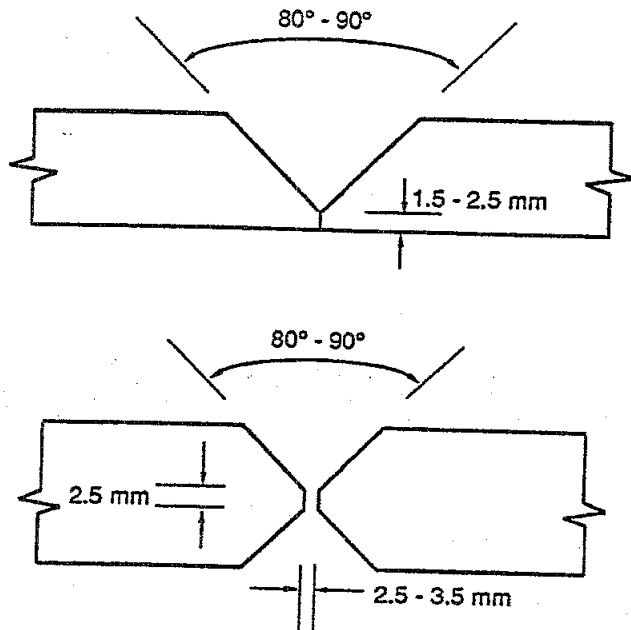
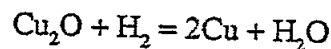


Figure 29. Typical joint preparations for welding copper. Note the wide groove angle.

Effect of oxygen

Copper contains oxygen when smelted, and to obtain the highest conductivity for electrical applications this oxygen is removed by deoxidation with phosphorus. Table 8 shows the oxygen and phosphorus levels of three grades of copper. If oxygen still remains in the metal it can react with hydrogen during welding to produce steam:



The production of steam can have serious consequences causing cracking and porosity and must be avoided by eliminating any hydrogen. This precludes the use of oxy-acetylene welding for this type of copper. Welds in electrolytic tough pitch copper which has a relatively high oxygen level are normally quite porous and lower in strength than welds in deoxidized copper.

Table 8. Oxygen and phosphorus levels of coppers.

Type of copper	UNS number	Cu	O	P
Oxygen-free copper	C10200	99.95		
Electrolytic tough pitch	C11000	99.90	0.04	
Phosphorus deoxidized (low phosphorus)	C12000	99.9		0.008
(high phosphorus)	C12000	99.9		0.02

Table 9. Filler metals for welding copper and copper alloys.

Covered electrodes(1)	Bare wire(2)	Common name
ECu	ERCu	Copper
ECuSi	ERCuSi-A	Silicon bronze
ECuSn-A	ERCuSn-A	Phosphor bronze
ECuSn-C		
ECuNi	ERCuNi	Copper-nickel
ECuAl-A2	ERCuAl-A2	Aluminum bronze
ECuAl-B	ERCuAl-A3	Aluminum bronze
ECuNiAl	ERCuNiAl	
ECuMnNiAl	ERCuMnNiAl	
	RBCuZn-A	Naval brass
	RCuZn-B	Low fuming brass
	RCuZn-C	Low fuming brass

1) For details see AWS A5.6-84
2) For details see AWS A5.7-84

Filler metals

Filler metal for welding copper usually contains phosphorus as a deoxidizer. Table 9 lists some typical filler metal types which are covered by AWS A5.6-84 "Specification for Covered Copper and Copper Alloy Arc Welding Electrodes" and AWS A5.7-84 "Specification for Copper and Copper Alloy Bare Welding Rods and Electrodes".

Postweld heat treatment

A range of other metallurgical problems can be encountered during welding of copper and its alloys, and although not difficult to weld specific procedures must be followed. Some alloys rely on work hardening or precipitation hardening for their strength, and are therefore likely to suffer a reduction in the strength in the HAZ. To restore full properties in precipitation hardened alloys complete heat treatment after welding is recommended, but a suitable filler metal that will respond to the heat treatment must be employed. Welding in the precipitation hardened condition is also likely to cause cracking in the HAZ and is not standard practice. As an example, beryllium copper can be welded using beryllium alloyed filler metal followed by a complete solution treatment and aging. If the weld heat input is not excessive the HAZ will not over age and good weld properties can be obtained by just a postweld aging omitting the solution treatment. Fig. 30 shows that proper heat treatment more than doubles the strength after welding.

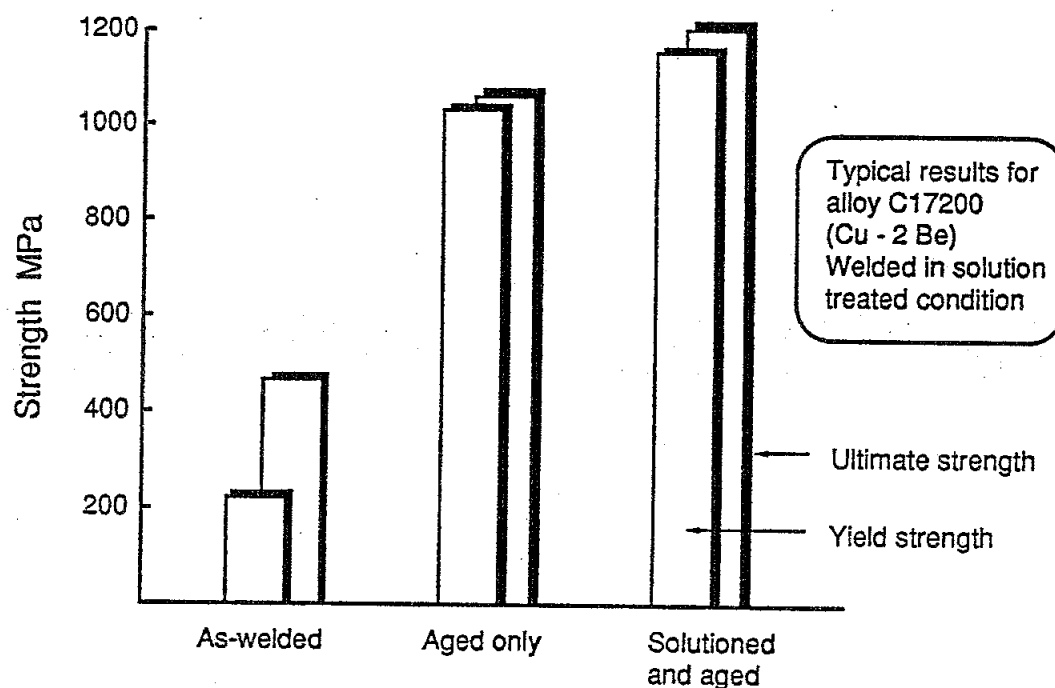


Figure 30. The effect of postweld heat treatment on the strength of welds in a precipitation hardening copper-beryllium alloy.

Shielding

Alloys containing highly oxidizable elements, such as beryllium and aluminum, form oxides which can be troublesome in welding. The metal in the vicinity of the weld must be maintained clean before and during welding. Good shielding of the arc is necessary to prevent the formation of oxides while welding. If the GTAW process is used, alternating current may be preferred because of the cleaning action during the electrode positive cycle. The aluminum oxide that forms on the surface of aluminum bronze and gives it its unique corrosion properties must be removed mechanically prior to welding.

Vaporization

In addition to oxidation, vaporization of alloy elements may cause problems. The boiling point of zinc 906°C is sufficiently low that during welding zinc vaporizes causing porosity, fuming, and of course reduction of the zinc content. Procedures for welding brass, particularly the high zinc brasses, must be designed to reduce zinc fuming by control of heat input, directing the arc onto the weld pool and filler metal rather than the parent metal, and by choice of consumables. Matching compositions are not available because the zinc would be lost, so phosphor bronze or aluminum bronze is used.

Hot cracking

One other major problem in welding copper alloys is hot cracking. A study of phase diagrams of the specific elements involved may, in some cases, give a clue as to the likely hot crack susceptibility. The copper-nickel diagram, for example, shows quite a wide solidification range, and copper-nickel alloys become highly susceptible to hot cracking during welding if impurity elements such as sulphur, lead, phosphorus, and bismuth are present. The copper-bismuth phase diagram shown in Fig. 31 demonstrates dramatically how even small quantities of bismuth can cause the retention of liquid phases down to low temperatures and result in a high susceptibility to hot cracking. Copper-nickel alloys should be carefully cleaned before welding to ensure no contamination with these elements takes place. Lead is deliberately used in some machining alloys but these should not be welded.

Two phase brass with 40% zinc is less susceptible to hot cracking than the single phase alloy. The same is true of the aluminum bronzes. The duplex structure found in the 9-15% aluminum alloy is essentially free of hot cracking when welded whereas the single phase 4-8% aluminum alloy is susceptible.

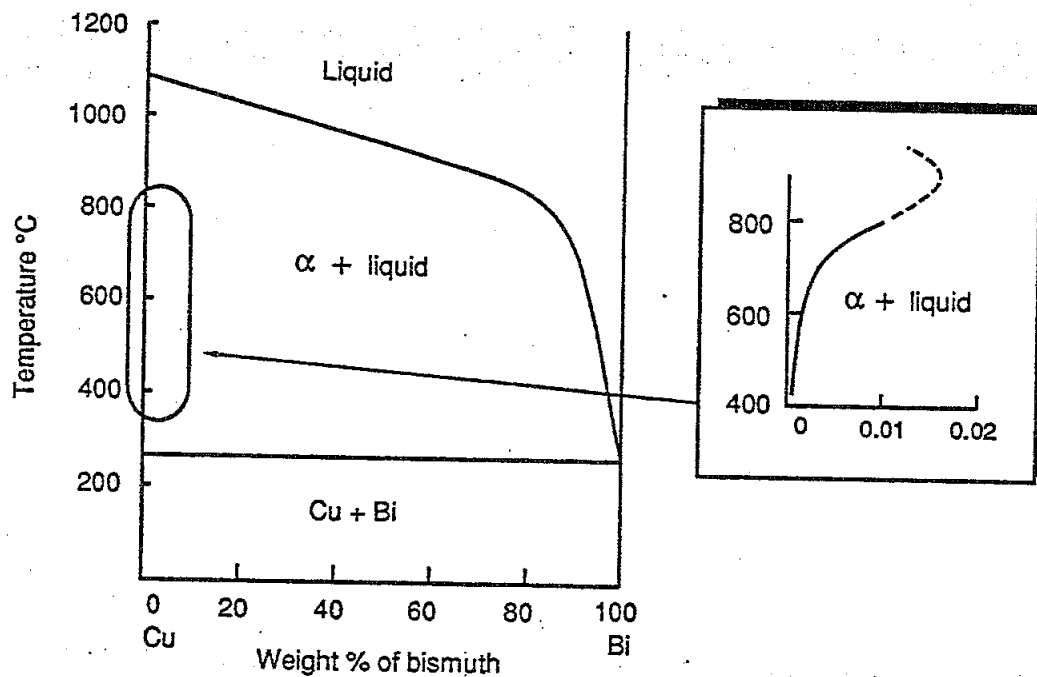


Figure 31. Part of the copper-bismuth phase diagram showing the limited solubility of bismuth in copper and the presence of liquid to very low temperatures. Bismuth, and other similar impurities, can cause hot cracking during welding of copper alloys.

MAGNESIUM AND ITS ALLOYS

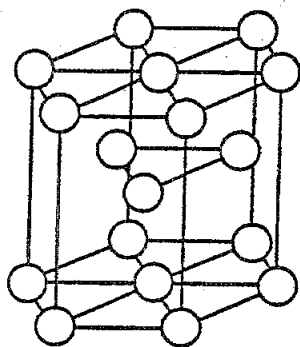


Figure 32. Magnesium has an hexagonal close packed structure with a closest atomic spacing of 3.196 Å.

Magnesium is a very light metal (Table 10) with good corrosion resistance making it suitable for a wide range of applications including aerospace, high speed equipment such as printing machines, material handling equipment, ladders, and light weight castings. Magnesium has an hexagonal close packed structure (see Fig. 32) that renders it difficult to cold work. Its room temperature ductility is quite low but rises substantially with increasing temperature. Forming operations are always carried out hot, between about 200°–300°C, including postweld straightening or peening. The element is highly reactive with oxygen readily forming an oxide layer on its surface. During welding the oxides break up more easily than with aluminum, but their ease of formation precludes the use of any but the inert gas shielded processes. It is well known that magnesium powder can ignite and burn spontaneously in air, but this behaviour does not occur in welding with the usual thicknesses of the metal. Good housekeeping, however, is essential: dust, shavings, and turnings being carefully removed. The addition of beryllium up to 0.001% reduces the tendency to ignition, and filler metals for GMAW and GTAW commonly have 0.0002 to 0.0008% beryllium specified.

The thermal properties of magnesium are listed in Table 11. The thermal conductivity is not as high as copper or aluminum but higher than steel. Its melting point is quite low, and relatively low energy is required to weld it. The high coefficient of expansion and low modulus of elasticity, on the other hand, cause high distortion, and proper fixturing is essential to maintain acceptable dimensional tolerances after welding.

Table 10. The low density is the most important property of magnesium.

Metal	Density	
	kg/m ³	lb/ft ³
Steel	7.83	489
Aluminum	2.77	173
Magnesium	1.78	111

Table 11. Thermal properties of magnesium.

Melting point	650°C	1200°F
Thermal conductivity	154 W/m.°K	90 BTU/hr/ft²°F
Expansion coefficient	27 x 10 ⁻⁶ /°C	15.1 x 10 ⁻⁶ /°F
Specific heat	0.25 cal/g/°C	0.25 BTU/lb/°F

Table 12. Nominal composition of wrought magnesium alloys.

