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Arc Welding of Nonferrous Metals

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The *Arc Welding of Nonferrous Metals* is a textbook for providing information to assist welding personnel study the arc welding technologies commonly applied in the equipment made from aluminum, aluminum alloys, copper, copper alloys, nickel, and nickel alloys.

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Forewords

Nonferrous metals are non-iron-based metals such as aluminum and aluminum alloys, copper and copper alloys, nickel and nickel alloys, titanium and titanium alloys, and magnesium and magnesium alloys. Today, nonferrous metals are used in various welding constructions for diverse industrial applications. However, their weldability is quite different from that of steel, due to specific physical and metallurgical characteristics. Therefore, the welding procedure for nonferrous metals should be thoroughly examined taking into account the inherent characteristics of the particular nonferrous metal to be welded, in order to get sound weldments.

This textbook focuses on the arc welding of aluminum, aluminum alloys, copper, copper alloys, nickel, and nickel alloys that are used more extensively over other nonferrous metals for industrial applications. This textbook consists of three chapters:

Chapter 1: Arc Welding of Aluminum and Aluminum Alloys
Chapter 2: Arc Welding of Copper and Copper Alloys
Chapter 3: Arc Welding of Nickel and Nickel Alloys

Chapter 1

Arc Welding of Aluminum and Aluminum Alloys

Contents

Introduction

Nowadays, aluminum and aluminum alloys are extensively used for various applications such as household utensils, autos, railroad cars, buildings, bridges, aircrafts, spacecrafts, ships, chemical equipment, water gates, and storage tanks, because of the inherent advantages of high strength-to-weight ratio, high notch toughness at cryogenic temperatures, excellent corrosion resistance, ease in extrusion, and good fabricability.

Aluminum and its alloys are readily joined with most of the known joining processes including welding, brazing, soldering, adhesive bonding, and mechanical fastening. Of these joining processes, welding is most widely used. The welding processes used for aluminum and its alloy assemblies are arc welding, stud welding, electron beam welding, laser beam welding, resistance welding, solid-state welding, and oxyfuel gas welding. Of these welding processes, arc welding is most extensively used. The arc welding processes used commonly in the assemblies are gas tungsten arc welding (GTAW) and gas shielded metal arc welding with solid wires (refer to as GMAW hereinafter).

Basically, aluminum and its alloys can successfully be arc welded by using conventional GTAW/GMAW equipment and techniques used for other metals, provided the welding procedure is suitable. However, occasionally specialized equipment or techniques, or both, are required due to the inherent unique physical and mechanical characteristics of aluminum and its alloys.

This section focuses on GTAW and GMAW of aluminum and its alloys and discusses diverse types of such metals and their weldability, suitable welding equipment, proper filler metals and welding procedures, and provides tips for sound welds.

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1. Types and features of aluminum and aluminum alloys

Aluminum and aluminum alloys are the lightest commercial metals in use in large quantities. Aluminum is easy to extrude and fabricate and has excellent corrosion resistibility. Various types of aluminum alloys are also available in response to demands for higher strength and superior corrosion resistibility for specific applications. This chapter discusses general characteristics, types and features of aluminum and its alloys.

1.1 General characteristics

The applications of aluminum and its alloys are expanding in various industrial fields because of its many advantages over other metals. The following paragraphs discuss the advantages of aluminum and its alloys for structural material. **Table 1.1** shows a comparison of physical properties between aluminum and mild steel.

(1) Lightweight:

As shown in Table 1.1, the density of aluminum is 2.7, which is about 1/3 of that of mild steel (7.86). This feature is one of the reasons why aluminum and its alloys are widely used for transportation vehicles such as autos, railway cars (**Photo 1.1**), aircrafts, and ships (**Photo 1.2**). By decreasing the weight of the transportation vehicles the energy consumption efficiency can be improved.

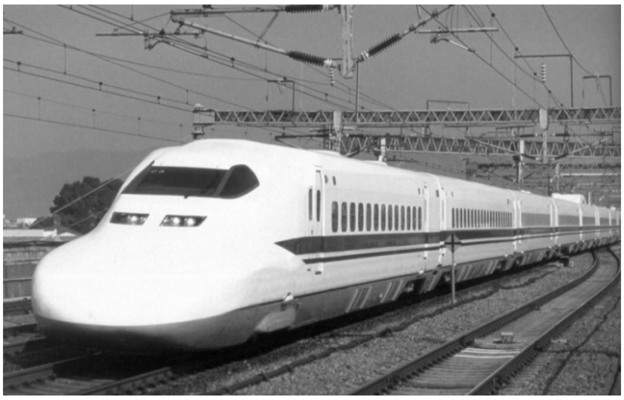


Photo 1.1
Shinkansen high-speed trains uses plates, extrusions, castings and forgings of aluminum alloy
(Source: Kobe Steel's brochure)

Photo 1.2
A fishing boat made of aluminum alloy structural components.
(Source: Kobe Steel's brochure)

(2) Strong:

The tensile strength of aluminum is much lower than that of mild steel; however, it can readily be strengthened by alloying with other elements such as copper, manganese, silicon, magnesium, and zinc. Aluminum and its alloys can further be strengthened by cold working (rolling, extrusion, drawing and forging), due to work hardening or strain hardening. The certain group of aluminum alloys can be strengthened by precipitation hardening heat treatment. With this heat treatment, the tensile strength of some alloys becomes comparable to or even higher than that of mild steel.

With lower specific gravity, the ratio of strength to specific gravity of many aluminum alloys is higher than that of mild steel. This advantage is useful particularly for transportation vehicles such as aircraft, spacecraft, autos, railroad cars, and boats.

(3) High resistance to corrosion:

Aluminum forms an oxide film (alumina) on its surfaces in the air. This oxide film is thin but dense enough to protect the base metal in corrosive atmospheres and solutions. In addition, alloying with magnesium provide aluminum with much higher resistance to corrosion. This is why aluminum alloys are extensively used in buildings, ships, and autos.

(4) Good workability:

Aluminum and its alloys can readily be formed plastically by rolling, extrusion, and forging. Aluminum alloys containing silicon have excellent castability. This is why products range with a wide variety including plates, extrusions (**Photo 1.3**), rods, wires, forgings and castings (**Photo 1.4**).

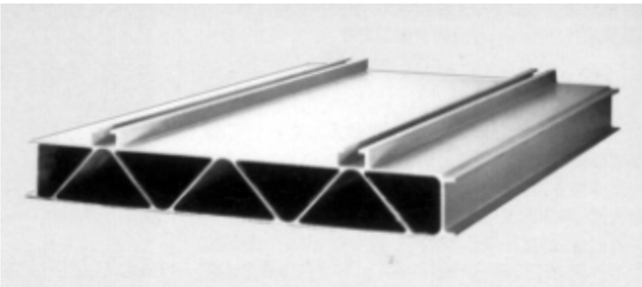


Photo 1.3
An extrusion of aluminum alloy for railroad car components
(Source: Kobe Steel's brochure)

Photo 1.4
Forgings and castings of aluminum alloy for automobile components
(Source: Kobe Steel's brochure)

***Table 1.1**. A comparison of physical properties between aluminum and mild steel [Ref. 6]*

Physical properties	Aluminum (99.9% or higher Al)	Mild steel (JIS SS400)
Density (g/cm^3)	2.7	7.86
Melting point (℃)	660	1500-1527
Average specific heat (0-100℃)(cal/g/℃)	0.22	0.11
Expansion coefficient (20-100℃) ($\times 10^{-6}$ ℃)	24	12
Thermal conductivity (cal/cm/s/℃)	0.52-0.54	0.12
Elasticity modulus (GPa)	59-69	206
Shear modulus (GPa)	25	82
Latent heat of fusion (cal/g)	97	66

(5) Good heat conductivity:

The thermal conductivity of aluminum and its alloys are about 3-4 times as large as that of mild steel. Therefore, aluminum can be hot by heating or cold by cooling more quickly than steel. This is why aluminum and its alloys are used for air conditioning equipment, combustion engine components, heat exchangers, and radiators.

(6) Excellent notch toughness at cryogenic temperatures:

Aluminum alloys are often used for cryogenic temperature process plants and LNG storage tanks because aluminum alloys offer high notch toughness at cryogenic temperatures (–196℃ for liquefied nitrogen, –183℃ for liquefied oxygen, and –162℃ for liquefied natural gas), thereby preventing brittle fracture of the equipment.

(7) Readily weldable:

With exception of some aluminum alloys, aluminum and its alloys are readily arc weldable. This is why a variety of constructions can be effectively fabricated.

1.2 Wrought products

Wrought aluminum and aluminum alloy products include plate, bars, shapes, pipes, wires, forgings, and foils. They are produced by plastic working processes such as rolling, extrusion, drawing, and forging, subsequent to the melting and casting processes. As shown in **Table 1.2**, the means by which the alloying elements strengthen aluminum is used to classify aluminum and its alloys into two groups: the nonheat-treatable and heat-treatable. They are also classified by the purity and main alloying elements with a four-digit numerical designation system. The first digit indicates the aluminum and aluminum alloy series. The second digit in individual series indicates consecutive modifications of an original type (0) of aluminum and its alloys; "N" is for the Japanese origin. For 1XXX series, the last two digits indicate the minimum aluminum purity (e.g., 1100: 99.00%Al min.).

Table 1.2 *Classification of wrought aluminum and aluminum alloy products*

Alloy group	Alloying system	Designation system	Alloy designation (1)
Nonheat-treatable type	Al: 99.00% min Al-Mn Al-Si Al-Mg	1XXX 3XXX 4XXX 5XXX	1100 3003 4043 5005, 5052, 5083
Heat-treatable type	Al-Cu Al-Mg-Si Al-Zn-Mg	2XXX 6XXX 7XXX	2219 6061, 6N01, 6063 7003, 7204(7N01)

Note (1) The alloy designations are as per the JIS H 4000:2014 (Aluminium and Aluminium Alloy Sheets, Strips and Plates), JIS H 4100:2006 (Aluminium and Aluminium Alloy Extruded Shape), and JIS Z 3232-2009 (Aluminium and Aluminium Alloy Welding Rods and Wires).

1.2.1 Nonheat-treatable type

Nonheat-treatable aluminum and its alloys cannot be strengthened by heat treatment. The initial strength of the aluminum and its alloys, thus, depends primarily on the effect of silicon, iron, manganese and magnesium contained as impurities or alloying elements. These chemical elements affect increase in strength either as dispersed phases or by solid-solution strengthening. The nonheat-treatable aluminum and aluminum alloy products are mainly found in the 1XXX, 3XXX, 4XXX and 5XXX series. Iron and silicon are the main impurities in commercial aluminum, but they add strength to the 1XXX series.