ATSM designation	Nominal composition* weight %			
	Al	Zn	Mn	Zr
AZ31B	3.0	1.0	0.5	
M1A			1.5	
AZ10A	1.2	0.4	0.5	
AZ31B	3.0	1.0	0.5	
AZ61A	6.5	1.0	0.2	
AZ80A	8.5	0.5	0.2	
M1A			1.5	
ZK21A		2.3		0.6
ZK60A		5.5		0.6

*(remainder Mg)

Alloys

Pure magnesium has a low strength with the yield strength being only about 20 MPa and the ultimate tensile strength about 90 MPa. For wrought forms of the metal and its alloys the yield stress is lower in compression than it is in tension. Because of the low strength of pure magnesium the metal is usually alloyed with at least two other elements. Most magnesium alloys are therefore ternary alloys, and are designated by a letter-number system that identifies the alloy elements and their percentage (Tables 12 and 13). The system is

Table 13. Nominal composition of magnesium casting alloys.

ATSM designation	Nominal composition weight % (remainder Mg)					
	Al	Zn	Mn	Zr	Th	Rare Earth
AM100A	10.0		0.2			
AZ63A	6.0	3.0	0.2			
AZ81A	7.6	0.7	0.2			
AZ91C	8.7	0.7	0.2			
AZ92A	9.0	2.0	0.2			
K1A				0.6		
ZE41A		4.2		0.7		1.2
ZH62A		5.7		0.7	1.8	
ZK51A		4.6		0.7		
ZK61A		6.0		0.8		

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

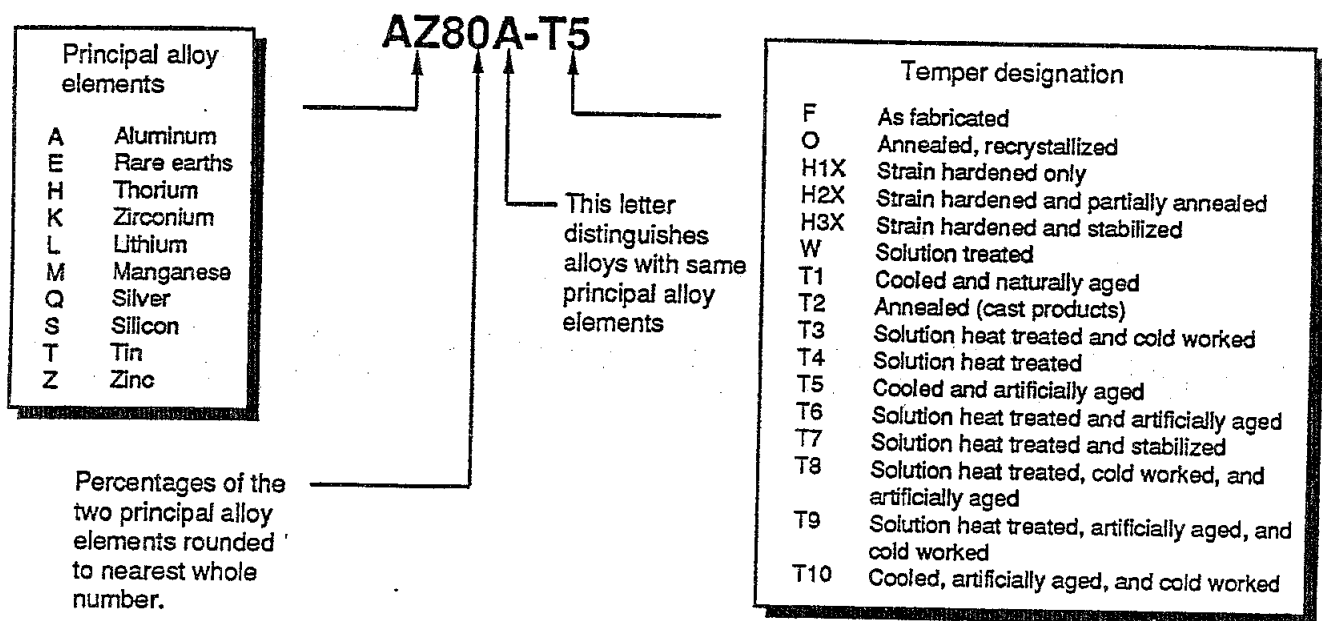


Figure 33. Designation system for magnesium alloys.

Heat treatment

explained in Fig. 33. Many of these alloys can be hardened by solution treating followed by aging. In Fig. 34 the binary phase diagram of magnesium and aluminum shows a rising solubility curve for aluminum illustrating how a 9% aluminum alloy may be suitable for age hardening. The full heat treatment involves solution heating at about 400°C which dissolves precipitates, rapidly cooling to room temperature, then aging at about 200°C. Table 14 shows the room temperature properties of some typical alloys. Magnesium alloys with aluminum and zinc as the major alloying elements are only suitable for room temperature service whereas those containing thorium have reasonable strength up to about 375°C as Fig. 35 shows.

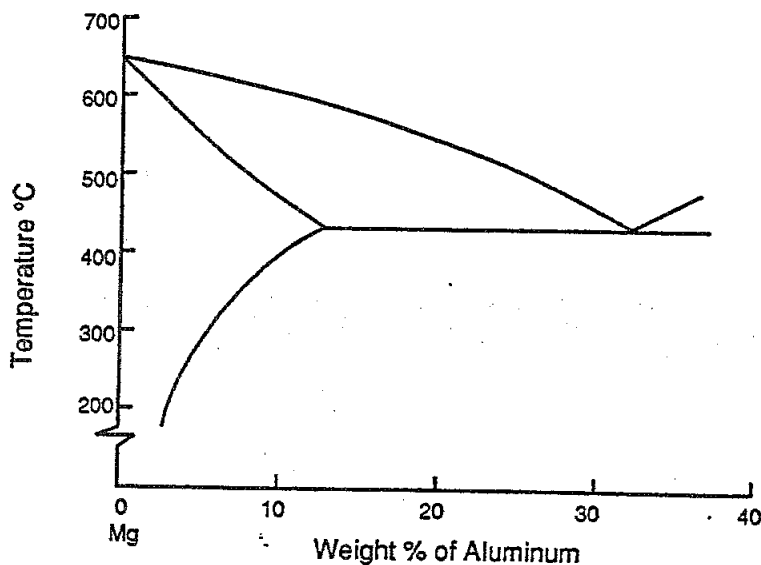
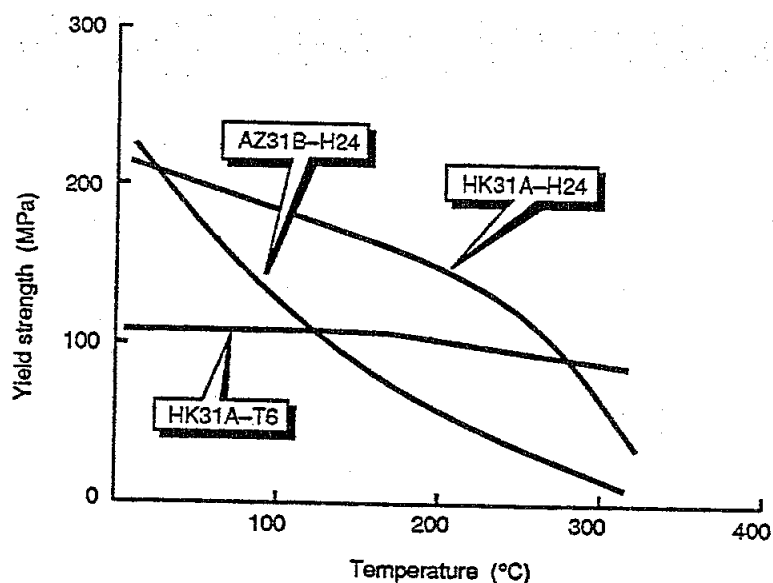


Figure 34. Part of the phase diagram for the magnesium-aluminum system. The rising solubility of aluminum in magnesium allows this alloy to be precipitation hardened.

Table 14. Room temperature properties of magnesium alloys.

ASTM designation	Tensile strength		Tensile yield strength		Compressive yield strength		Elongation % in 50 mm
	MPa	(ksi)	MPa	(ksi)	MPa	(ksi)	
AZ31B-0	255	(37)	152	(22)	110	(16)	21
AZ31B-H24	289	(42)	220	(32)	179	(26)	15
HK31A-H24	227	(33)	207	(30)	152	(22)	9
HM21A-T8	234	(34)	172	(25)	131	(19)	10
M1A-0	234	(34)	131	(19)			18
M1A-H24	269	(39)	200	(29)			10
AZ10A-F	241	(35)	152	(22)	76	(11)	10
AZ31B-F	262	(38)	200	(29)	96	(14)	15
AZ61A-F	310	(45)	227	(33)	131	(19)	16
AZ80A-F	338	(49)	248	(36)	152	(22)	11
AZ80A-T5	379	(55)	276	(40)	241	(35)	7
HM31A-T5	303	(44)	262	(38)	186	(27)	8
M1A-F	255	(37)	179	(26)	83	(12)	11
ZK21A-F	289	(42)	227	(33)	172	(25)	10
ZK60A-F	338	(49)	255	(37)	193	(28)	14
ZK60A-T5	358	(52)	303	(44)	248	(36)	11

Figure 35. Yield strength of magnesium alloys as a function of temperature. Those containing thorium have good elevated temperature strength.



Cleaning

The highly reactive nature of magnesium and the sensitivity to cracking of some alloys demand that extra care is taken to avoid any form of contamination during welding. Careful cleaning of the magnesium surface prior to welding is essential. This necessitates removal of any protective coating by mechanical or by chemical treatment. All traces of oil, grease, and dirt must be removed, and elaborate cleaning procedures, including cleaning of filler wires, are often specified to ensure the metal is clean enough before welding.

Shielding

The high affinity for oxygen demands that extremely good shielding from the atmosphere be achieved. Only inert gases can be used, and back shielding is usually required when no permanent backing bar is employed. Temporary backing bars have small grooves prepared in them to facilitate proper bead formation, and holes are provided for the back shielding gas.

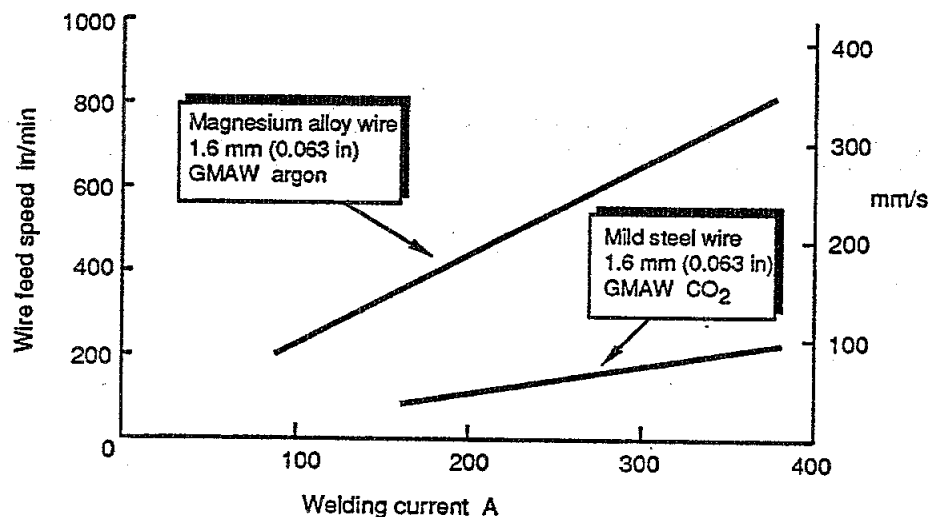


Figure 36. For a given current the volume of weld metal deposited from a magnesium electrode is more than three times that from a steel electrode.

Joint design

Both GTAW and GMAW are used for welding magnesium. GTAW is normally run with AC to improve the cleaning action. DC welding with electrode negative is not suitable since it does not provide the cleaning action that breaks up oxides on the surface of the weld puddle. When using GMAW argon shielding gas is required since helium causes excessive spatter and poorer control over metal transfer. With GMAW the high melting rate of the electrode provides a large volume of added metal (Fig. 36), and joints must be designed with a wide angle and wide root opening to accommodate this metal as Fig. 37 illustrates. With conventional joint preparations fusion defects, undercut, and incomplete penetration may result.

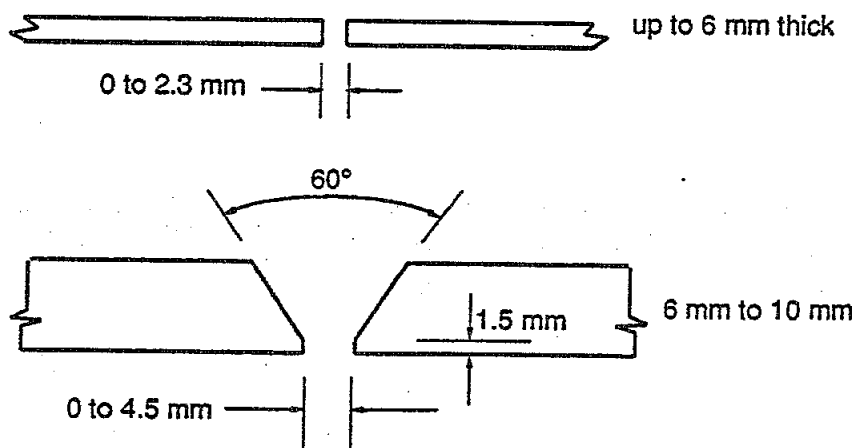


Figure 37. Typical joint geometries for GMAW in magnesium.

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

Table 15. Filler metals for magnesium and its alloys.

Filler metal designation	Composition weight %										
	Al	Be	Mn#	Zn	Cu*	Fe*	Ni*	Si*	Zr	RE	Other*
ER AZ61A	5.8-7.2	0.0002-0.0008	0.15	0.40-1.5	0.05	0.005	0.005	0.05			0.30
ER AZ101A	9.5-10.5	0.0002-0.0008	0.13	0.75-1.25	0.05	0.005	0.005	0.05			0.30
ER AZ92A	8.3-9.7	0.0002-0.0008	0.15	1.7-2.3	0.05	0.005	0.005	0.05			0.30
ER EZ33A				2.0-3.1					0.45-1.0	2.5-4.0	0.30

* max # min (refer to AWS A5.19 for details)

Cracking

Filler metals

A number of the magnesium alloys are susceptible to hot cracking. Zinc, in particular, promotes hot cracking although there is little effect for zinc levels less than 2%. Those alloys with over 5% zinc are very crack sensitive. Conversely, thorium improves resistance to hot cracking. Filler metals for magnesium welding are covered by AWS A5.19-80 "Specification for Magnesium Alloy Welding Rods and Bare Electrodes". Filler metal compositions are given in Table 15. The ER EZ33A is recommended for high temperature service conditions but should not be used with alloys containing aluminum. The most common filler metals for room temperature applications are ER AZ61A and ER AZ92A. The former has less crack sensitivity in welding wrought metals, but the latter filler metal is less crack sensitive for welding cast Mg-Al-Zn and Mg-Al alloys.

Postweld heat treatment

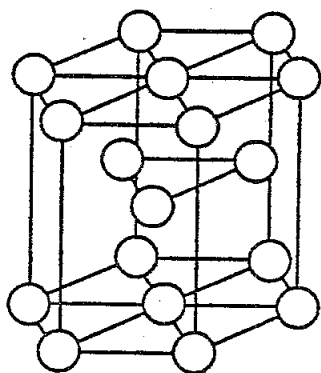
Preheating is sometimes necessary, particularly on thin, restrained sections and is typically in the range 175°-400°C, but it must not exceed the solution treating temperature. Most alloys require a postweld heat treatment to achieve specified properties and may involve a full solution treatment followed by aging or just a post weld aging. Alloys containing more than 1.5% aluminum are susceptible to stress corrosion cracking which occurs adjacent to the weld. These materials always require a stress relief after welding to prevent this type of cracking. Some typical treatments are shown in Table 16.

Table 16. Typical heat treatments for welds in magnesium alloys.

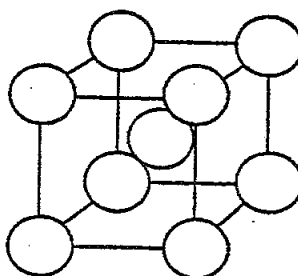
Alloy	Temper before welding	Temper after post weld treatment	Post weld heat treatment
AZ63A	T4	T4	0.5 hr at 387 °C
	T4 or T6	T6	0.5 hr at 387 °C + 5 hrs at 218 °C
	T5	T5	5 hrs at 218 °C
AZ81A	T4	T4	0.5 hr at 415 °C
AZ91C	T4	T4	0.5 hr at 415 °C
	T4 or T6	T6	0.5 hr at 415 °C + either 4 hr at 215 °C or 16 hr at 168 °C
AZ92A	T4	T4	0.5 hr at 410 °C
	T4 or T6	T6	0.5 hr at 410 °C + either 4 hr at 260 °C or 5 hr at 218 °C
AM100A	T6	T6	0.5 hr at 415 °C + 5 hr at 218 °C
EK41A	T4 or T6	T6	16 hr at 204 °C
	T5	T5	16 hr at 204 °C
EZ33A	F or T5	T5	5 hr at 215 °C; 2 hr at 343 °C + 5 hr at 215 °C
HK31A	T4 or T6	T6	16 hr at 204 °C; 1 hr at 315 °C + 16 hr at 204 °C
HZ32A	F or T5	T5	16 hr at 315 °C
K1A	F	F	none
ZE41A	F or T5	T5	2 hr at 329 °C; 2 hr at 329 °C + 16 hr at 176 °C
ZH62A	F or T5	T5	16 hr at 249 °C; 2 hr at 329 °C + 16 hr at 176 °C
ZK51A	F or T5	T5	16 hr at 176 °C; 2 hr at 329 °C + 16 hr at 176 °C
ZK61A	F or T5	T5	48 hr at 149 °C
	T4 or T6	T6	2-5 hr at 499 °C + 48 hr at 129 °C

TITANIUM AND ITS ALLOYS

In this section we deal with the main metallurgical features of welding titanium and its alloys. Zirconium, being very similar to titanium, has almost identical welding characteristics, and many of the ideas discussed for titanium are equally applicable to zirconium and zirconium alloys.



α phase. Below 885°C



β phase. Above 885°C

Figure 38. Titanium has either an hexagonal close-packed (α) structure or a body-centred cubic (β) structure.

Structure

Titanium has an hexagonal close-packed structure, the α phase, at room temperature but undergoes a transformation to body-centred cubic, β phase, on heating above 885°C. Fig. 38 illustrates the crystal structure of the two phases of titanium. Most alloy elements stabilize the beta phase, lowering the transformation temperature and allowing β to be present in the microstructure at room temperature. Aluminum, however, raises the transformation temperature and stabilizes the α phase. The presence of β phase improves the toughness, increases strength, enhances hot working behaviour, but generally has a negative effect on weldability. Alloys of the single phase α type containing aluminum can only be strengthened by cold working and are invariably supplied in the annealed condition for welding. Titanium alloys of the α - β or β type can be strengthened through heat treatment involving solution treating, quenching, and aging. The increase in strength is attributed to the formation of fine particles of α phase dispersed throughout the β that is retained after quenching.

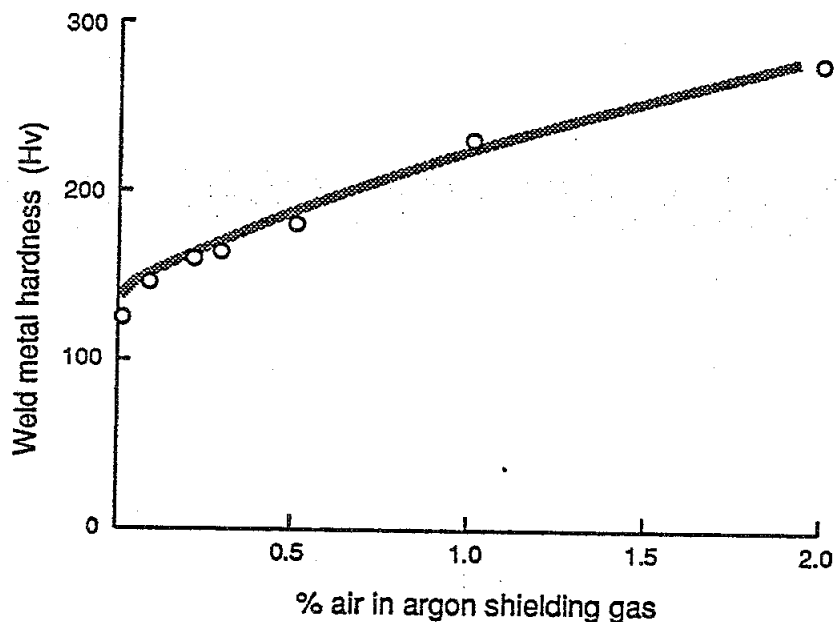
The elements with small atomic size, notably oxygen, hydrogen, carbon, and nitrogen, form interstitial solid solutions with titanium. These are normally considered as impurity elements and can have severe detrimental effects in welding. Hydrogen is more soluble in

Oxygen

the β phase than the α , and on cooling hydrogen will precipitate out in plates as a hydride throughout the α grains causing a marked decrease in toughness. Even in α - β alloys where the solubility for hydrogen is higher the metal suffers from hydrogen embrittlement, particularly at slow strain rates.

Oxygen is a highly effective interstitial solid solution strengthener, but increase in strength is accompanied by a decline in the ductility such that welds contaminated with oxygen are unacceptably brittle. The rapid increase of strength and hardness with oxygen fortunately provides a means of monitoring oxygen contamination in welding. If the weld exceeds some preset maximum hardness level it is likely to contain unacceptable levels of oxygen. The graph in Fig. 39 shows the relation between hardness and the percentage of air in deliberately contaminated shielding gas revealing just how sensitive this metal is to small quantities of oxygen.

Figure 39. Increase in weld metal hardness due to the presence of oxygen from air contamination of the shielding gas.



Basic considerations in welding

Physical properties of titanium are shown in Table 17 where they are compared with those of other metals. The melting point is slightly higher than that of steel, but the thermal conductivity is substantially lower. Consequently it is not difficult to melt and form acceptable bead shapes. The physical properties of titanium do not create any serious difficulties in welding, and most of the problems that are encountered are due to the metal's chemical properties. The strong affinity for oxygen and the high solubility of oxygen, nitrogen, and hydrogen demand special attention to the shielding system in welding. Only the inert gas shielded processes are suitable, and even these require additional shielding devices.

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

Table 17. Thermal properties of titanium compared with other metals.

Property	Titanium	Steel	Aluminum	Copper
Melting temperature °C (°F)	1668 (3034)	1536 (2799)	660 (1220)	1083 (1981)
Thermal conductivity W/m.°K	16	46	222	394
Expansion coefficient $\times 10^{-6}/^{\circ}\text{C}$ (°F)	8.4 (4.7)	11.8 (6.6)	23.6 (13.1)	16.5 (9.2)
Density Mg/m ³ (lb/ft ³)	4.85 (303)	7.83 (489)	2.77 (173)	8.9 (556)

Weld pool shielding

Welding is best carried out in a chamber, but where performed in the open a trailing shield, reverse side shielding system, and perhaps secondary shielding are required as Fig. 40 illustrates. Prior to arc ignition the system must be purged with pure argon to remove any air. Behind the arc the cooling metal must be shielded until it has cooled below 400°C to prevent oxidation. Typically, a trailing shield might be about 150 mm (6 in.) long and follow the design shown in Fig. 41. Oxidation causes a discolouration of the metal which can be used to monitor contamination. A light straw colour indicates a minor degree of oxidation which in most cases is acceptable, but a darker colour indicates unacceptable contamination.

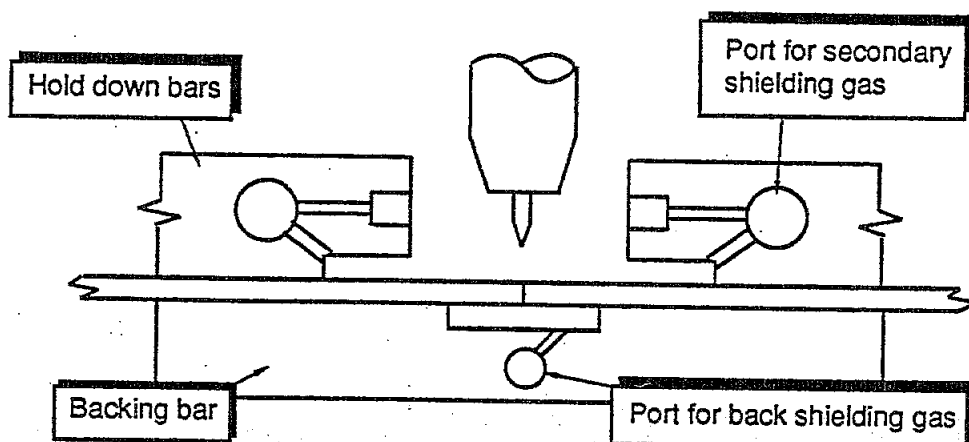


Figure 40. Typical shielding system for welding thin plates of titanium.

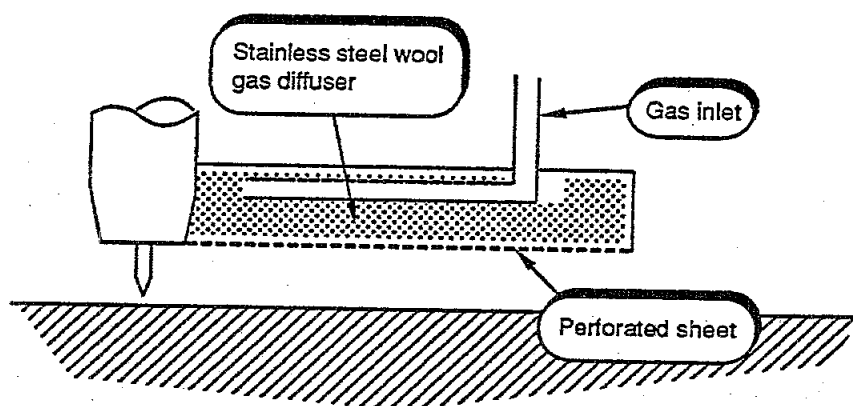


Figure 41. Typical design of a trailing shield for welding titanium. The metal behind the arc must be protected from the air until it has cooled below 400°C.

Hydrogen

Particular attention to sources of hydrogen must be paid. Moisture is the most common source, and even the gas used for shielding should have a guaranteed low moisture as indicated by its dew point which should be below -60°C. Fig. 42 demonstrates the effect of dew point of argon shielding gas on the mechanical properties of the weld and the hydrogen content. If a water cooled torch is being used it may be necessary to circulate warm water through the system to prevent condensation. All oils, grease, and other sources of hydrocarbons should be removed before welding. Halogen free materials are often specified for any degreasing operation since chlorides and other halogens can cause stress corrosion cracking when the metal is heated. A light oxide on the plate will need to be removed by pickling.