The strength of nonheat-treatable aluminum and its alloys can be increased by strain hardening in cold working processes such as rolling, extrusion, drawing, and forging. In this case, annealing heat treatment (300-400℃) [Ref. 3] may be applied to relieve strain of the crystals, thereby decreasing the strength and increasing the ductility of the metals. The 5XXX alloys containing magnesium tend to decrease strength and increase ductility by age softening, if they are left for long time after cold working. To prevent the age softening, stabilization heat treatment (130-170℃ for about 2h) [Ref. 3] is applied.

1.2.2 Heat-treatable type

Heat-treatable aluminum alloys are found primarily in the 2XXX, 6XXX, and 7XXX series. The initial strength of the alloys in this group depends on chemical composition, just as in the nonheat-treatable alloys. Alloying elements such as copper, magnesium, zinc, and silicon, either singularly or in various combinations, show a marked increase in solid solubility in the matrix of the alloy with increasing temperature; it is, therefore, possible to subject them to thermal treatments that will impart much strengthening. Mechanical properties of heat-treatable aluminum alloys can be improved by solution heat treatment (450-550℃) [Ref. 3] and subsequent water quenching, followed by natural or artificial aging (100-250℃) [Ref. 3]. With this series of heat treatments, the alloys increase their strength by precipitation hardening.

The relationship between aging temperature, aging time and Vickers hardness of a heat-treatable aluminum alloy is shown in **Fig. 1.1**. With a higher aging temperature, a maximum hardness can be attained faster; however, the maximum hardness is lower. In contrast, with a lower aging temperature, the hardness reaches a maximum slower, which is higher than the former. An excessive aging over the time where the maximum hardness is attained decreases hardness — thus decreases strength and increases ductility.

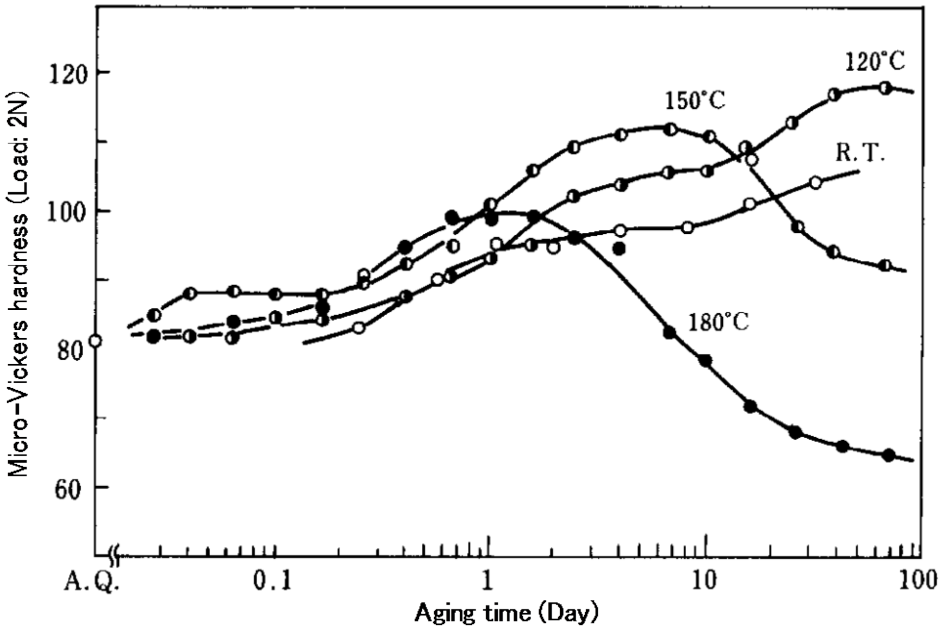


Figure 1.1 *Age hardening curves of an Al-4%Cu alloy after solution heat treatment by 520℃ and subsequent water quenching (A.Q.) [Ref. 3]*

The heat-treatable aluminum alloys may additionally be strengthened by cold working. It may also be annealed to attain maximum ductility. The annealing involves holding the alloy at an elevated temperature and controlled cooling to achieve maximum softening.

1.2.3 Chemical and mechanical properties

Table 1.3 shows the main chemical composition of and typical applications for aluminum and aluminum alloy products suitable for arc welding. Typical mechanical properties of these products are shown in **Table 1.4**. Note that the mechanical properties of aluminum and its alloys depend on the condition of work hardening, annealing, or tempering.

Table 1.3 *Chemical compositions and applications of wrought aluminum and aluminum alloy products* [1]

Alloy design.	Content of main elements (%) [2]									Typical applications
	Al	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	
1100	99.00 min	Si+Fe: 0.95		0.05-0.20	0.05	-	-	0.10	-	General utensils, Building materials, Electric appliances
3003	Rem	0.6	0.7	0.05-0.20	1.0-1.5	-	-	-	-	General utensils, Building materials, Shipbuilding materials
5005	Rem	0.3	0.7	0.20	0.20	0.50-1.1	0.10	0.25	-	Building inner/outer materials, Railroad car's inner materials
5052	Rem	0.25	0.40	0.10	0.10	2.2-2.8	0.15-0.35	0.10	-	Materials for shipbuilding, railroad cars and buildings
5083	Rem	0.40	0.40	0.10	0.40-1.0	4.0-4.9	0.05-0.25	0.25	0.15	Materials for shipbuilding and railroad cars, Cryogenic storage tanks
2219 [3]	Rem	0.20	0.30	5.8-6.8	0.20-0.40	0.02	-	0.10	0.02-0.10	Aerospace vehicles
6061	Rem	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.15	Materials for shipbuilding and railroad cars, Buildings
6N01	Rem	0.40-0.9	0.35	0.35	0.50[4]	0.40-0.8	0.30[4]	0.25	0.10	Material of railroad cars
6063	Rem	0.20-0.6	0.35	0.10	0.10	0.45-0.9	0.10	0.10	0.10	Materials for buildings and civil constructions, Furniture
7003 [5]	Rem	0.30	0.35	0.20	0.30	0.50-1.0	0.20	5.0-6.5	0.20	Materials for railroad cars and welding constructions
7204 [6]	Rem	0.30	0.35	0.20	0.20-0.7	1.0-2.0	0.30	4.0-5.0	0.20	Railroad cars, Buildings

Note: (1) Excerpted from JIS H 4000:2014 (Aluminium and Aluminium Alloy Sheets, Strips and Plates) and JIS H 4100:2006 (Aluminium and Aluminium Alloy Extruded Shape: 6N01, 6063, 7003)
(2) Single values are maximum.
(3) Zr: 0.10-0.25%, V: 0.05-0.15%.
(4) Mn+Cr: 0.50% max when agreed to between supplier and purchaser.
(5) Zr: 0.05-0.25%
(6) V: 0.10% max, Zr: 0.25% max.

Table 1.4 *Mechanical properties of wrought aluminum and aluminum alloy products* (1)

Alloy designation	Temper designation and description (2)		Tensile strength (N/mm^2)	0.2% proof strength (N/mm^2)	Elong-ation, A_{50mm} (%)
1100 (A1100P)	O	Annealed	75-105	25 min	30 min
	H16	Work hardened only	135-165	115 min	4 min
3003 (A3003P)	O	Annealed	95-135	35 min	25 min
	H16	Work hardened only	165-205	145 min	4 min
5005 (A5005P)	O	Annealed	105-145	35 min	22 min
	H32	Work hardened + Stabilized	120-155	85 min	7 min
5052 (A5052P)	O	Annealed	170-215	65 min	19 min
	H32	Work hardened + Stabilized	215-265	155 min	9 min
5083 (A5083P)	O	Annealed	275-350	125-200	16 min
	H32	Work hardened + Stabilized	305-380	215-295	10 min
2219 (A2219P)	T62	Solution heat treated + Artificially aged	370 min	250 min	7 min
	T81	Solution heat treated + Cold worked + Artificially aged	425 min	315 min	7 min
6061 (A6061P)	T4	Solution heat treated + Naturally aged	205 min	110 min	16 min
	T6	Solution heat treated + Artificially aged	295 min	245 min	10 min
6N01	T5	Cooled from a high temperature shaping process + Artificially aged	245 min	205 min	8 min
	T6	Solution heat treated + Artificially aged	265 min	235 min	8 min
6063	T5	Cooled from a high temperature shaping process + Artificially aged	150 min	110 min	8 min
	T6	Solution heat treated + Artificially aged	205 min	170 min	10 min
7003	T5	Cooled from a high temperature shaping process + Artificially aged	285 min	245 min	10 min
7204 (A7204P)	T4	Solution heat treated + Naturally aged	315 min	195 min	11 min
	T6	Solution heat treated + Artificially aged	335 min	275 min	10 min

Note (1) Excerpted from JIS H 4000:2014 (Aluminium and Aluminium Alloy Sheets, Strips and Plates) and H 4100:2006 (Aluminium and Aluminium Alloy Extruded Shape: 6N01, 6063, 7003). Mechanical properties are for certain thickness ranges which include 3 mm.
(2) As per JIS H0001:1998 (Aluminium, Magnesium and Their Alloys−Temper Designation)

1.3 Casting products

Aluminum alloy castings are produced by various casting processes such as sand casting, steel mold casting, and die casting. Aluminum alloy castings are classified as the nonheat-treatable type and heat-treatable type according to their chemical composition — **Table 1.5**. **Table 1.6** shows the main chemical composition and typical applications of aluminum alloy castings suitable for arc welding (usually, for repair welding of foundry defects). The mechanical properties of such cast alloys are summarized in **Table 1.7**.

Al-Mg alloy (AC7A) is also known as hydronalium, which offers excellent corrosion resistibility against seawater in particular and comparatively high strength and elongation. Al-Si-Mg alloy (AC4C) features good castability due to containing Si and precipitation hardenability by heat treatment because of containing Mg. Al-Si-Cu alloy (ADC12) features higher strength due to containing Cu. The majority of aluminum alloy die castings use Al-Si-Cu alloy. Al-Si-Cu-Mg alloy offers better toughness due to the lower content of Si and improved hardenability by heat treatment because of alloying with Cu and Mg.

Table 1.5 *Classification of aluminum alloy castings suitable for arc welding* (1)

Alloy group	Alloying system	Alloy designation	Casting process
Nonheat-treatable type	Al-Mg	AC7A	Sand or steel mold
Heat-treatable type	Al-Si-Mg Al-Si-Cu Al-Si-Cu-Mg	AC4C ADC12 AC4D	Sand or steel mold Die casting Sand or steel mold

Note (1) Excerpted from JIS H 5202:2010 (Aluminium Alloy Castings) and JIS H 5302:2006 (Aluminium Alloy Die Castings) except for the alloy group description.