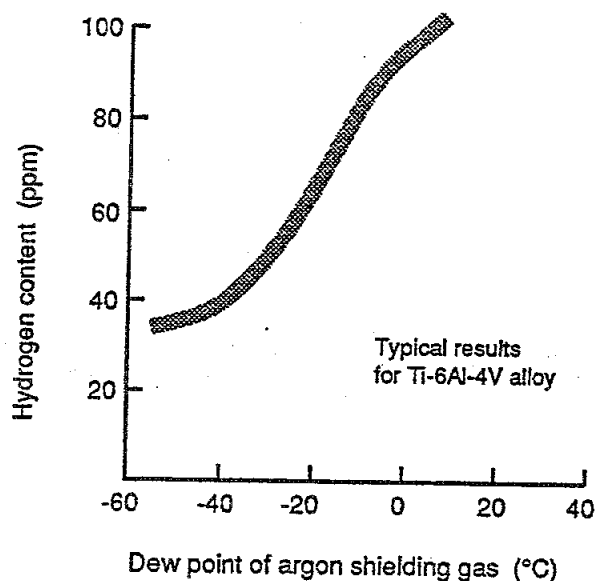


Figure 42. Effect of shielding gas dew point on the weld metal hydrogen content in a typical titanium alloy. To minimize the effects of hydrogen, argon with a dew point below -60°C is often specified.

Porosity

Titanium is especially sensitive to porosity, there being a host of possible causes. Sometimes it is difficult to pin down a particular source, and special care is required to eliminate any contaminant that could produce a gas. Drawing compound caught in a seam of a filler wire, fingerprints, dirt on the joint faces, dirt from grinding wheels, have all been cited as possible causes of porosity. Welding technique may be a factor, with the high heat input of the GMAW process appearing to favour low porosity. Rubber hoses should not be used in gas systems because they absorb air, and nozzles for GTAW should be larger than normal to provide good shielding. A short arc, no longer than the electrode diameter, is recommended to avoid turbulence and air entrapment.

Filler metals

You will find specifications for filler metals covered by AWS A5.16-90 "Specification for Titanium and Titanium Alloy Welding Electrodes and Rods" and some examples are given in Table 18. The main feature of the specification is the limit placed on the maximum level of interstitial elements. To minimize contamination in welding, filler wires should be cleaned with acetone prior to use.

Table 18. Composition of filler metals for titanium and titanium alloys.

Filler metal designation	Composition weight % (remainder titanium)								
	C	O	H	N	Al	V	Sn	Fe	Other
ERTi-1	0.03	0.10	0.005	0.015					
ERTi-2	0.03	0.10	0.008	0.020				0.10	
ERTi-3	0.03	0.10-0.15	0.008	0.020				0.20	
ERTi-4	0.03	0.15-0.25	0.008	0.020				0.20	
ERTi-5	0.05	0.18	0.015	0.030	5.5-6.7	3.5-4.5		0.30	0.005 Y
ERTi-5ELI	0.03	0.10	0.005	0.012	5.5-6.5	3.5-4.5		0.15	0.005 Y
ERTi-6	0.08	0.18	0.015	0.050	4.5-5.8		2.0-3.0	0.50	0.005 Y
ERTi-6ELI	0.03	0.10	0.005	0.012	4.5-5.8		2.0-3.0	0.20	0.005 Y
ERTi-7	0.03	0.10	0.008	0.020				0.20	0.12/0.25 Pd
ERTi-9	0.03	0.12	0.008	0.020	2.5-3.5	2.0-3.0		0.25	0.005 Y
ERTi-9ELI	0.03	0.10	0.005	0.012	2.5-3.5	2.0-3.0		0.20	0.005 Y
ERTi-12	0.03	0.25	0.008	0.020				0.30	0.2/0.4 Mo
ERTi-15	0.03	0.10	0.005	0.015	5.5-6.5			0.15	0.6/0.9 Ni 0.5/1.5 Mo 1.5/2.5 Nb (Cb) 0.5/1.5 Ta

Refer to AWS A5.16-90 for details and notes.

The heat affected zone

The phase change that occurs in titanium on heating will take place in the heat affected zone adjacent to the weld. On cooling the HAZ transforms back to an alpha or alpha-beta structure. The resulting properties of the HAZ will vary with the alloy composition, pure titanium suffering little change in the HAZ while alpha-beta alloys undergo substantial changes in properties. Some of these latter alloys have poor weldability because of cracking. This is a serious problem with the very high strength Al-Mo and Al-V-Sn types. Cracking results simply from the high strength and low ductility and occurs more readily under conditions of high restraint. Preheating to 150°C may have an ameliorating effect in some cases but is not commonly applied. Improvement of the ductility of the weld can be achieved by using very low interstitial filler metals which are listed in AWS A5.16.

CAST IRON

Alloys of iron and carbon in the range 1.7–4.5% are known as cast irons. They are easily made by remelting pig iron, have a lower melting point than steel, and are excellent materials for making castings. They are capable of producing sharp castings with good surface finish in a wide range of sizes. A typical example of a product made from cast iron is shown in Fig. 43. Castings in most cast irons can be machined.

Pipes	Automotive parts
Rolls	Cylinder blocks
Machinery parts	Crank cases
Forming dies	Crank shafts

Figure 43. Typical component made of cast iron.

Need for welding

Since these metals are used primarily for castings they are not welded as often as wrought steel, but there are occasions when welding is necessary. Sometimes corrections need to be made to the casting when it is produced to avoid scrapping it because of some imperfection or error in the foundry process. Castings that have been damaged in service may be reclaimed by welding. It is quite common to repair cracks in castings by welding or braze welding. Finally, welding may be employed in joining several small castings to make a larger component that could not, perhaps, have been cast as a single piece.

Cast iron is not easy to weld—the most common problem being cracking—but a thorough understanding of the metallurgy involved will assist in prescribing a suitable procedure. The metallurgy of cast irons is complex, and there are a wide range of structures that can be formed even from material of the same composition. The starting point for developing a welding procedure must therefore be an understanding of the type of iron being considered, how it was produced, and how it will respond to the thermal effects of welding.

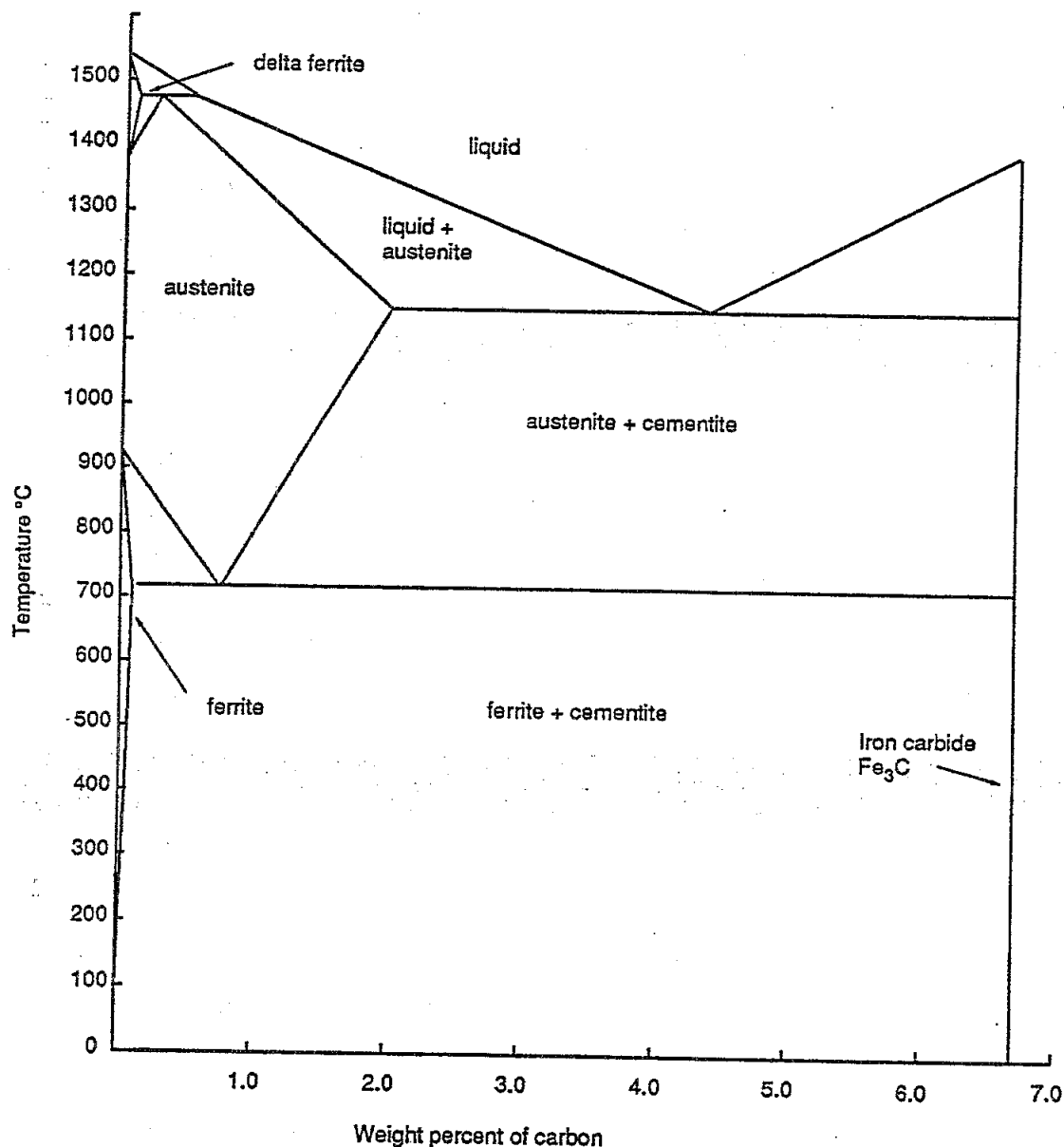


Figure 44. Iron-iron carbide phase diagram. Iron carbide is the form most commonly taken by carbon in steels but is not the most stable form of carbon.

Phase diagrams

Let us start by considering the conventional iron-carbon diagram. The diagram that most people are familiar with and shown in Fig. 44 is not really an iron-carbon diagram but an iron-iron carbide diagram. It is, in fact, an equilibrium phase diagram for iron carbide. Iron carbide is the form that carbon assumes in a steel when it is not in solution so this diagram is particularly useful when dealing with steels. But iron carbide is not the most stable form of carbon in iron. It is a metastable phase. The most stable form is graphite: free carbon where the atoms of carbon are not combined with atoms of iron.

Graphite

A phase diagram can be constructed for iron and the equilibrium phase graphite. If we superimpose this on the conventional iron-iron carbide diagram the graphite lines are slightly displaced, as Fig. 45 shows. This is particularly noticeable for the liquidus line above 4.3% carbon implying that under equilibrium cooling conditions liquid iron of, say, 5% carbon would precipitate graphite from the melt before any iron carbide could form. The overall shape of the two diagrams is, however, the same allowing us to consider the two as slight distortions of each other and not as completely separate diagrams.

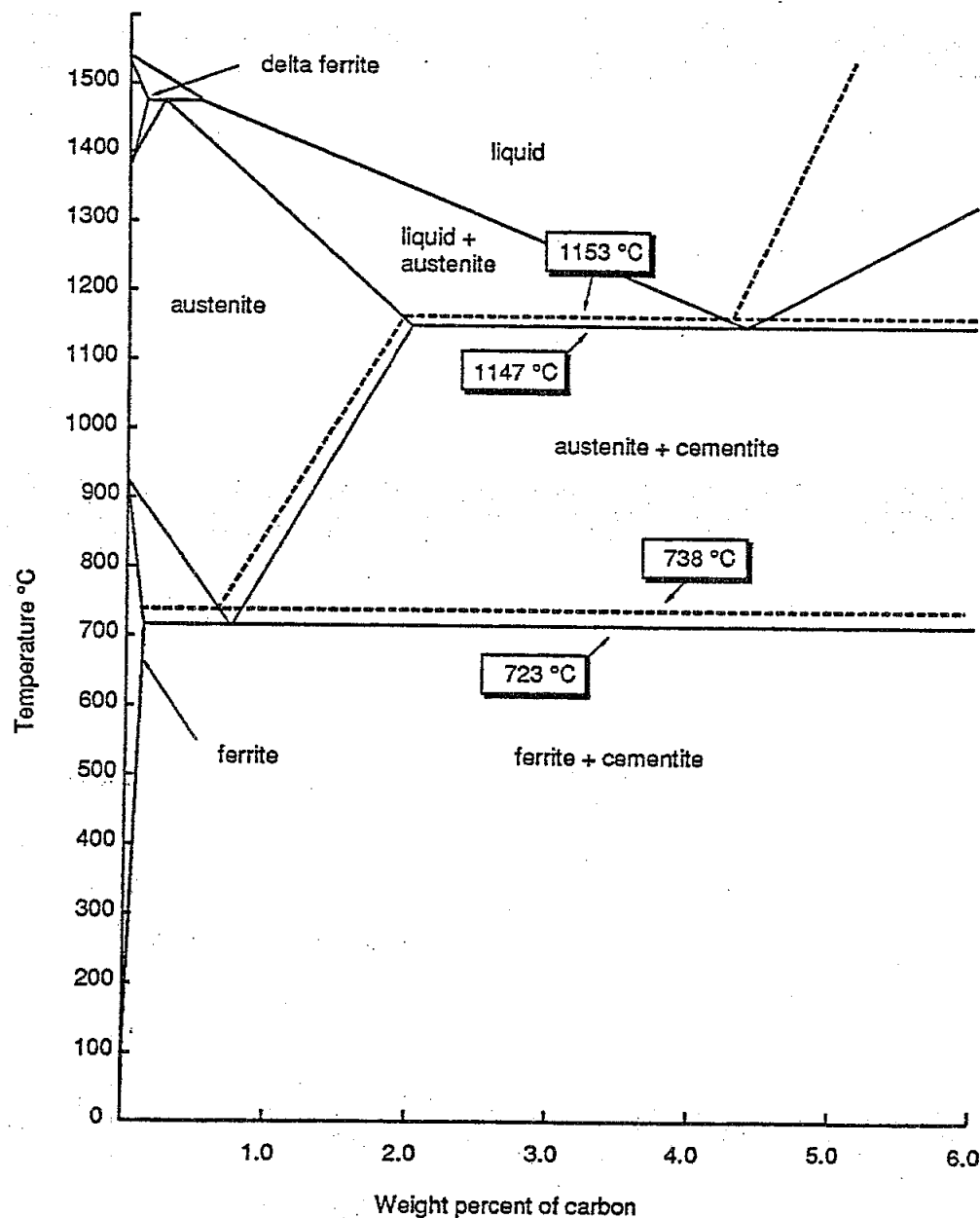


Figure 45. The iron-graphite phase diagram shown by the dotted lines and superimposed on the iron-iron carbide diagram. Graphite is the most stable form of carbon in iron and often occurs in cast irons.

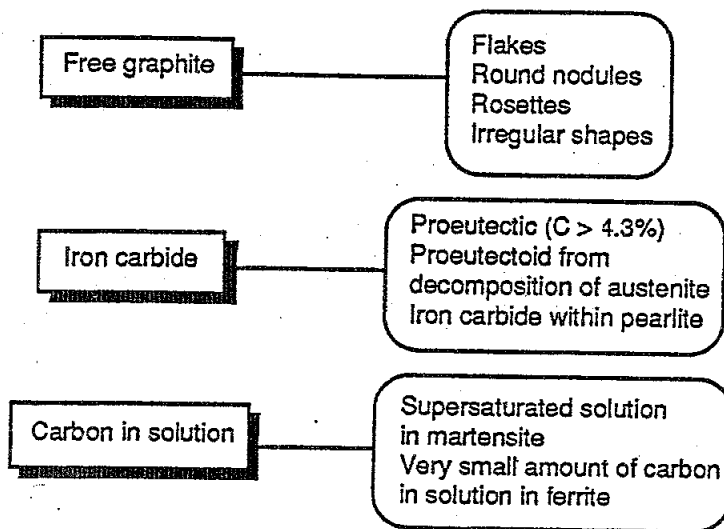


Figure 46. Forms of carbon in cast iron.

Forms of carbon

The possibility of carbon existing as free graphite as an alternative to iron carbide adds to the complexity of cast iron metallurgy. Consider for a moment (Fig. 46) the possible forms that carbon could now take in an iron carbon alloy:

- Free graphite. The graphite could take on many shapes, appearing as flakes, star shaped rosettes, or round nodules.
- As iron carbide (cementite) within pearlite.
- 'Free' proeutectoid cementite from the decomposition of austenite.
- 'Free' proeutectic cementite from solidification if the iron has more than 4.3% carbon.
- Martensite with carbon trapped as a supersaturated solution.

The properties of the cast iron, and the properties of welds in it, will depend on which forms are present. They depend not only on the composition but also on the cooling rate and whether any heat treatment has been applied. The first important factor in determining whether the carbon is present as graphite is the composition. Alloy elements can be classed as graphitizers, those tending to promote the formation of graphite, or carbide formers tending to promote the formation of carbides. The relative power of some graphitizers is listed in Table 19. The most important is silicon.

Graphitizers

The second important factor in promoting graphite is cooling rate. A slow cooling rate from the melt is necessary for graphite formation. A fast cooling rate, experienced for example in a casting with metal chills, will not produce any graphite.

Table 19. Elements that act as graphitizers in cast iron.

Element	Effect as a graphitizer relative to silicon
Silicon	100%
Aluminum	50%
Titanium	40%
Nickel	35%
Copper	20%

Types of cast iron

There are four basic types of cast iron which result from the various combinations of composition, cooling rate and heat treatment:

- White iron
- Gray iron
- Malleable iron
- Ductile iron

We will discuss these four types individually in the succeeding sections.

White iron

White iron is so called because when fractured it has a white or silvery appearance. This iron contains no graphite and is very hard and brittle. It cannot be machined or welded but has very good wear resistance. Sometimes white iron can be produced on the skin of another more ductile iron to provide excellent wear resistance in the surface. Rolls are sometimes made this way. White iron is important because it is the starting point of malleable iron. The composition of a typical white iron is given in Table 20 where you will note the low levels of graphitizers such as silicon. The metallurgical structure of a white iron can be deduced by following through the iron-iron carbide phase diagram as shown in the sequence of Figs. 47 to 50.

Table 20. Composition of white iron.

Composition (weight %)				
C	Si	Mn	S	P
1.8-3.6	0.5-1.9	0.25-0.8	0.06-0.20	0.06-0.18

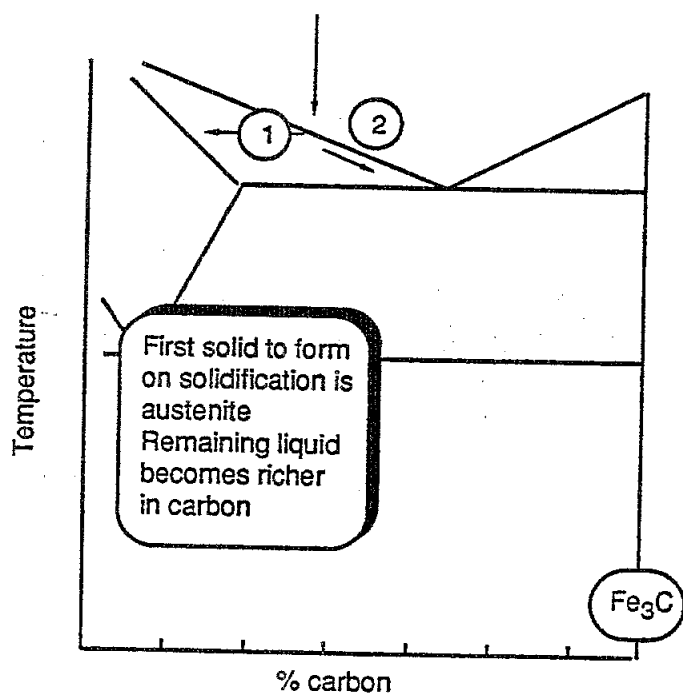


Figure 47. Solidification of hypoeutectic cast iron. First solid to form is austenite. Remaining liquid becomes richer in carbon as it cools.

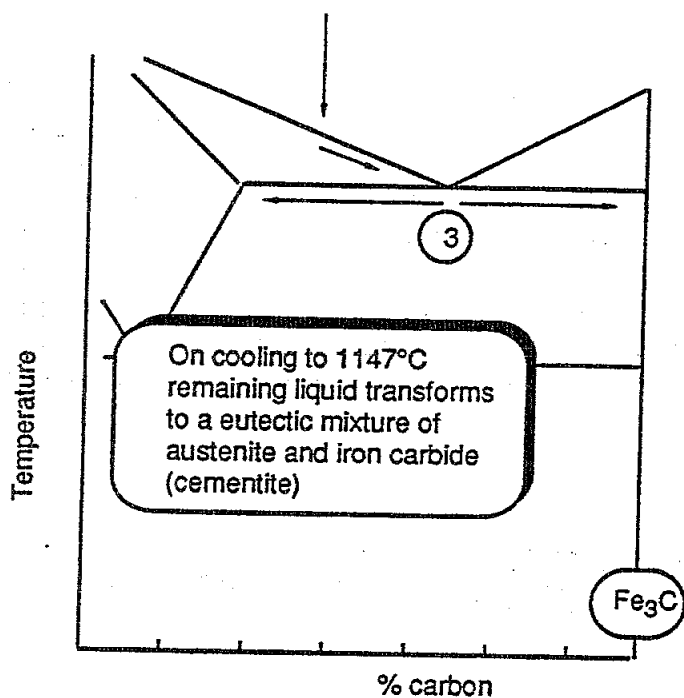


Figure 48. Remaining liquid solidifies as a eutectic comprising iron-carbide and austenite. At this point two types of austenite exist—the pro-eutectic austenite and the austenite within the eutectic.

Figure 49. As the solid continues to cool the solubility of the austenite for carbon decreases. Thus the austenite rejects carbon in the form of iron-carbide (cementite) which forms around the edge of the austenite grains.

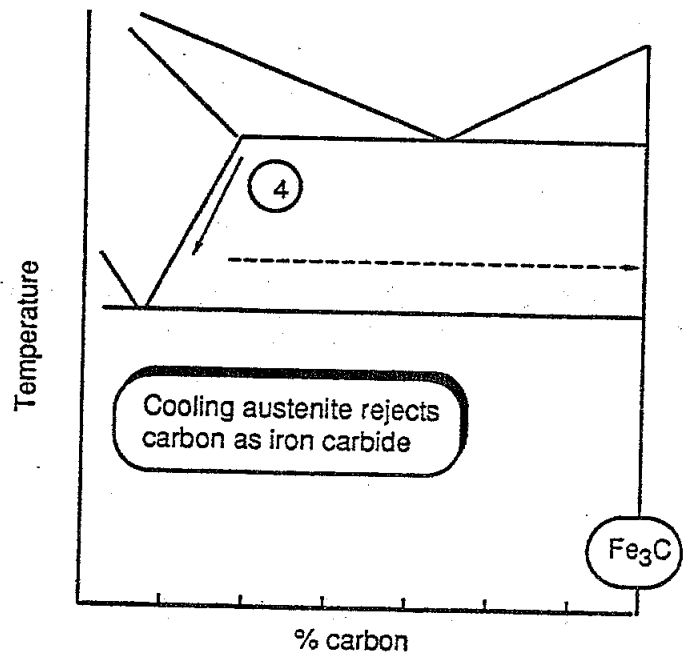
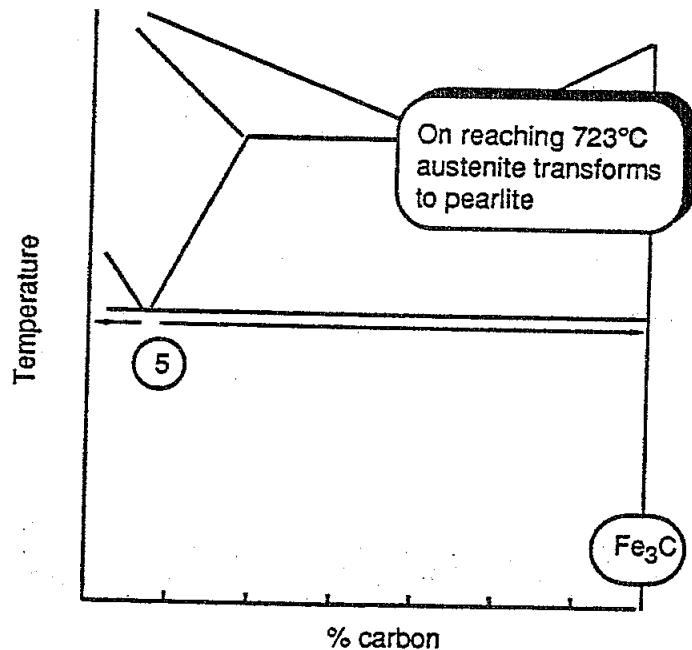


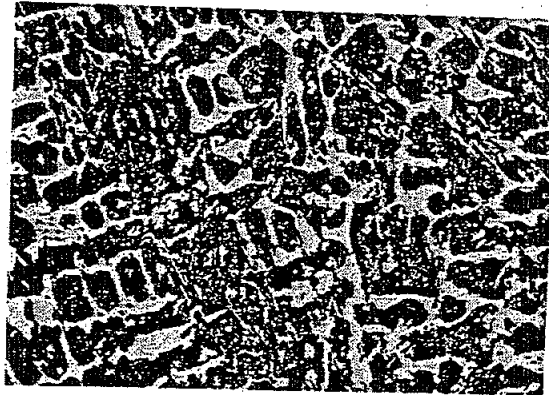
Figure 50. On cooling to the eutectoid temperature 723°C the austenite now has only 0.8% carbon in solution. At this temperature the austenite transforms to the eutectoid pearlite. The final structure of a white iron is therefore pearlite and cementite.



Cooling of a hypoeutectic cast iron

In the range of interest, 1.7 to 4.5% carbon, the diagram shows a eutectic where the presence of 4.3% carbon depresses the melting point of pure iron from 1553°C down to 1152°C. It is this substantial lowering of the melting point that makes this alloy suitable for casting. If we consider the eutectic in terms of the iron-iron carbide diagram (Fig. 44) we see that the eutectic is a mixture of austenite with 1.7% carbon and cementite (iron carbide, Fe_3C). If the iron has less than 4.3% C (hypoeutectic) the eutectic will be preceded by the formation of austenite from the melt (step 1 in Fig. 47) whereas for iron exceeding 4.3% C (hypereutectic) precipitation of cementite precedes the eutectic. Irons of more than 4.3% C are rarely encountered so need not be discussed in any further detail.