Table 1.6 *Chemical compositions and applications of aluminum alloy castings suitable for arc welding* (1)

Alloy desig.	Content of main elements (%) (2)									Typical applications (3)
	Al	Cu	Si	Mg	Zn	Fe	Mn	Ni	Ti	
AC7A (4)	Rem	0.10	0.20	3.5-5.5	0.15	0.30	0.6	0.05	0.20	Marine and architectural parts
AC4C (5)	Rem	0.20	6.5-7.5	0.20-0.4	0.3	0.5	0.6	0.05	0.20	Oil pressure parts, transmission cases, flywheel housings, and aircraft parts
ADC12 (6)	Rem	1.5-3.5	9.6-12.0	0.3	1.0	1.3	0.5	0.5	0.30	Cars, motor cycles, and farming machine parts
AC4D (7)	Rem	1.0-1.5	4.5-5.5	0.4-0.6	0.5	0.6	0.5	0.3	0.2	Cylinder heads, cylinder blocks, crank cases, and fuel pump bodies

Note (1) Excerpted from JIS H 5202:2010 (Aluminium Alloy Castings) and JIS H 5302:2006 (Aluminium Alloy Die Castings).
(2) Single values are maximum.
(3) As per JIS H 5202:1999 (Aluminium Alloy Castings) and H 5302:2000 (Aluminium Alloy Die Castings) for reference.
(4) Pb: 0.05% max, Sn: 0.05% max, Cr: 0.15% max.
(5) Pb: 0.05% max, Sn: 0.05% max, Cr: 0.05% max.
(6) Pb: 0.2% max, Sn: 0.2% max.
(7) Pb: 0.1% max, Sn: 0.1% max, Cr: 0.05% max.

Table 1.7 *Mechanical properties of aluminum alloy castings* [(1)]

Alloy designation	Temper designation and description		Tensile strength (N/mm^2)	0.2% proof strength (N/mm^2)	Elong-ation (%)
AC7A	F	As fabricated	210 min	—	12 min
AC4C	F	As fabricated	150 min	—	3 min
	T6	Solution heat treated + Artificially aged	230 min	—	2 min
ADC12	F	As fabricated	228 [(2)]	154 [(2)]	1.4 [(2)]
AC4D	F	As fabricated	160 min	—	—
	T6	Solution heat treated + Artificially aged	290 min	—	—

Note (1) Excerpted from JIS H5202:2010 (Aluminium Alloy Castings) and H5302:2006 (Aluminium Alloy Die Castings).
(2) Typical mechanical properties of die castings in the as-cast condition; the mechanical properties of ADC12 shall be agreed to between supplier and purchaser as per the JIS standard.

2. Weldability and filler metal selection

2.1 Weldability of aluminum and aluminum alloys

Aluminum and its alloys can readily be arc welded except specific types of aluminum alloys; however, their inherent physical and metallurgical characteristics should sufficiently be understood in order to implement successful arc welding. Following are typical characteristics of aluminum and its alloys that can be drawbacks in arc welding.

(1) Higher specific heat, latent heat of fusion, and thermal conductivity

Aluminum and its alloys feature lower melting point but higher specific heat, latent heat of fusion and thermal conductivity compared with steel; therefore, a larger amount of heat is needed in a short time to fuse aluminum and its alloys relative to steel.

(2) Stronger oxide film

Aluminum and its alloys produce strong oxide films on their surfaces when heated at high temperatures and fused, unless the surface is shielded sufficiently with an inert gas. The oxide film prevents fusion between the base metal and the filler metal.

(3) Larger distortion

Welding aluminum and its alloys causes much more distortion compared with welding steel because the expansion coefficient of aluminum and its alloys is larger than that of steel.

(4) Softening of heat-affected zone

The heat-affected zone (HAZ) of the base metal (except the annealed type) features lower hardness — thus lower strength — than that of the nonheat-affected zone because the effects of work hardening and aging (precipitation hardening) of the base metal can be cancelled by the heat of arc. That is, the HAZ becomes annealed condition, which is generally called "softening."

Figure 2.1 shows schematically how the softening can occur in the HAZ of a nonheat-treatable aluminum alloy (3003-type base metal; 1100-type filler metal). Softening of the work-hardened aluminum alloy occurs in the weld zone heated at temperatures over 250℃; consequently, the hardness (or strength) of the weld decreases to the same level as that of the annealed type. The width of the softened zone increases as the degree of work hardening increases. In contrast, the annealed type aluminum alloy exhibits even hardness across the weld.

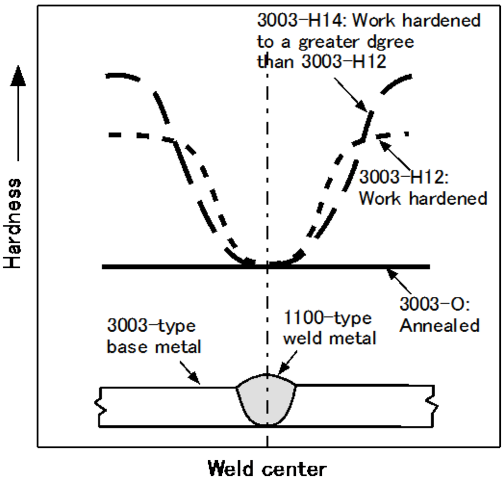


***Figure 2.1** variations in weld hardness distribution of nonheat-treatable aluminum [Ref. 5]*

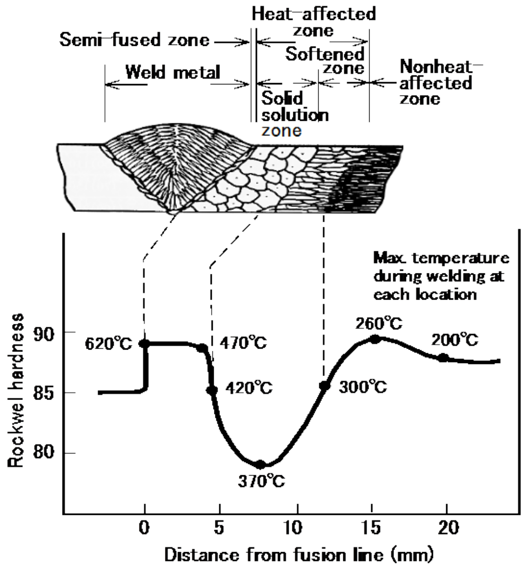


***Figure 2.2** Weld hardness distribution of heat-treatable aluminum of Alloy 6061-T4 (230A, 63 cm/min, after aging) [Ref. 5]*

In the case of heat-treatable aluminum alloys, the weld hardness exhibits a complicated distribution as shown in **Fig. 2.2** according to the microstructure affected by the temperature at which individual zone was heated. The solid solution zone can be formed at where heated at the solution treatment temperature (450-550℃) or higher. In this zone, precipitates are dissolved in the matrix, thereby causing coarse crystal grains. The softened area can be created, at where heated at the temperatures higher than the aging temperature range (150-250 ℃), by excessive precipitation and partial annealing.

The softening phenomenon causes the weld joint tensile strength of aluminum and its alloys in the as-welded condition to fall in a certain level according to the alloy system regardless the degrees of work hardening and heat treatment, as shown in **Table 2.1**.

The degree of softening varies depending on the type of aluminum alloy and the amount of heat input. In the case of Al-Zn-Mg alloys (e.g. Alloy 7N01), the weld softened zone can be gradually recovered increasing its hardness according to the time elapsed after welding due to excellent natural age hardening characteristic.

***Table 2.1** A comparison on GTAW weld joint tensile strength of nonheat-treatable and heat-treatable aluminum and aluminum alloys [Ref. 4]*

Alloy group	Base metal (Alloy desig.)	Filler metal (Alloy desig.)	Base metal strength			Butt weld joint strength		
			Tensile strength (MPa)	0.2% proof strength (MPa)	Elong-ation (%)	Tensile strength (MPa)	0.2% proof strength (MPa)	Elong-ation (%)
Nonheat-Treatable type	1100-O	1100	64	38	35	93	38	25
	1100-H14	1100	118	110	9	93	45	20
	1100-H18	1100	182	166	6	93	45	15
	3003-O	1100	110	48	32	110	48	25
	3003-H14	1100	144	138	8	110	59	20
	3003-H18	1100	200	186	4	110	59	15
Heat-Treatable type	6063-T4	4043	159	96	39	145	96	17
	6063-T5	4043	207	179	16	145	96	17
	6063-T6	4043	227	200	18	145	86	17
	6061-T4	4043	241	145	22	200	138	8
	6061-T6	4043	310	217	12	193	124	5

(5) More sensitive to hot cracking

Hot cracking is the most noticeable type of cracking in welding aluminum and its alloys, which may occur in the welds at temperatures close to the solidus of the base metal and filler metal during the weld cooling cycle, if the welding procedure (including type of base metal, type of filler metal and welding parameters) is inappropriate. Hot cracking in the welds is caused mainly by the segregation of alloying elements and low-melting-point constituents at the grain boundaries. Refer to Section 3.6.2 for prevention of hot cracking.

In general, pure aluminum offers the lowest crack susceptibility among aluminum and its alloys. In contrast, Cu-bearing aluminum alloys exhibit higher crack susceptibility. For instance, aluminum alloys with high copper content, such as Alloy 2024 (Al-4.5%Cu-1.5%Mg), also known as super duralumin, and Alloy 7075 (Al-1.6%Cu-2.5%Mg-5.5%Zn), also known as extra super duralumin, are not acceptable for arc welding. The amounts of other alloying elements such as Mg, Zn and Si affect crack sensitivity.

(6) More likely to cause porosity

The arc welding of aluminum and its alloys is more likely to cause porosity in weld metals, relative to welding other metals. It is reported that the main cause of porosity is hydrogen in the weld metal. Refer to Section 3.6.1 for details.

2.2 Filler metal selection

Varieties of filler metals are available for GTAW and GMAW. For example, **Table 2.2** shows chemical and mechanical properties of GTAW filler wires and GMAW wires specified by the JIS standard.