Figure 51. Photomicrograph of white iron showing the pearlite and cementite structure.



Structure of white iron

The eutectic mixture will not remain stable down to room temperature because the austenite must start to decompose as it is cooled. As the temperature is lowered from the eutectic the austenite has a decreasing solubility for carbon (step 4 in Fig. 49) and so will reject carbon as iron carbide (cementite). Finally the temperature reaches 723°C—the eutectoid temperature—and the austenite has an equilibrium carbon content of 0.8% C. This transforms to pearlite as shown in step 5 in Fig. 50. Thus an iron that does not form graphite will have a structure comprising:

- Pearlite surrounded by cementite inherited from the proeutectic austenite.
- Pearlite surrounded by cementite inherited from the austenite/cementite eutectic.

Since the structure of white iron is comprised entirely of pearlite and cementite we can see at a glance why it is hard and brittle. The typical hardness of a white iron is about 450Hv. Fig. 51 shows a photomicrograph of white cast iron.

Gray Iron

The presence of higher silicon levels and a reduction in the cooling rate of the casting encourage the formation of graphite and the production of gray iron. The fracture appearance is gray because of the graphite flakes present in the metal. A typical analysis is shown in Table 21 where the higher silicon level should be noted. The presence of carbon as graphite rather than cementite lowers the strength but improves the ductility and machining properties making gray iron a more useful material in most cases for castings than white iron. Typical properties are given in Table 22. Gray iron finds applications in automotive engine cylinder blocks, pipes, agricultural equipment, brake drums, and similar components.

Table 21. Composition of gray cast iron.

ASTM Specification	Composition (weight %)				
	C	Si	Mn	S	P
A48, A159, A278, A319	2.5-4.0	1.0-3.0	0.25-1.00	0.02-0.25	0.05-1.0

Structure of gray iron

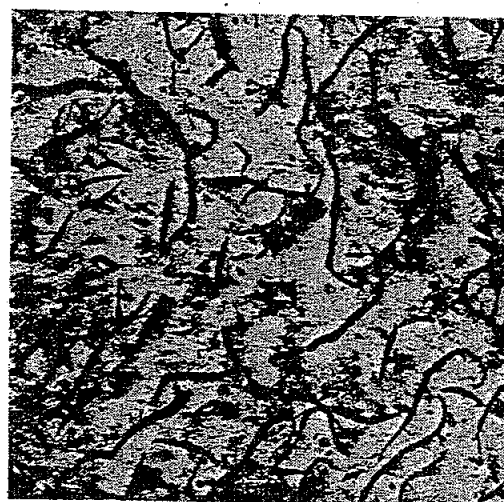
The structure of a gray iron (shown in Fig. 52) consists of flakes of graphite in a pearlite matrix possibly with some regions of ferrite present. Annealing of gray iron at about 500°C provides an opportunity for further decomposition of some of the pearlite to form graphite, which attaches itself to the existing flakes, and free ferrite appearing as pools around the graphite flakes.

Table 22. Mechanical properties of gray iron.

Class or Grade*	Minimum tensile strength ksi (MPa)	Hardness range HB
G1800	18 (124)	187 max
20	20 (138)	
G2500	25 (172)	170-229
25	25 (172)	
G3000	30 (207)	187-241
30	30 (207)	
G3500	35 (241)	207-255
35	35 (241)	
G4000	40 (276)	217-269
40	40 (276)	
45	45 (310)	
50	50 (345)	
55	55 (379)	
60	60 (413)	

* For details refer to ASTM A 159 and A 48

Figure 52. Typical microstructure of gray cast iron. Note the graphite flakes.



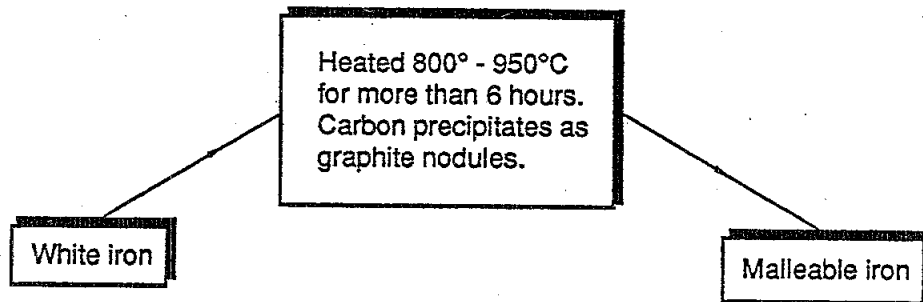


Figure 53. Malleable iron is produced from white iron by heating for an extended time above the austenite transformation temperature.

Malleable iron

Although the ductility of gray iron is better than that of white iron it is still quite low. The presence of graphite as thin flakes weakens the structure, a crack easily running along the flakes with little deformation. Further increases in the ductility of cast iron can be achieved by reheating a white iron to produce malleable iron. In its cast form white iron contains no graphite but heating for several hours in the range 800°C to 950°C allows the carbon dissolved in the austenite to precipitate as graphite nodules (Fig. 53). As the metal cools, the excess carbon in the austenite precipitates out on the nodules to leave a structure of graphite in a matrix of ferrite. The matrix can be modified to pearlite, pearlite/ferrite, or even martensite by quenching after heating or by alloying. Fig. 54 illustrates how cooling rate can affect the resulting structure.

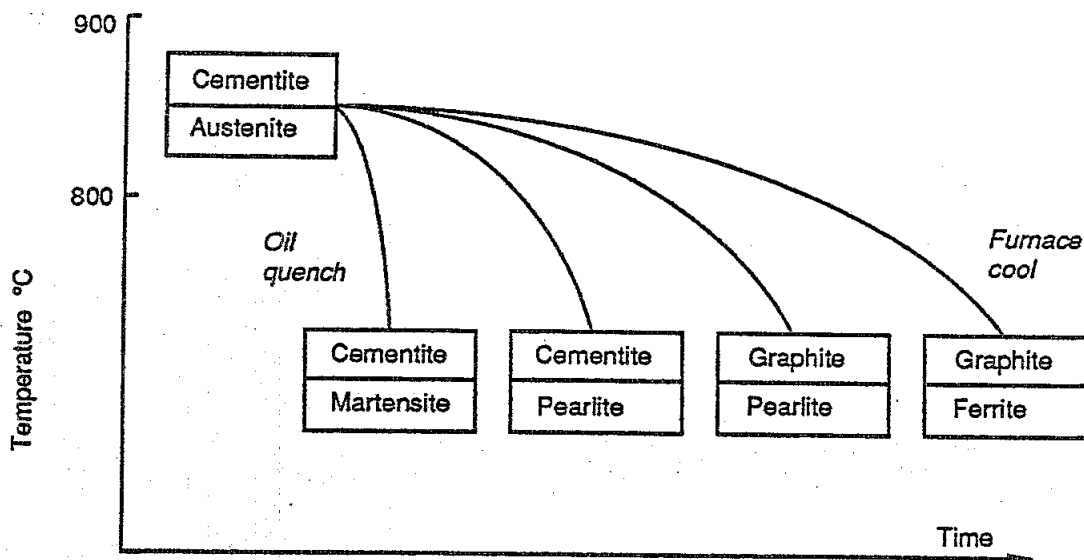


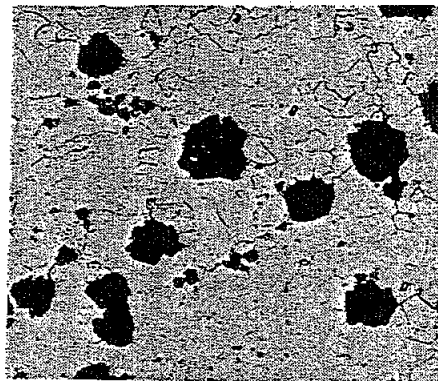
Figure 54. The structure of malleable iron can be changed by controlling the rate of cooling after heating.

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

Table 23. Composition ranges for malleable iron.

ASTM Specification	Composition (weight %)				
	C	Si	Mn	S	P
A47, A197, A220, A338, A602	2.0 - 2.6	1.1 - 1.6	0.20 - 1.0	0.04 - 0.18	0.18 max

Figure 55. Typical microstructure of malleable cast iron. Note the shape of the graphite nodules which gives this iron greater ductility than a gray iron with graphite present as flakes.



Graphite form

An important feature of the malleable irons is that the graphite precipitates out as nodules or rosettes rather than flakes. An example of this is shown in Fig. 55. This form does not provide the planes of weakness present in a gray iron and contributes to the improved ductility. A disadvantage of the malleable irons, however, is that a separate heat treatment of the castings is required to achieve the desired properties. Composition ranges for malleable iron are given in Table 23, and typical properties are shown in Table 24.

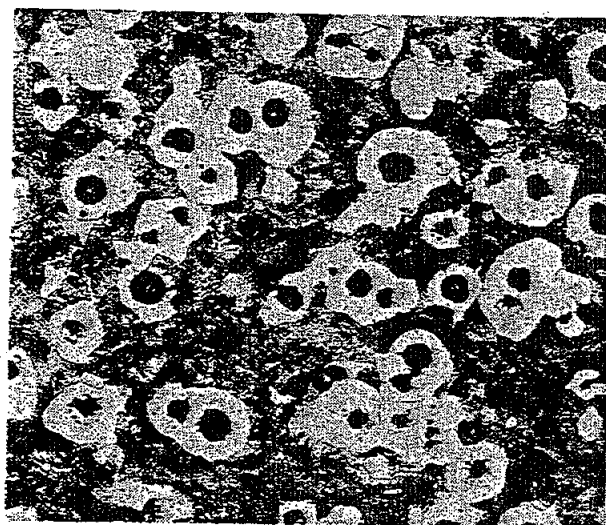
Table 24. Mechanical properties of several grades of malleable iron.

ASTM specification	Grade or class	Tensile strength		Yield strength		Hardness HB	Elongation % in 50 mm
		MPa	(ksi)	MPa	(ksi)		
A47 (ferritic type)	32510	345	50	224	32	156 max	10
	35018	365	53	241	35	156 max	13
A220 (pearlitic)	40010	414	60	276	40	149-197	10
	45006	448	65	310	45	156-207	6
	50005	483	70	345	50	179-229	5
	60004	552	80	414	60	197-241	4
	70003	586	85	483	70	217-269	3
A602 (automotive) (martensitic)	M3210	345	50	224	32	156 max	10
	M4504	448	65	310	45	163-217	4
	M5003	517	75	345	50	187-241	3
	M5503	517	75	379	55	187-241	3

Ductile iron

Ductile iron allows a casting of increased ductility to be produced without the heat treatment needed in a malleable iron. Improved ductility is achieved in a similar way by changing the shape of the graphite to round nodules rather than flakes, but this is accomplished by inoculating with certain alloy elements and not by heat treatment. The elements that have the property of modifying the graphite shape are magnesium and cerium. Cerium is a rare earth metal and is normally used as misch metal which is a mixture of rare earth metals with about 50% cerium. Fig. 56 illustrates the nodules formed in ductile iron which can be compared with those in malleable iron.

Figure 56. Typical microstructure of a ductile iron. Note the shape of the graphite nodules which is the result of alloy additions to the iron.



Compacted iron

Recently a modification of ductile iron known as compacted iron has been employed. Made in the same way as ductile iron but with special control of the materials used for inoculation, compacted iron has graphite in the form of irregular shapes that provide improvement of specific properties. Thermal shock resistance is better than ductile iron, and shrinkage on freezing is less.

Effect of alloy elements

Alloying elements may be added to cast irons to control the formation of pearlite by increasing the hardenability of the metal. This is similar to the behaviour in steels, and sufficient quantities may be added to cause martensite to form instead of pearlite. Nickel is one element used in this way. Notice that nickel also has a separate role as a graphitizer. Thus it may be added to encourage the formation of graphite in a manner similar to silicon and also to increase the hardenability. Chromium, on the other hand, increases hardenability but is a strong carbide former and will encourage cementite formation at the expense of graphite.

Impurities

Phosphorus is normally regarded as an impurity, which forms a eutectic phosphide, and is kept as low as possible, but it does improve the fluidity of the liquid and is sometimes deliberately present to help make sharp castings in thin sections. Sulphur is considered an impurity and is kept as low as possible. Its effect, as in steel, can be minimized by the presence of manganese, but since the latter is a carbide former and not a graphitizer there may be restrictions on the level of manganese that can be tolerated.

Carbon equivalent

The strength of cast iron can be related to a carbon equivalent that combines the effect of carbon, phosphorus and silicon:

$$CE = \%C + 1/3 (\%Si + \%P)$$

Fig. 57 shows a relation between the carbon equivalent and the strength. Notice that increasing the carbon equivalent *lowers* the strength. This may seem odd since we usually expect more carbon to raise the strength, but in a cast iron more carbon means more graphite and less pearlite causing a drop in strength. Carbon and silicon tend to have similar effects not only on the strength but also on the amount of graphite present. Increasing carbon while simultaneously reducing silicon will keep the strength and the amount of graphite constant.

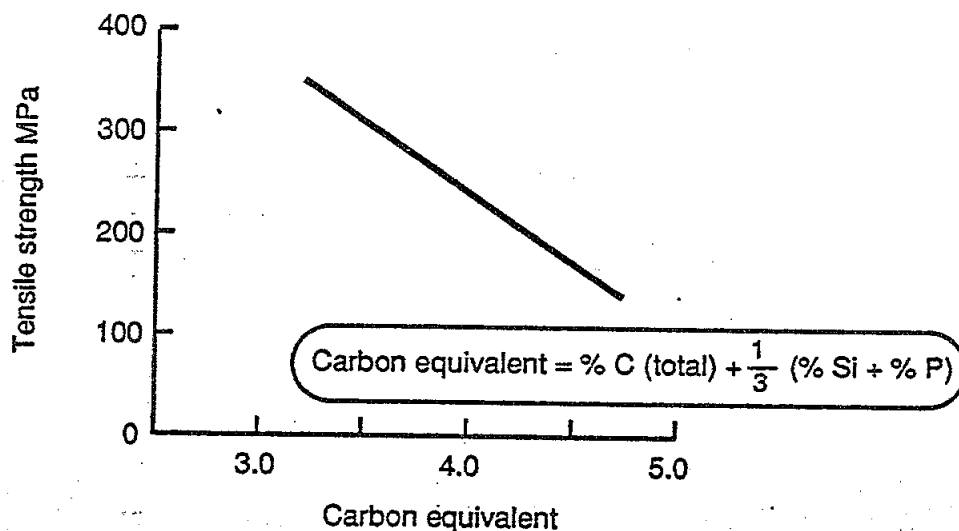


Figure 57. Relation between the strength of cast iron and the carbon equivalent.

Basic considerations in welding

Welding sequence

The welding engineer is faced with a number of serious difficulties in developing a welding procedure for cast iron. First, since many cast irons are inherently of low ductility they are liable to crack on welding simply from the stresses set up due to thermal contraction. Clearly, the more ductile the cast iron the easier it will be to weld without it cracking. It may be that arc welding is not the most suitable method. Brazing may be better in some cases. Even with arc welding, studding to provide mechanical strength to the joint and to prevent the weld metal from lifting out may be recommended. To help minimize stresses, welds can be deposited in short lengths in various parts of the work such that each has an opportunity to cool and contract before another pass is deposited on it (Fig. 58). Block welding may also be beneficial in reducing welding stresses.

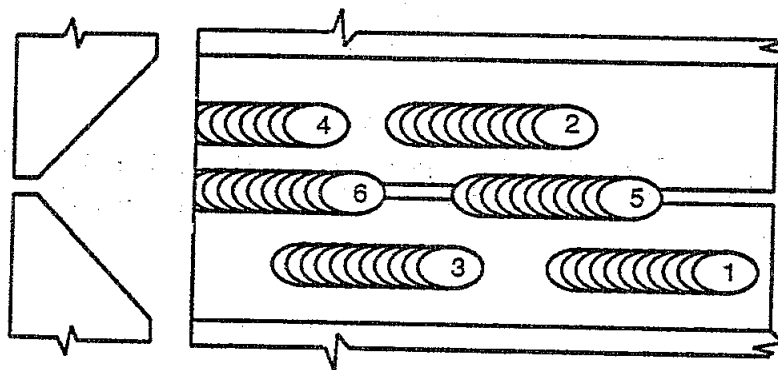


Figure 58. Method of minimizing welding stresses by depositing short beads separately allowing each to cool before depositing the next layer. This method reduces both longitudinal and transverse stresses.

Heat affected zone

Second, the carbon diluted into the weld metal may produce undesirable properties on cooling, perhaps causing it to crack. Third, in the heat affected zone the heat from welding may put the cast iron through a thermal cycle that results in a brittle region that could crack. In addition to the conventional HAZ there is a region next to the weld metal where partial melting may occur. Looking at the iron-iron carbide phase diagram in Fig. 59 you can see a wide region where liquid and austenite can exist together. Let us consider the metallurgical structures that could be formed in the various regions adjacent to the weld metal.

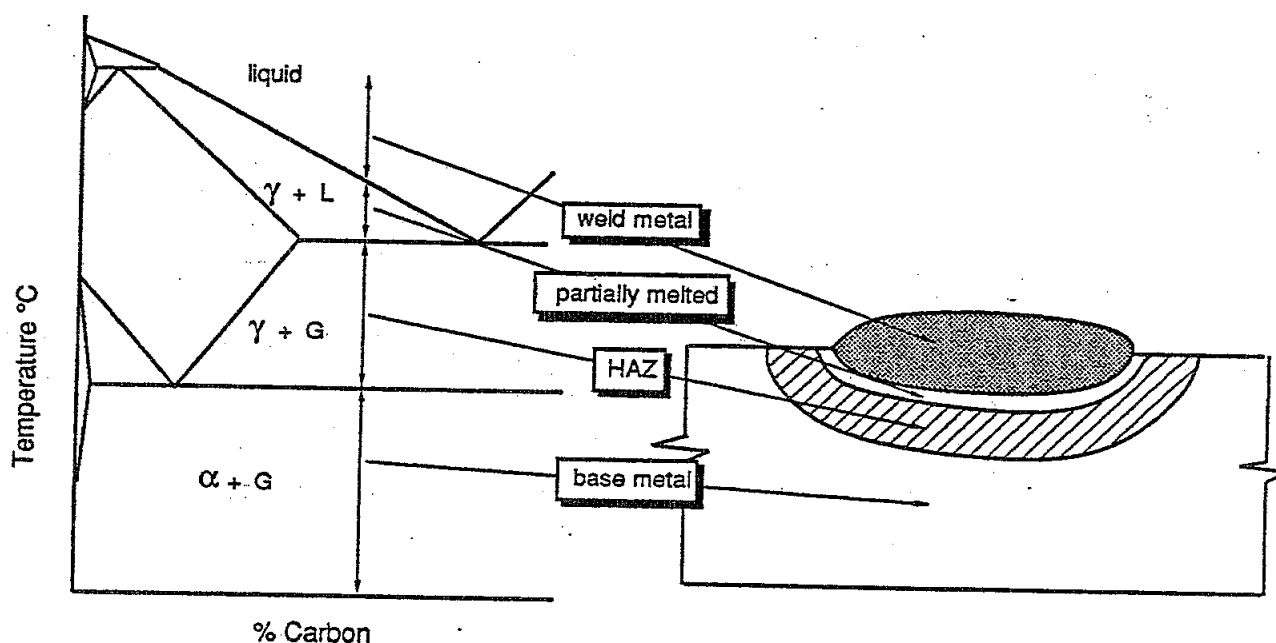


Figure 59. Various regions of the heat affected zone shown in relation to the phase diagram. Note the region of partial melting.

Partially melted region

In the partially melted region the liquid formed could produce either a gray or a white iron structure on cooling. Since a weld cools much faster than the original casting a white iron, free cementite, or a martensite structure can be produced even if the original casting was gray. A low heat input will reduce the width of the heated zone, and a high preheat will minimize the tendency to produce white iron structure. Ductile irons may also suffer problems in the partially melted zone. A wide partially melted zone in a ductile iron may result in losses of magnesium or cerium thus losing the control of graphite in that region.

Austenite region

In the part of the HAZ that reaches 800°C to 1150°C the matrix transforms to austenite, and the graphite starts to dissolve into it. The extent of this dissolution depends on the shape of the graphite: flakes having a high surface to volume ratio dissolve more readily than round nodules. The austenite with carbon in solution transforms to hard, brittle martensite if cooled rapidly, this being a major source of cracking problems. To avoid the martensite formation preheating the material before welding is essential. With adequate preheat the cooling rate through the transformation is slow enough for pearlite to

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

Preheat

form. The level of preheat required depends on the initial matrix structure of the iron. An iron with a pearlitic matrix requires a higher preheat than one with a ferritic matrix. Some typical ranges are suggested in Table 25, and the effect of preheat temperature on the HAZ hardness of a gray iron is shown in Fig. 60. The method of preheating is critical and where possible should be done in such a way as to place the resulting weld in compression.

Table 25. Typical preheat ranges for welding cast iron.

Type of cast iron	Microstructure	Preheat range	
		°C	(°F)
Gray	Ferritic	20 - 300	(70 - 600)
Malleable		20 - 150	(70 - 300)
Malleable	Pearlitic	20 - 300	(70 - 600)
Ductile	Ferritic	20 - 150	(70 - 300)
Ductile	Pearlitic	20 - 300	(70 - 600)

Filler metals

For arc welding of cast irons there are three main types of filler metals that could be selected:

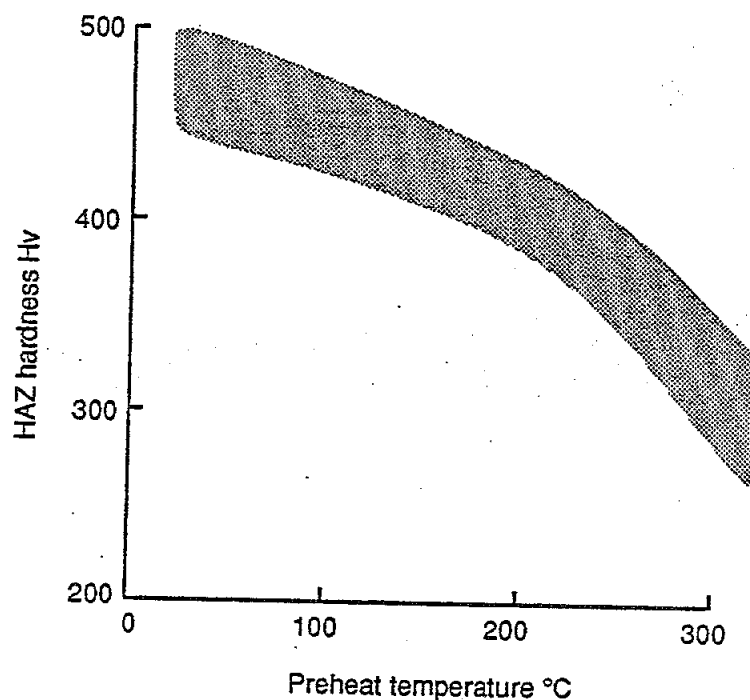
- steel
- cast irons
- non-ferrous (nickel based) alloys.

Stainless steels and copper based alloys have also been used to a limited extent. Since the parent metal is low in ductility there is an advantage in choosing a filler metal that is lower in strength and very ductile. This will then accommodate the shrinkage strains from welding without causing the cast iron to crack. This is obviously not possible if for some reason a weld of matching strength is required but is otherwise recommended.

Steel filler metal

If steel is used as a filler the dilution must be kept very low to minimize pickup of carbon. Heat input should be low to minimize the width of the HAZ and keep the penetration down. The first pass of a weld with E48018 on cast iron has typically 1 to 1.5% carbon making it very hard, brittle, and liable to crack. A weld made with a steel electrode on cast iron cannot be machined. For these reasons mild steel electrodes are normally only recommended for repairs in nonstructural applications and where subsequent machining is not required.

Figure 60. Graph showing the effect of preheat on the heat affected zone hardness. Typical results for a gray iron.



Cast iron filler

Cast iron as a filler may be preferred in some cases since the dilution problem does not exist in the same way, and the lower melting point allows lower heat inputs to be used. The ductility, however, is not as high, and therefore a cast iron weld metal does not have the same capacity to absorb the shrinkage. There is substantial loss of carbon and silicon in the weld metal, and the filler must make up for this if a white iron weld metal is to be avoided. The filler will have higher silicon than the casting, but even this may not be enough, and additional alloying with copper or nickel as graphitizers may be needed. Cast iron electrodes are included in AWS A5.15-90 "Specification for Welding Electrodes and Rods for Cast Iron".

Nickel based filler metals

Non-ferrous alloys, notably nickel and nickel alloys, are widely used for welding cast irons and offer many advantages. Nickel in the solid state does not have a high solubility for carbon. When, therefore, nickel is diluted with cast iron during welding the carbon is rejected on solidification and forms graphite. The nickel matrix remains ductile. This mechanism is shown schematically in Fig. 61. The process of graphite formation is accompanied by volumetric expansion which counter balances the shrinkage due to cooling. This minimizes any contraction stresses during the solidification process. Careful balance of alloying elements can optimize the volume change on solidification to further reduce the risk of cracking.

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

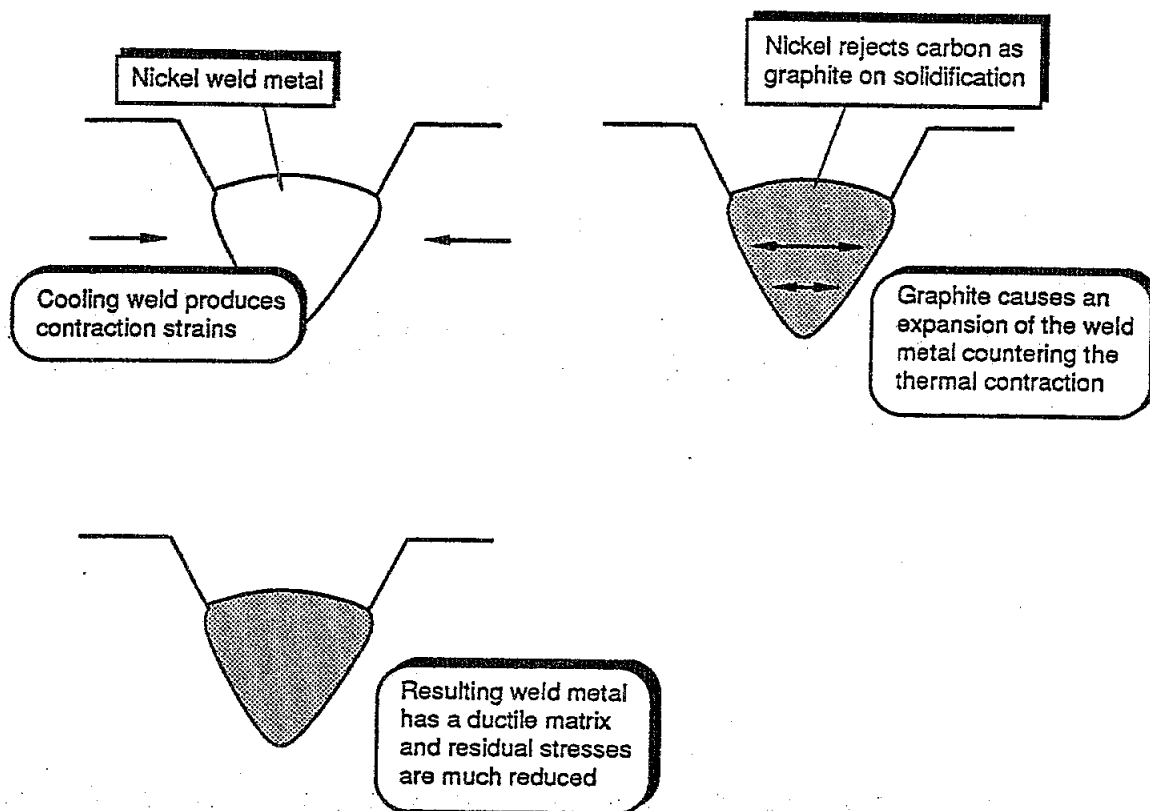


Figure 61. Illustration of means by which nickel weld metal minimizes stresses and cracking in cast iron welds.