***Table 2.2** Chemical and mechanical properties of filler metals* (1)

Filler metal (Alloy desig.)	Content of main elements in wire (%) (2)									Joint tensile test	
	Al	Si	Fe	Cu	Mn	Mg	Zn	V	Ti	Base metal for test (Alloy desig.)	TS (3) (N/mm^2)
A1070	99.70 min	0.20	0.25	0.04	0.03	0.03	0.04	0.05	0.03	A1100P-O or A1200P-O	55 min
A1100	99.00 min	Si+Fe: 0.95		0.05-0.20	0.05	-	0.10	-	-		75 min
A1200	99.00 min	Si+Fe: 1.00		0.05	0.05	-	0.10	-	0.05		
A2319 (4)	Rem	0.20	0.30	5.8-6.8	0.20	0.02	0.10	0.05-0.15	0.10-0.20	A2219P-T62 or A2014P-T6	245 min
A4043	Rem	4.5-6.0	0.8	0.30	0.05	0.05	0.10	-	0.20	A6061P-T6	165 min
A4047	Rem	11.0-13.0	0.8	0.30	0.15	0.10	0.20	-	-		
A5554	Rem	0.25	0.40	0.10	0.50-1.0	2.4-3.0	0.25	Cr: 0.05-0.20	0.05-0.20	A5454P-O	215 min
A5654	Rem	Si+Fe: 0.45		0.05	0.01	3.1-3.9	0.20	Cr: 0.15-0.35	0.05-0.15	A5254P-O	205 min
A5356	Rem	0.25	0.40	0.10	0.05-0.20	4.5-5.5	0.10	Cr: 0.05-0.20	0.06-0.20	A5083P-O	265 min
A5556	Rem	0.25	0.40	0.10	0.50-1.0	4.7-5.5	0.25	Cr: 0.05-0.20	0.05-0.20		275 min
A5183	Rem	0.40	0.40	0.10	0.50-1.0	4.3-5.2	0.25	Cr: 0.05-0.25	0.15		

Note: (1) Excerpted from JIS Z 3232:2009 (Aluminium and Aluminium Alloy Welding Rods and Wires)
(2) Single values are maximum. (Be is specified as maximum for all the alloys)
(3) In the as-welded condition
(4) Zr: 0.10-0.25%

In selecting an appropriate filler metal, crack susceptibility, joint tensile strength, ductility, corrosion resistibility and weld metal-to-base metal color matching after anodic oxidation treatment should be taken into account. A guide to the selection of filler metals for general purpose welding of various aluminum and aluminum alloy combinations, including castings, is presented in **Table 2.3**. Among these various filler metals, A4043 and A5356 are major filler metals. The following paragraphs discuss key notes for better selection of the filler metal.

(1) A filler metal of A4043 offers excellent resistibility against hot cracking, which is suitable for 6XXX series and aluminum alloy castings. However, it has such drawbacks that the weld metal exhibits low ductility and toughness, and due to a high Si content, poor color matching to 5XXX and 6XXX series base metal after anodic oxidation treatment. In addition, it is not suitable for welding high magnesium (3% or more Mg) 5XXX series alloys because intermetallic compound of Mg_2Si develops excessively in the weld metal, thereby decreasing the ductility and increasing the crack sensitivity of the weld metal.

Table 2.3 *A quick guide to the selection of GTAW/GMAW filler metals for general applications (Excerpted from JIS Z 3604:2002)* [a,b,c,d]

Base metal \ Base metal	AC7A	AC4D	AC4C ADCl2	A7003 A7N01	A6061 A6N01 A6063 A6101	A5086 A5083 A5056	A5154 A5254 A5454	A5052 A5652	A5005 A5N01	A2219	A2014 A2017	A3004	A1200 —	A1100 A3003 A3203	A1070 A1050
A1070 A1050	(2)(5) A4043	(6) A4043	(5)(6) A4043	(2)(4)(5) A5356	(5)(7) A4043	(2) A5356	(2)(4)(5) A5356	(2)(5) A4043	(1)(4)(5) A1100	(4)(5) BA4145	BA4145	(2)(5) A4043	(1)(4)(5) A1200	(1)(4)(5) A1100	(1)(4)(5) A1070
A1100 A3003 A3203	(2)(5) A4043	(6) A4043	(5)(6) A4043	(2)(4)5) A5356	(5)(7) A4043	(2) A5356	(2)(4)(5) A5356	(2)(5) A4043	(1)(4)(5) A1100	(4)(5) BA4145	BA4145	(2)(5) A4043	(1)(4)(5) A1200	(1)(4)(5) A1100	
A1200	(2)(5) A4043	(6) A4043	(5)(6) A4043	(2)(4)(5) A5356	(5)(7) A4043	(2) A5356	(2)(4)(5) A5356	(2)(5) A4043	(1)(4)(5) A1200	(4)(5) BA4145	BA4145	(1)(4) A1200	(1)(4)(5) Al200		
A3004	(2) A4043	(5) A4043	A4043	(2)(3)(4) A5356	(2)(3)(5)(7) A4043	(2) A5356	(2)(3) A5356	(2)(3)(4)(5) A5356	(2)(3)(4) A5356	(4)(5) BA4145	BA4145	(2)(3)(4) A5356			
A2014 A2017	—	(6) A2319	BA4145	—	BA4145	—	—	—	BA4145	(9) BA4145	(9) BA4145				
A2219	(5) A4043	(4)(5)(6) A2319	(4)(5) BA4145	(5) A4043	(5)(6) A4043	—	(5) A4043	(5) A4043	(5)(6) A4043	(4)(5)(6) A2319					
A5005 A5N01	(2)(3) A5356	(5) A4043	(5) A4043	(2)(3) A5356	(2)(3)(5)(7) A4043	(2) A5356	(2)(3) A5356	(2)(3)(4)(5) A5356	(2)(3)(4)(8) A5356						
A5052 A5652	(2) A5356	(5) A4043	(2)(3)(5) A4043	(2)(3) A5356	(2)(3)(5)(7) A4043	(2) A5356	(2)(3) A5356	(2)(3)(4) A5356							
A5154 A5254 A5454	(2)(3) A5356	—	(2)(3)(5) A4043	(2)(3) A5356	(2)(3)(4) A5356	(2)(3) A5356	(2)(3) A5356								
A5086 A5083 A5056	(2) A5356	—	(2)(4)(5) A5356	(2) A5356	(2) A5356	(2) A5183									
A6061 A6N01 A6063 A6101	(2)(3)(4)(5) A5356	(5)(6) A4043	(2)(3)(5) A4043	(2)(3)(4)(5) A5356	(2)(3)(5) A4043										
A7003 A7N01	(2)(3) A5356	(5) A4043	(2)(3)(5) A4043	(2) A5356											
AC4C ADC12	(2)(3)(5) A4043	(5)(6) A4043	(5)(8) A4043												
AC4D	—	(5)(6)(8) A4043													
AC7A	(2)(3)(8) A5356														

[General remarks]

a. This guide is for selecting filler metals suitable for general applications that are used at room or lower temperatures. In the case where the service temperature is over 65℃, A5356, A5183, A5556 and A5654 are not recommended.
b. The designators of BY and WY for rods and wires are omitted.
c. The designators for the shape of wrought base metal are omitted; any shapes are applicable.
d. BA4145 is a brazing filler metal specified in JIS Z 3263, which may be suitable for 2XXX alloys.

[Alternative filler metals]

(1) A1100 or A1200 may be used.
(2) A5356, A5556 or A5183 may be used.
(3) A5654 or A5554 may be used.
(4) A4043 may be used for some applications.
(5) A4047 may be used.
(6) BA4145 may be used.
(7) In the case where color matching is important after anodic oxidation treatment, A5356 should be used.
(8) A filler metal having the same chemical composition as the base metal may be used.
(9) A2319 may be used.

(2) A Filler metal of A5356 is widely used for 5XXX series alloys (e.g., 5083) and 6XXX series alloys (e.g., 6061), and the consumption of this filler metal reaches 60% of the total consumption of aluminum and aluminum alloy filler metals. This filler metal contains a small amount of Ti to provide a fine microstructure and thereby improve mechanical properties of the weld metal. Where a good color match after anodic oxidation treatment is needed (e.g., ornamental or architectural applications) in welding 5XXX and 6XXX series alloys, filler metal A5356 is a good choice.

(3) In most aluminum and aluminum alloy weldments, the weld metal is not a heat-treatable composition or only mildly responsive (by dilution of elements of the base metal) to strengthening by thermal treatment. Therefore, when heat-treatable alloy weldments are to be postweld heat treated, the filler metal selection is more limited. In the welding of Alloys 2219 and 2014, the heat-treatable filler metal of A2319 will provide the highest strength.

(4) Such filler metals as A5183, A5356, A5556, and A5654, which contain Mg in excess of 3% in the nominal level, are not suitable for applications where temperature is sustained above 65℃, because they may be sensitized to stress-corrosion cracking. This would include the lengthy aging treatments used in postweld thermal treatments. A filler metal of A5554 and other filler metals listed in Table 2.3 (excepting the above ones) are suitable for elevated temperature services.

(5) Al-Mg filler metals are highly resistible to general corrosion when used with base metals having similar Mg content. However, the A5XXX series filler metals can be anodic to the 1XXX, 3XXX and 6XXX series base metals. Therefore, in an immersed service, the weld metal will be corroded with pitting to protect the base metal, at varying rates according to the difference in electrical potential of the weld metal and base metal. In this case, Al-Si filler metals, such as A4043 and A4047, would be preferred for improved corrosion resistance over a filler metal of A5356, when welding the base metal of Alloy 6061.

3. Welding processes and procedures

Gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) are most widely used for welding aluminum and its alloys. The individual principles of the GTAW and GMAW processes for welding aluminum and its alloys are similar respectively to those for welding other metals. However, aluminum and its alloys use specific welding procedures different from those used in welding ordinary steels to create sound welds. This section discusses essential techniques needed specifically for welding aluminum and its alloys, excluding the principles and techniques of GTAW and GMAW common to all kinds of metals.

3.1 Gas tungsten arc welding

3.1.1 Electrical characteristics of power sources

GTAW uses generally either direct current (DC) or alternating current (AC) but aluminum and its alloys mostly use AC due to balanced characteristics — **Fig. 3.1**. In AC-GTAW welding, the cleaning action (oxide removal action) for removing an oxide film on the surface of the base metal will take place only during the half cycle of the current cycle when the electrode is positive (DCEP). During the other half cycle when the electrode is negative (DCEN), the arc fuses the base metal more deeply. The cleaning action is indispensable to create a clean surface on the base metal and thereby facilitate sufficient fusion between the molten metal and the base metal. The cleaning action is believed to take place in such a way that the cathode spots (minute points of the oxide film formed on the surface of the base metal) carry high-density currents, by which the spots are fused selectively one after another to remove all the oxide film beneath the arc — **Photo. 3.1**.