Advantages

The result then, of using nickel as a filler is a ductile weld metal of low strength with minimum contraction stresses and low risk of cracking. Further advantages are obtained by using nickel-iron electrodes. Apart from being lower cost they produce a stronger, more ductile weld rendering them suitable for use on high strength gray cast irons. In addition, the nickel-iron alloys have a greater tolerance for phosphorus and have a lower coefficient of thermal expansion reducing the risk of cracking on heavy sections.

Postweld heat treatment

Postweld heat treatment is commonly applied to welds in cast iron although gray irons are sometimes used after welding without any heat treatment. In many cases a simple stress relief is all that is required but occasionally various types of anneal are specified. A simple stress relief is similar to that used on structural steels and involves heating at about 625°C for 1.5 hours per 25mm of thickness followed by a slow furnace cool.

Summary

Non-ferrous metals may have physical and chemical properties significantly different from those of steel. The consequence of this is that welding procedures suitable for steel are rarely applicable to non-ferrous metals. Each metal must be treated on its own merits. The major elements of the welding procedure are determined from an analysis of the physical, chemical, and metallurgical properties of the metal or alloy.

In this module we have discussed the role of thermal conductivity, oxide formation, effects of alloying elements, and other properties on the welding behaviour of metals in general. We have discussed the metallurgical aspects of welding specific non-ferrous alloys in detail as examples. For each metal discussed we have shown how the properties determine such procedural details as gas shielding system, joint geometry, heat input limitations, and selection of electrodes. Although not a non-ferrous metal, cast iron has been treated in the same way since its metallurgy is quite different from steel.

Having successfully completed this module you will be able to list those properties of non-ferrous metals and cast irons that affect welding behaviour; identify the major potential problems expected in welding these materials; and determine the main elements of a welding procedure to successfully weld them. For detailed aspects of welding procedures and before determining procedures for specific alloys you are strongly recommended to consult additional resources particularly material suppliers.

Additional Resources

Below are listed a few additional sources of information that may assist you in your study of the Welding Metallurgy of Non-Ferrous Metals and Cast Iron.

1. If you wish to study the Welding of Aluminum which was not included in this Module refer to the Welding Institute of Canada Modules 24 to 29.
2. Welding aspects of non-ferrous metals and cast iron 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.
3. There are many articles in the *Welding Journal* and other publications covering procedures for welding specific non-ferrous alloys. There is also an extensive literature on research into various problems associated with welding non-ferrous metals. A useful source of information on welding cast iron is the suppliers of electrodes as well as some of the nickel companies who have done extensive research on welding of cast iron.

GUIDES AND EXERCISES

MODULE 23

WELDING METALLURGY OF NON-FERROUS METALS AND CAST IRON

**WELDING METALLURGY OF NON-FERROUS METALS
AND
CAST IRON**

MODULE 23

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.

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

MODULE 23

Guide 1

Carefully read pages 1 to 9 and answer the following questions:

1. A metal has a free energy of oxide formation at room temperature of -300 kcal. Which of the following processes are likely to be suitable for welding it?
 - a) SMAW
 - b) SAW
 - c) electron beam
 - d) GTAW in a chamber
 - e) oxy-acetylene
2. A certain metal is susceptible to nitrogen porosity. Which of the following is a likely cause of porosity in welding this metal?
 - a) damp electrodes
 - b) air entrainment during GTAW
 - c) cleaning fluid left on the work piece
3. The melting point of copper is lower than that of steel. Why, then, does it take a higher heat input to weld copper than it does to weld steel?
4. Is the distortion in welding non-ferrous metals likely to be higher or lower than in steel?
5. Metal A forms a simple eutectic with metal B at 8%B. The maximum solubility of B in A is 4%B. What composition range is most likely to give a risk of hot cracking during welding?
 - a) 7 to 8% B
 - b) 5 to 7% B
 - c) 0.5 to 0.7% B
 - d) 2 to 4% B

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 23

Guide 2

Carefully read pages 9 to 17 and answer the following questions:

1. Precipitation hardening in nickel alloys is often accomplished by using—
 - a) copper
 - b) iron
 - c) aluminum
2. What element is used in nickel filler metals to control weld metal porosity?
3. Why would filler metal still be added when using GTAW on thin sheets of nickel?
4. Estimate the minimum number of layers of nickel filler you would expect to use when welding nickel clad steel by the method shown in Fig. 18 and where the maximum iron specified for the final layer is 5%.
5. Strain age cracking is more likely to occur in—
 - a) precipitation hardening nickel alloys
 - b) pure nickel
 - c) solid solution strengthened nickel alloys

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 Non-Ferrous Metals and Cast Iron

MODULE 23

Guide 3

Carefully read pages 18 to 27 and answer the following questions:

1. True or false?
"The cold working properties of brass are good up to about 40% zinc but deteriorate above this"
2. What element is used for deoxidation in copper?
3. Copper alloys with 1.5 – 2.5% beryllium can be strengthened by _____.
4. Which shielding gas will give the greatest penetration in GTAW of copper?
5. What is the main reason for preheating copper for welding?
6. Which of the following elements may promote hot cracking during welding of copper-nickel alloys?
 - a) tin
 - b) bismuth
 - c) iron
 - d) lead

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 23

Guide 4

Carefully read pages 28 to 34 and answer the following questions:

1. What is the crystal structure of magnesium?
2. For what purpose is up to 0.0008% beryllium commonly included in magnesium filler metals?
 - a) precipitation hardening
 - b) reduce the tendency to ignition
 - c) deoxidation of the weld pool
3. What is the approximate composition of AZ80A?
4. Which element is commonly used in magnesium alloys for elevated temperature service?
5. Which of the following processes are commonly used for welding magnesium?
 - a) SMAW
 - b) GTAW
 - c) FCAW
 - d) GMAW with argon
 - e) GMAW with CO₂
6. What welding problem may be anticipated for magnesium alloys with greater than 5% zinc?

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 Non-Ferrous Metals and Cast Iron

MODULE 23

Guide 5

Carefully read pages 35 to 40 and answer the following questions:

1. The effect of oxygen in titanium is—
 - a) to increase the hardness
 - b) to reduce the hardness
 - c) has no effect
2. Why is a trailing shield used in welding titanium?
 - a) to cool the weld rapidly
 - b) to prevent exposure of the weld to air until it has cooled
 - c) to remove oxides from the weld metal
3. What should be specified when purchasing argon for welding titanium to reduce the risk of hydrogen contamination?
4. How could contamination from titanium filler wires be kept to a minimum?
 - a) by heating the wires prior to use
 - b) using within 2 hours of removal from the oven
 - c) keeping well oiled to prevent oxidation
 - d) cleaning with acetone prior to use

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 23

Guide 6

Carefully read pages 41 to 52 and answer the following questions:

1. Cast irons have carbon in the range—
 - a) 0.8 – 1.7%
 - b) 0 – 1.7%
 - c) 1.7 – 4.5%
 - d) 4.5 – 6.7%
2. What is the most stable form of carbon in iron?
3. Which of the following elements promote graphite?
 - a) chromium
 - b) silicon
 - c) vanadium
 - d) aluminum
4. True or false?

"White cast iron is comprised entirely of ferrite and martensite"
5. Malleable iron is made by heating what material?
6. What is used to control the shape of the graphite in ductile iron?
 - a) heating at 800°–950°C for several hours
 - b) using low levels of graphitizers
 - c) inoculating with elements such as cerium

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 Non-Ferrous Metals and Cast Iron

MODULE 23

Guide 7

Carefully read pages 52 to 59 and answer the following questions:

1. Calculate the carbon equivalent to determine which of the following two cast irons is the stronger:
 - a) 3.8% C; 2% Si; 0.08% P
 - b) 3.2% C; 2.5% Si; 0.09% P
2. Which of the following welding techniques may help to reduce stresses?
 - a) long stringer beads with high heat input
 - b) block welding
 - c) depositing short lengths, allowing each to cool before depositing the next layer
 - d) always weld vertically up
3. How can the risk of martensite formation best be avoided in welding cast irons?
 - a) use a high preheat
 - b) use a high heat input
 - c) use a stringer bead technique
4. Would you use a steel filler metal to repair a cast iron if you wished to machine it after?
5. List two advantages nickel-iron electrodes have over nickel electrodes for welding cast iron.

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 23

ANSWERS

Guide 1

1. c) and d)
2. b)
3. because of the higher thermal conductivity
4. higher
5. d)

Guide 2

1. c)
2. titanium
3. to add sufficient titanium to control porosity
4. at least three
5. a)

Guide 3

1. true
2. phosphorus
3. precipitation hardening
4. helium
5. to facilitate fusion
6. b) and d)

Guide 4

1. h.c.p.
2. b)
3. 8.5% Al, 0.5% Zn
4. thorium
5. b) and d)
6. hot cracking

Guide 5

1. a)
2. b)
3. dew point
4. d)

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

Answers continued

Guide 6

1. c)
2. graphite
3. b) and d)
4. false
5. white cast iron
6. c)

Guide 7

1. a) CE = 4.49; b) CE = 4.06. b) is stronger
2. b) and c)
3. a)
4. no
5. lower cost
stronger and more ductile
greater tolerance for phosphorus
lower coefficient of thermal expansion

MODULE 23

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. Metal A forms a simple eutectic with metal B at 10%. The maximum solubility of B in A is 5% B. What composition range is most likely to give a risk of hot cracking during welding?
 - (a) 0.25 to 0.5% B
 - (b) 2.5 to 5% B
 - (c) 8 to 10% B
 - (d) 7 to 8% B
 - (e) up to 1% B
2. Zirconium has a free energy of oxide formation similar to that of aluminum. Which of the following is likely to be a suitable welding process for it?
 - (a) GTAW
 - (b) SMAW
 - (c) FCAW
 - (d) SAW
 - (e) GMAW with CO_2
3. In GTAW of thin nickel what is a likely result of insufficient filler metal?
 - (a) HAZ cracking
 - (b) oxide inclusions
 - (c) cold laps
 - (d) porosity
 - (e) strain age cracking
4. Which of the following copper alloys can be strengthened by precipitation hardening?
 - (a) Cu - 5% nickel
 - (b) Cu - 5% zinc
 - (c) Cu - 1.5% bismuth
 - (d) Cu - 5% tin
 - (e) Cu - 1.5% beryllium
5. Why is oxy-acetylene not suitable for welding electrolytic tough pitch copper?
 - (a) the heat input is too high
 - (b) carbon contaminates the weld pool
 - (c) there is an excessive loss of zinc
 - (d) there is excessive oxidation of the weld pool
 - (e) hydrogen reacts with copper oxide to produce steam causing cracking

Welding Metallurgy of Non-Ferrous Metals and Cast Iron

MODULE 23

TEST continued

6. Which of the following elements is used in magnesium alloys for elevated temperature service?
 - (a) thorium
 - (b) aluminum
 - (c) zinc
 - (d) beryllium
 - (e) manganese
7. What could result if the argon shielding gas used for welding titanium has a high dew point?
 - (a) loss of ionization in the arc
 - (b) hydrogen contamination of the weld pool
 - (c) slower cooling rates after welding
 - (d) reduction in weld hardness
 - (e) higher gas flow rates
8. Which of the following elements used in cast iron does not promote graphite?
 - (a) aluminum
 - (b) titanium
 - (c) copper
 - (d) silicon
 - (e) chromium
9. What is the reason for adding magnesium or cerium to cast iron?
 - (a) as a graphitizer
 - (b) for deoxidation
 - (c) to form graphite flakes
 - (d) to control the shape of the graphite
 - (e) to control fluidity
10. What effect will increasing the preheat have on a weld in gray cast iron?
 - (a) reduces the HAZ hardness
 - (b) promotes the formation of martensite
 - (c) prevents iron carbide from forming
 - (d) increases the risk of cracking
 - (e) lowers the carbon equivalent

Canadian Welding Bureau
Answer Sheet
Module 23

Complete the "Answer Sheet" and compare your answers with those in the "Test Key." If you score less than 70% we suggest you restudy the material.

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

QUESTION	ANSWER				
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 sheet below is provided in the event you wish to retest yourself.

QUESTION	ANSWER				
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 23**

Compare your answer sheet to this key.

QUESTION	ANSWER				
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