CURRENT TYPE	DCEN	DCEP	AC (BALANCED)
ELECTRODE POLARITY	NEGATIVE	POSITIVE	
ELECTRON AND ION FLOW PENETRATION CHARACTERISTICS			
OXIDE CLEANING ACTION	NO	YES	YES-ONCE EVERY HALF CYCLE
HEAT BALANCE IN THE ARC (APPROX.)	70% AT WORK END 30% AT ELECTRODE END	30% AT WORK END 70% AT ELECTRODE END	50% AT WORK END 50% AT ELECTRODE END
PENETRATION	DEEP; NARROW	SHALLOW: WIDE	MEDIUM
ELECTRODE CAPACITY	EXCELLENT e.g., 1/8 in. (3.2 mm) 400 A	POOR e.g., 1/4 in. (6.4 mm) 120 A	GOOD e.g., 1/8 in. (3.2 mm) 225 A

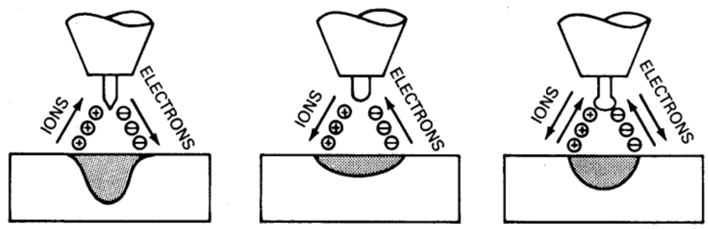


Figure 3.1 *Characteristics of current types for gas tungsten arc welding [Ref. 9]*

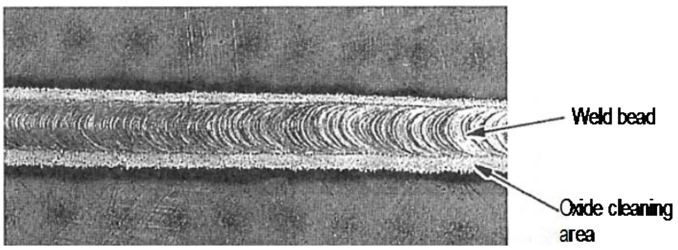


Photo 3.1 *An aluminum weld cleaned by the oxide cleaning action of the arc [Ref. 7]*

In addition to conventional thyristor-type and iron-movable-type power sources, inverter-type power sources are widely used recently. The inverter-type power source offers lighter weight, smaller size, higher electric efficiency, and the following advanced weldability due to the rectangular wave current as shown in **Fig. 3.2**, compared with the thyristor type.

(1) More stable arcs due to less ripples of current
(2) Better arc starting due to quicker current response
(3) More accurate, fine current control

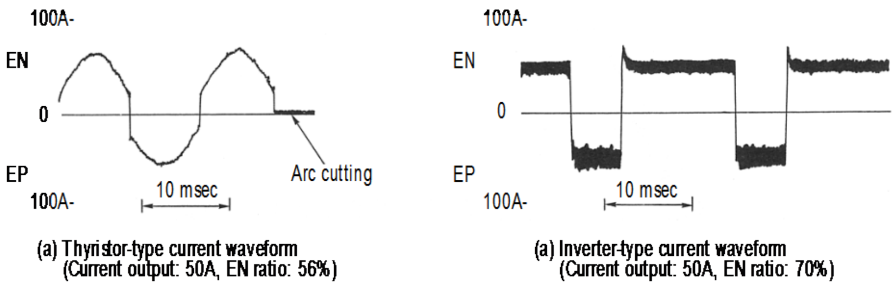


Figure 3.2 *A comparison of output current waveforms of thyristor- and inverter-type power sources [Ref. 1]*

The AC-DC GTAW power source features the benefits of AC-GTAW and DCEN-GTAW power sources: smoother bead appearance, better arc concentration, deeper penetration, and better capacity of electrode. **Figure 3.3** shows an example of the output current waveform of this type of power source.

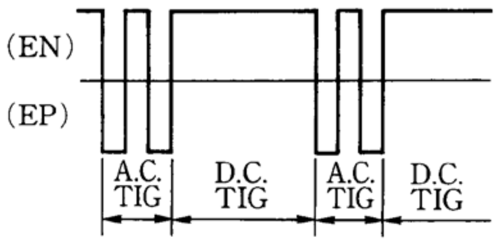


Figure 3.3 *A typical output current waveform of AC-DC combined inverter-type GTAW power source [Ref. 1]*

3.1.2 Types of tungsten electrodes and edge preparation

Pure tungsten and zirconia tungsten (0.25%ZrO_2) electrodes with a hemispherical-shaped tip (**Fig 3.4**) are commonly used for AC-GTAW welding due to better arc stability. Ceriated tungsten (2%CeO_2) and lanthana tungsten (1%La_2O_3) electrodes are also used for AC-GTAW due to a reduced rate of burn-off.

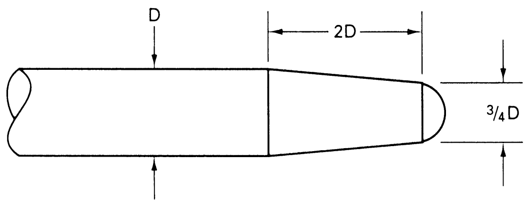


Figure 3.4 *A typical tungsten electrode shape grounded for AC-GTAW aluminum welding, having a hemispherical-shaped tip [Ref. 2]*

3.1.3 Types of shielding gases

Argon is the most commonly used shielding gas for welding aluminum and its alloys due to better arc starting characteristics and improved cleaning action, especially with alternating current. AC-GTAW also uses a mixture of argon and helium with 50 percent or more argon to take advantage of higher travel speeds because helium transfers more heats into the work than argon.

3.2 Gas metal arc welding

3.2.1 Electrical characteristics of power sources

GMAW of aluminum and its alloys uses generally constant-voltage type direct current power sources with electrode positive polarity (DCEP) because of better oxide cleaning action, deeper penetration, smoother spray droplet transfer, and automatic self-regulation for stable arcs.

In spray arc, the filler metal will be transferred across the arc as a stream of fine, superheated droplets having excellent directivity when the welding current and arc voltage are above certain threshold values. These values will depend upon the electrode alloy, size, and feed rate. For example, with a 1.6-mm aluminum wire, the use of high currents over approximately 140A (critical current) with an appropriate arc voltage provides spray arc, resulting in good bead appearance with regular ripples in all welding positions. The spray transfer mode may be continuous or intermittent. Intermittent droplet transfer is called pulse spray arc, in which the arc can be of spray even with a low average current below the critical current due to an intermittent high current larger than the critical. Pulse spray arc is suitable for welding sheet metals having 2 mm or less thickness by using a 1.2- or 1.6-mm wire (better wire feedability than with a smaller diameter wire), thereby minimizing excessive melt-through of the base metal.

3.2.2 Wire feeder, conduit, and contact tube

In semiautomatic welding, there are three drive systems for delivering the electrode wire from the spool to the arc. These systems are designated push, pull, and push-pull. In the push system that is used most commonly, as shown in **Fig. 3.5 (a)**, the wire feeding rolls are located near the spool and the wire electrode is pushed to the welding torch through a conduit that is about 3 m long. With the push system, the use of a smaller size wire or a longer conduit may deteriorate the wire feedability. In this case, the push-pull system is available (**Fig. 3.5 (b)**), in which the wire is fed through the conduit by two sets of rolls (one near the spool and another in the welding torch), which permits conduit lengths of 6 m or more. **Figure 3.5 (c)** shows an example of the pull system, also known as a reel torch system, where the rolls are located in the welding torch and the wire is pulled from the reel.

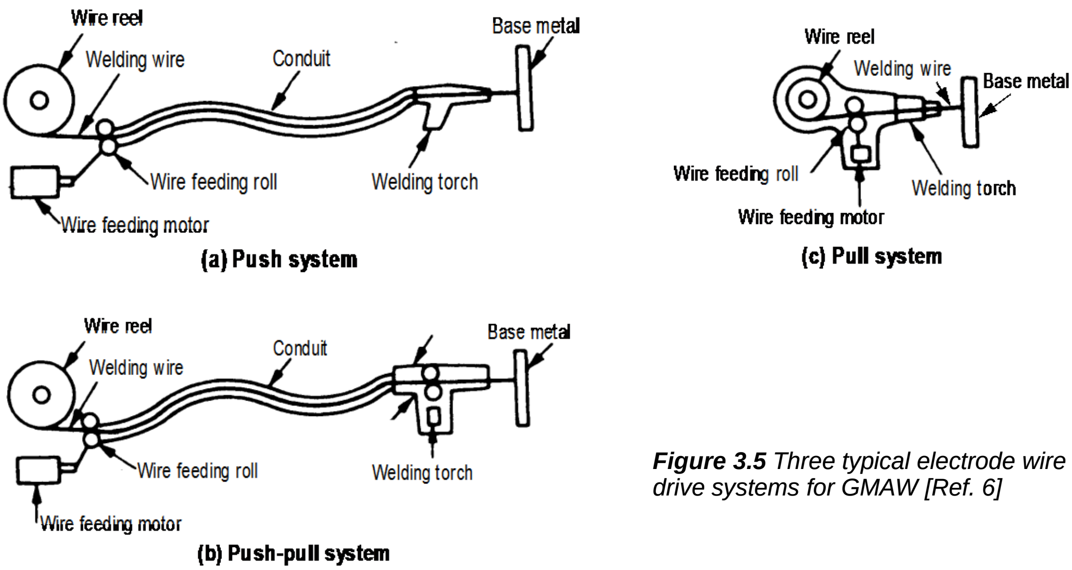


***Figure 3.5** Three typical electrode wire drive systems for GMAW [Ref. 6]*

The most important function of the wire feeder is to feed electrode wires ranging form soft aluminum to hard aluminum alloys at a designated feeding speed without causing deformation and scratches of the wire. Radiused or 120-degree-V-grooved drive rolls on top (pressure rolls) and bottom (feeding rolls) are preferred over serrated rolls because they do not mark the wire nor load the electrode conduit with fine aluminum chips shaved from the wire by the drive rolls. The four-roll driving system with two sets of pressure and feeding rolls of specific materials (e.g., ceramic or stainless steel) different from those for steel wires is commonly used to increase the area of contact between the wire and rolls, thereby improving the driving force with smaller surface pressures — **Photo 3.2**.

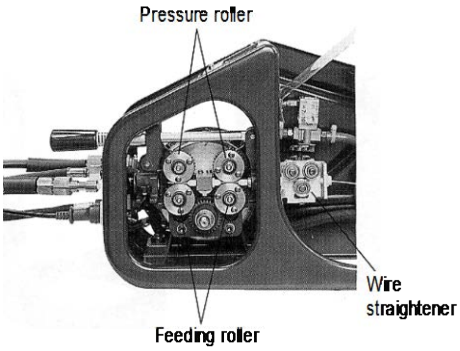


***Photo 3.2** A typical 4-roll driving system consisting of two sets of pressure rolls and feeding rolls [Ref. 1]*

As shown in Photo 3.2, the wire straightener is used to reduce the cast in the wire as it comes off the spool and thereby decrease the load to the conduit liner and facilitate stable electric supply at the welding torch. The conduit liner uses a plastic (e.g., Teflon) tube with low skid resistance to prevent buckling of the wire.

With aluminum and its alloy wires, as compared with steel wires, the contact pressure between the wire and the inside surface of the contact tube is lower; consequently, the electric supply tends to become instable. In order to overcome this drawback, a straight contact tube with sufficient length (100-150 mm) is preferred so that the wire has numerous contacts with the inside diameter of the contact tube to minimize arcing. The longer contact tube can also straighten the lower-strength aluminum wire to stabilize the position of the wire as it emerges from the contact tube.

3.2.3 Gas shielding

Argon is the most commonly used shielding gas for semiautomatic GMAW in the spray transfer mode. It provides excellent arc stability, bead shape, and penetration. Helium-argon mixtures (50-75%He/bal. Ar) are also used for specific applications (e.g., double-sided single-run welding of a thick plate) to improve penetration characteristics — **Fig. 3.6**.

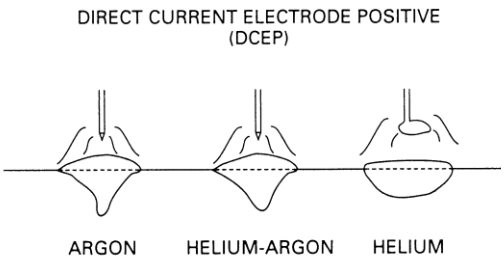


***Figure 3.6** Influence of shielding gas on weld profile [Ref. 2]*

The purity of the shielding gas is of utmost importance. Only gases having a dew point of −60°C or lower [Ref. 2] should be used, and care must be taken to prevent contamination. Dust, dirt, and moisture can accumulate in the gas cylinder fittings, which should be carefully cleaned and blown out before use. All hose connections and other fittings must be pressure-tight since entrance of air or escape of shielding gas will affect the weld. Plastic (e.g., Teflon) hose is recommended to use for the gas passage from the outlet of the gas piping of copper or stainless steel to the welding torch. Conventional rubber and vinyl chloride hoses are likely to absorb moisture due to their higher moisture permeability. The moisture in the shielding gas is one of the factors that cause porosity in welds.

The use of contaminated shielding gas and insufficient shielding can be one of the causes to smut. Smut consists mainly of oxides of aluminum and magnesium, which deposits showing black color at the outside of the oxide cleaning area of an aluminum weld — **Photo 3.3**. Smut is made by oxidized vapors of aluminum and magnesium in the arc atmosphere. Contamination and insufficient shielding can be occurred by many factors such as high-velocity wind, invasion of air through an imperfection in the gas passage, irregular gas flow, excessively low gas flow rate, excessive nozzle standoff, and excessively high arc voltage.

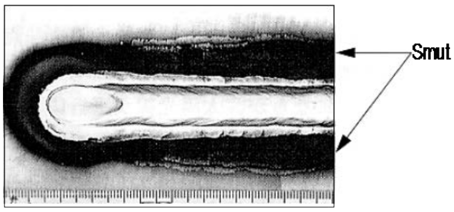


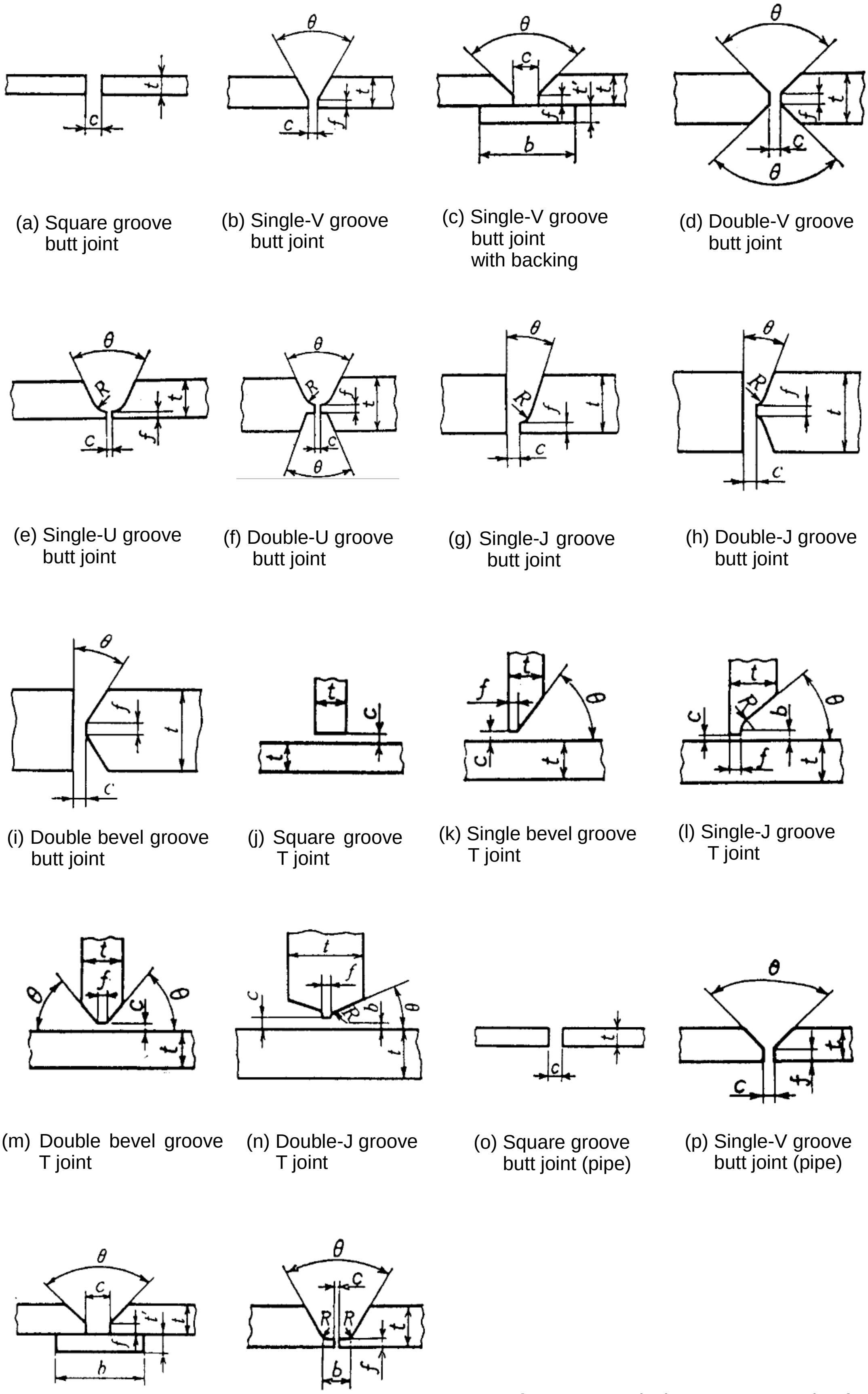
***Photo 3.3** Smut deposited at the outside of the oxide cleaning area of an aluminum weld [Ref. 10]*

Main means to decrease smut other than using appropriate shielding:
(1) Use an A4XXX series filler metal containing no Mg. Welding of 5XXX series alloys with A5XXX series filler metals that contain larger amounts of Mg is more likely to cause smut.
(2) Use forehand technique with a push angle of 10-20 degrees. The use of backhand technique causes deposition of smut on the surfaces of the oxide cleaning area and weld bead, too.
(3) Remove oxide film, oil and other dirt from the fusion surfaces of the base metal before welding.

3.3 Welding groove preparation

Figure 3.7 and **Table 3.1** show typical welding groove shapes and sizes, respectively, for GTAW/GMAW of aluminum and its alloys in butt joints of plates, T joints of plates and butt joints of pipes, respectively. For processing the grooves, mechanical means is commonly used: shear, band saw, disk saw, jigsaw, nibbler, milling, rotary planer, and the like.

The fusion surfaces of the groove should be cleaned right before welding by removing oxide film and other dirt to facilitate better fusion and prevent porosity, by means of either one or a combination of the following methods.
(1) Degreasing with organic solvents such as thinner, benzin, acetone, and methanol
(2) Polishing with stainless steel wire brush, file, vinyl buff, and the like
(3) Chemically treating with acid and alkaline



(a) Square groove butt joint

(b) Single-V groove butt joint

(c) Single-V groove butt joint with backing

(d) Double-V groove butt joint

(e) Single-U groove butt joint

(f) Double-U groove butt joint

(g) Single-J groove butt joint

(h) Double-J groove butt joint

(i) Double bevel groove butt joint

(j) Square groove T joint

(k) Single bevel groove T joint

(l) Single-J groove T joint

(m) Double bevel groove T joint

(n) Double-J groove T joint

(o) Square groove butt joint (pipe)

(p) Single-V groove butt joint (pipe)

(q) Single-V groove butt joint with backing (pipe)

(r) Single-U groove butt joint (pipe)

Figure 3.7 *Typical groove geometries for plate and pipe joints for GTAW/GMAW of aluminum (Source: JIS Z 3604:2002)*

Table 3.1 *Typical groove geometries for plate and pipe joints for GTAW/GMAW of aluminum and its alloys (Source: JIS Z 3604:2002)*

Type of joint	Type of groove (1)	Wall thick. t (mm)	Root face f (mm)		Root gap c (mm)		Groove or bevel angle Φ (deg.)		Note
			GTAW	GMAW	GTAW	GMAW	GTAW	GMAW	
Butt joint, plate	a	6 max	—	—	3 max	2 max	—	—	Corners may be chamfered
	b	4-25	3 max	3 max	3 max	3 max	60-110	50-80	Back gouged and back welding
	c	4 min	3 max	3 max	3-6	3-6	45-70	45-70	b: 20-50 t': 4-10
	d	8 min	2 max	2 max	3 max	3 max	50-90	50-90	Back gouged and back welding
	e	16 min	3-5	3-5	2 max	2 max	40-60	40-60	R: 4-8 Use backing or back gouged and back welding
	f	16 min	3 max	3 max	2 max	2 max	40-60	40-60	R: 6-8 Back gouged and back welding
	g	16 min	—	3-5	—	2 max	—	40-60	R: 6-8 Back gouged and back welding
	h	16 min	—	3 max	—	2 max	—	40-60	R: 6-8 Back gouged and back welding
	i	16 min	—	3 max	—	2 max	—	40-60	Back gouged and back welding
T-joint, plate	j	1 min	—	—	2 max	2 max	—	—	Partial grooving is permissible
	k	4-12	2 max	2 max	2 max	2 max	50-60	50-60	Use backing or back gouged and back welding
	l	10 min	2-4	2-4	2 max	2 max	40-60	40-60	b: 6 max R: 4-8 Use backing or back gouged and back welding
	m	8-25	2 max	2 max	2 max	2 max	50-60	50-60	Back gouged and back welding
	n	16 min	3 max	3 max	2 max	2 max	40-60	40-60	b: 6 max R: 4-8 Back gouged and back welding
Butt joint, pipe	o	3 max	—	—	2 max	2 max	—	—	Corners may be chamfered
	p	3-15 O. Dia: 20-600	2 max	—	3 max	—	80-90(2) 80-110(3)	—	—
	q	3-30 O. Dia: 30-1200	2 max	2 max	6 max	6 max	70-80(2) 70-110(3)	60-90	b: 20-50 t': 2-5
	r	3-30 O. Dia: 30-1200	1-3	1-3	3 max	3 max	60-70	60-70	b: 7 max R: 3-5 Root pass by GTAW is preferable in GMAW

Note (1) Refer to Fig. 3.7
(2) For horizontal rolled pipe
(3) For vertically or horizontally fixed pipe

3.4 Welding conditions

Essential welding conditions for GTAW/GMAW include welding current, arc voltage, welding speed and shielding gas flow rate. Proper welding conditions depend on thickness of base metal, size of filler metal, type of joint, shape of groove, and welding position. **Tables 3.2** and **3.3** show examples of welding conditions for several types of welding joints for GTAW and GMAW, respectively. The most appropriate welding conditions should be examined for individual assemblies and confirmed by procedure testing.

Table 3.2 *Examples of welding conditions for GTAW [Ref. 1]*

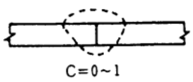
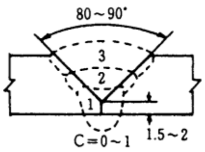
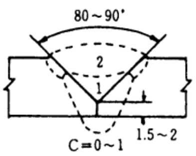
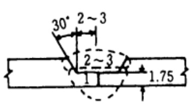
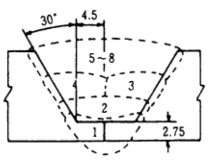
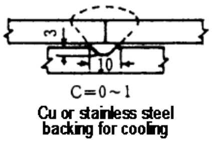
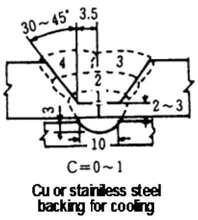
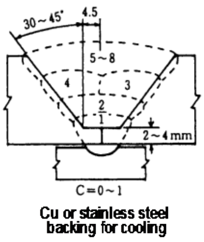
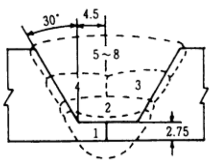
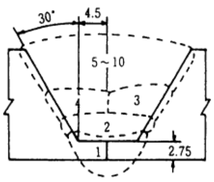
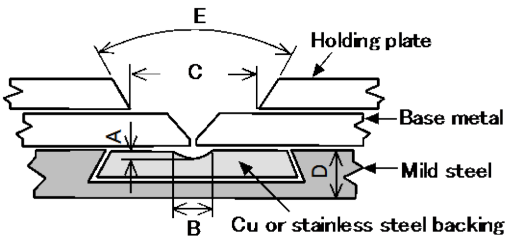
Wall thick. (mm)	Type of joint, Groove preparation, Pass sequence	Welding position	Pass No.	Welding current (A)	Welding speed (mm/min)	W elect-rode size (mm)	Filler metal size (mm)	Ar flow rate (l/min)
3 (Plate)		F	1	110-130	150-200	2.4 or 3.2	2.4 or 3.2	10
		V	1	110-130	150-200	2.4 or 3.2	2.4 or 3.2	10
8 (Plate)		F	1	210-230	120-180	4.0 or 4.8	3.2	12
			2	210-230	120-180		3.2	
			3	200-220	120-180		4.0	
		V	1	210-230	150-200	4.0 or 4.8	3.2	12
			2	200-220	120-180		4.0	
4 (Pipe)		Horizon-tally fixed or Vertically fixed	1	90-125	120-180	2.4	2.4	10-12
			2	110-130	150-200	3.2	3.2	
			3	120-130	150-200	3.2	3.2	
12-15 (Pipe)		Horizon-tally fixed or Vertically fixed	1	180-200	120-180	3.2	3.2	12-15
			2	200-240	150-200	4.0	4.0	
			3-8	200-260	150-200	4.0	4.0	

Table 3.3 *Examples of welding conditions for GMAW [Ref. 1]*

Wall thick. (mm)	Type of joint, Groove preparation, Pass sequence (1)	Welding position	Pass No.	Welding current (A)	Arc voltage (V)	Welding speed (mm/min)	Filler metal size (mm)	Ar flow rate (l/min)
3 (Plate)		F	1	120-140	13-15	450-550	0.8-1.2	20
		V	1	120-140	13-15	450-550	0.8-1.2	20
8 (Plate)		F	1	180-220	25-28	500-700	1.6	20-25
			2-4	200-240	24-26	450-600	1.6	
		V	1	180-220	25-28	500-700	1.6	20-25
			2-4	180-230	22-26	450-600	1.6	
		V (Pulse)	1	155-165	22-24	500-700	1.6	20-25
			2-4	160-180	22-24	450-600	1.6	
20 (Plate)		F	1	180-220	25-28	500-700	1.6	20-25
			2-8	200-240	22-26	450-600	1.6	
		V	1	180-220	25-28	500-700	1.6	
			2-8	180-230	22-26	450-600	1.6	
12-15 (Pipe)		Horizon-tally fixed or Vertically fixed	1-2	GTAW (Refer to 12-15 pipe in Table 3.2)				
			3-8	210-230	22-26	400-600	1.6	20-25
20 (Pipe)		Horizon-tally fixed or Vertically fixed	1-2	GTAW (Refer to 12-15 mm pipe in Table 3.2)				
			3-10	210-230	22-26	400-600	1.6	20-25

Note (1) Typical backing block setup and size for cooling the root pass weld:



Thickness	A	B	C	D	E
1.6 max	0.5	3.2	12.7	12.7-15.9	120 deg max
2.0-4.8	1.1-1.2	4.8	19.1-25.4	12.7-15.9	Approx. 120 deg
6.4 min	2.4	6.4	25.4	12.7-15.9	90 deg max

3.5 Welding distortion and countermeasures

The amount of welding distortion in welding aluminum and its alloys is larger than in welding steels because the thermal expansion of aluminum and its alloys is larger than that of steel. In addition, removal of distortion in aluminum and aluminum alloy assemblies is more difficult than in steel assemblies. This is because aluminum and its alloys are prone to deform by buckling and have larger thermal conductivity and lower melting point, which require stricter controls of applied forces in mechanical means and heats in thermal means in removing distortion. Furthermore, strain-hardened and heat-treatable types can loose strength if the heating temperature for removal of distortion is excessive. Therefore, preventive measures against distortion should be employed in design and fabrication of structures by using the following common techniques.

1) Minimize welding lines by using larger width plates, extrusion shapes, and flanged plates.
2) Design welding grooves with appropriate size and fillet leg length.
3) Estimate possible amounts of angular distortion and shrinkage and prevent them by using restraining jigs. **Table 3.4** shows examples of the amounts of shrinkage generated in welding aluminum and aluminum alloy assemblies. **Figure 3.8** illustrates how to prevent welding distortion by using the presetting techniques or jigs.

Table 3.4 *Examples of welding shrinkage in welding aluminum and aluminum alloy assemblies (Plate thickness: 4.5-16 mm) [Ref. 1]* (Unit: mm)

Direction of shrinkage	Butt welding	Fillet welding
Longitudinal shrinkage along a welding line	0.5-1.0 per 1000	0.5-1.0 per 1000 (2)
Transverse shrinkage perpendicular to a welding line	1.5-3.0 per one welding line (1)	0.5-1.2 per one welding line

Note (1) Affected largely by shape of groove, root opening, and welding conditions.
(2) Affected by size of fillet, size of welding plate and welding conditions. Intermittent fillet welding generally results in a half of this amount

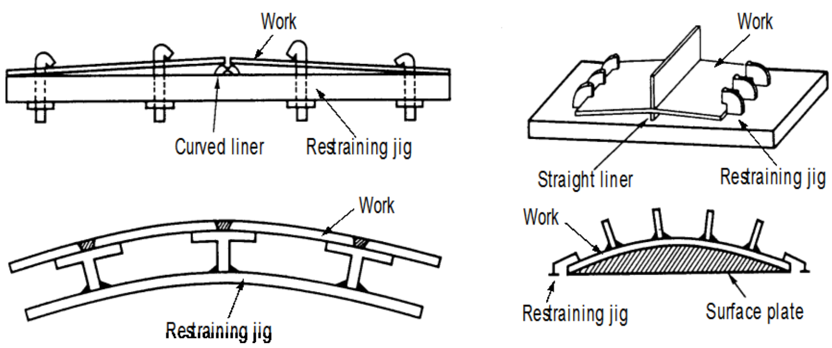


Figure 3.8 *Examples of presetting methods for preventing distortion*

4) Assemble the components of the work in good accurate in the fitting and tacking processes.

5) Follow the appropriate welding sequence as stated below:
   (1) Complete a particular joint first that is expected to generate the largest distortion.
   (2) Use a symmetrical deposition method in principle.
   (3) Proceed the welding towards the free ends of the work.
6) Restrain the work by using jigs suitable for the shape and size of a structure, welding location in the work, and the welding process. **Figure 3.9** illustrates typical restraining jigs used in welding aluminum and its alloys.

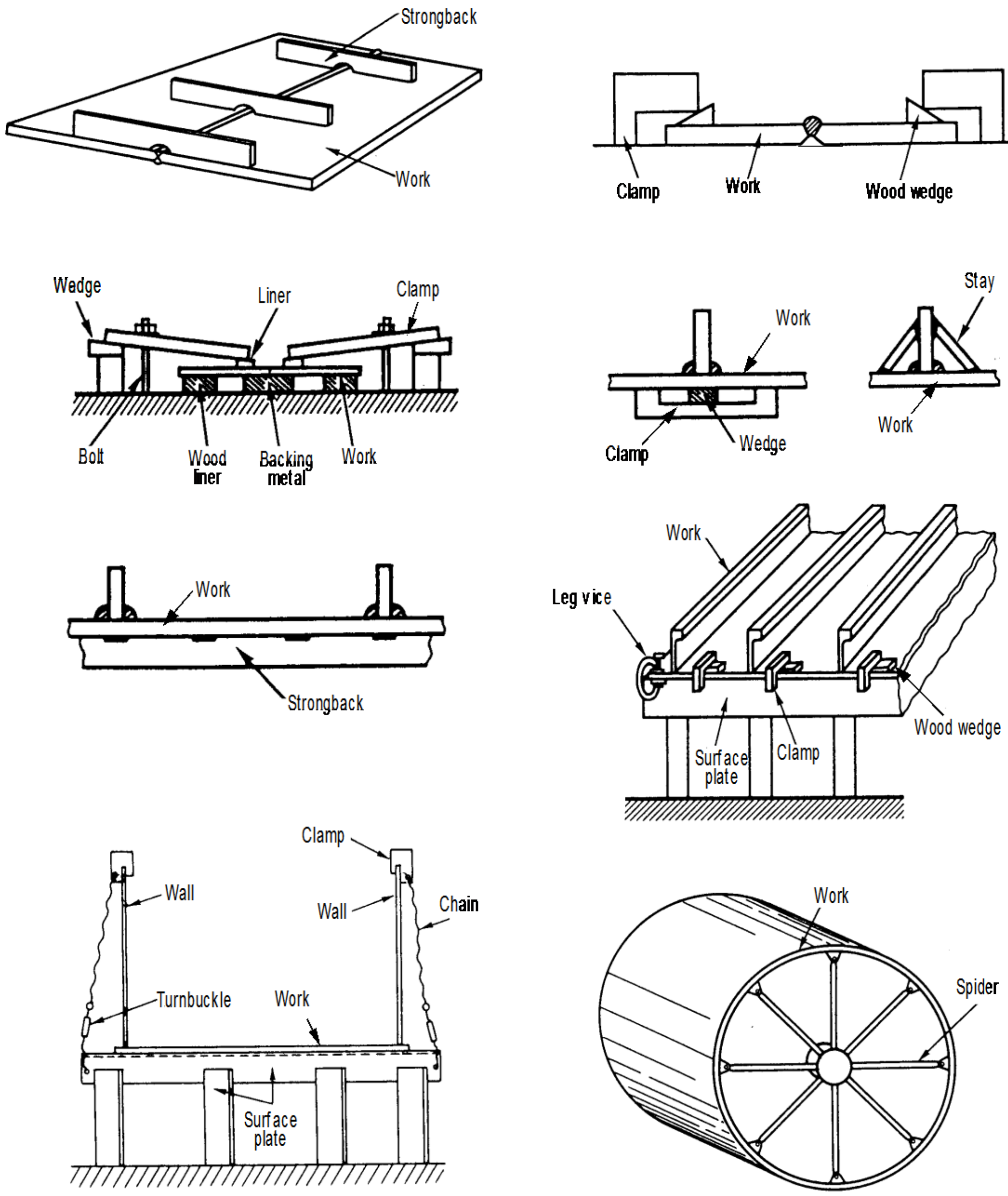


Figure 3.9 *A variety of restraining jigs [Ref. 1]*

Even when an appropriate restraining means has been employed to minimize distortion, the welded assembly may contain welding distortion at a large or small degree; in this case, such distortion has to be reduced to ensure the assemblage accuracy to the job specification. Distortion removal methods used in aluminum and aluminum alloy assemblies include mechanical means such as rolling, jacking up, hammering, and peening, and thermal means such as heating followed by rapid cooling and heating followed by hot forming. These methods are in principle the same as those for steel assemblies; however, the following techniques should be used because the mechanical and thermal characteristics of aluminum and its alloys are quite different from those of steels.

1) In rolling and hammering, put such buffer materials as craft papers, wood plates, and rubber sheets in between the work and the tools to protect the work.
2) Peening may be accomplished by shot peening with a multiple-point peening gun. Peening is effective for thin welds; however, excessive peening causes work hardening of the weld and thereby reduces the ductility of the weld. Peening should be applied after ensuring the weld contains no surface defects such as incomplete fusion or cracks because such defects could be covered-up by peening and thus left undetected by subsequent inspection.
3) In spot heating and line heating, control the heating temperature within the limits as shown in **Table 3.5**. Particularly, where the strength of a structure is designed based on the strain-hardened or heat-treated strength of the pertinent aluminum or aluminum alloy, the heating temperature must be controlled more strictly. If the work is heated excessively, it will be softened markedly, decreasing the strength of the material to the extent that cannot satisfy the design requirement.

Table 3.5 *Permissible temperature ranges for heating aluminum and its alloy weld assemblies (Source: JIS Z 3604:2002)*

Alloy designation	Temper designation	Heating temperature range (℃)	
		Heating followed by rapid cooling	Heating followed by hot forming
A1070 A1050 A1100 A1200	O	450 max	400 max
	H112	300 max	300 max
	H12, H14, H22, H24	200 max	200 max
A2014 A2017 A2219	O	450 max	400 max
	T4, T6, T42, T62, T861, T87	300 max	200 max
A3003 A3203 A5005 A5052 A5154 A5254 A5056 A5083 A5N01	O	450 max	400 max
	H112	350 max	350 max
	H12, H22, H32	300 max	250 max
	H14, H24, H34	300 max	250 max
A6101 A6061 A6N01 A6063	T4, T5, T6	250 max	250 max
A7003 A7N01	T4, T5, T6	300-350	200 max

Note: Heating time should be minimized.

3.6 Weld discontinuities and preventive measures

Main discontinuities that may occur in aluminum and aluminum alloy welds are blowholes and cracking. This section discusses causes of and preventive measures against blowholes and cracks.

3.6.1 Blowholes

Blowholes in aluminum and its alloy weld metals are bubbles of hydrogen caused by dissolved hydrogen in the molten weld metal and remained in the solidified weld metal. As shown in **Table 3.6 and Fig. 3.10**, the solubility of hydrogen in aluminum is very much different from that of steel. The temperature of a molten metal right under a welding arc is believed to be approximately 2000℃ for both molten steel and aluminum. At this high temperature, the solubility of hydrogen in the molten steel and aluminum is almost the same as shown in Fig. 3.10. However, the amounts of hydrogen to be discharged due to a decrease of hydrogen solubility in conjunction with a decrease of temperature during the solidification process are markedly different between them because of different liquidus temperatures, as shown with the dark-color arrows in Fig. 3.10. That is, aluminum has to discharge a larger amount of dissolved hydrogen by approximately 40 times as large as that in the case of steel, during solidification of the molten metal. Therefore, aluminum is more likely to generate bubbles of hydrogen — thus larger amounts of blowholes can be remained — in the weld metal.

Table 3.6 *A comparison of hydrogen solubility between aluminum and iron in solidification* (1) *[Ref. 8]*

Type of metal	Hydrogen solubility at molten-metal temperature right under a welding arc (cc/100g)	Hydrogen solubility at liquidus temperature (cc/100g)	Hydrogen solubility ratio at solidification of molten metal (%)
Aluminum	3.7 at 1900℃	0.07 at 660℃	1.9
Iron	4.2 at 2093℃	3.0 at 1537℃	71.4

Note: (1) Hydrogen solubility: the amount of dissolved hydrogen in the metal tested in the argon atmosphere containing 1% hydrogen

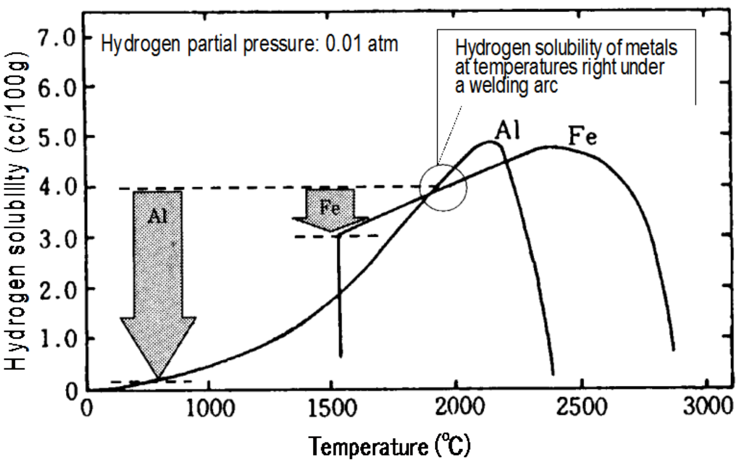


Figure 3.10 *A comparison of hydrogen solubility as a function of temperature between aluminum and iron [Ref. 8]*

As discussed above, dissolved hydrogen is believed to be the major cause of blowholes, based on experimental data. With respect to actual welding, several sources of hydrogen can be estimated as shown in **Fig. 3.11**. The largest source of hydrogen is the air around a welding arc; secondly, welding wires; followed by other sources such as shielding gas and base metal. The following paragraphs discuss how to minimize the hydrogen invasion into the arc atmosphere for each source of hydrogen.

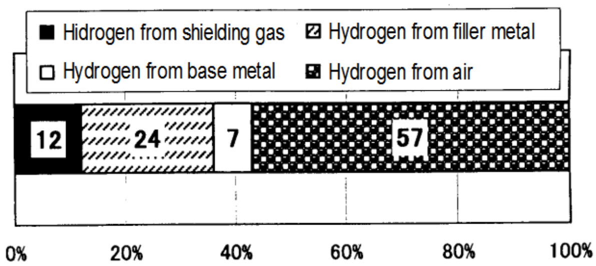


Figure 3.11 *Ratios of sources of the hydrogen invaded into the arc atmosphere [Ref. 8]*

(1) How to minimize hydrogen from air:
- Keep the shielding gas from the welding torch in regular flow by using an appropriate gas flow rate and a gas orifice.
- Use an adequate-diameter nozzle to cover fully the molten crater.
- Use a windscreen to maintain the shielding in good condition.
- Minimize the humidity and dust in the workshop.

(2) How to minimize hydrogen from filler metals:
- Keep filler metals in a dry condition to prevent moisture deposition onto their surfaces because the major source of hydrogen of a filler metal is its surface area.
- Keep filler metals in a polyethylene bag to prevent them from moisture, dust and dirt after took them out from the package.
- Handle filler metals by clean-glove hands.
- Avoid the use of a filler metal left unpacked for a long time because invisible but thin oxide film is formed on the surface of the filler metal, which can be transformed to hydroxide film by reacting with due point water in the atmosphere.

(3) How to minimize hydrogen from shielding gas:
- Use plastic (e.g., Teflon) hoses for the shielding gas passage because conventional rubber and vinyl chloride hoses have higher water permeability and hence are prone to pick up much more moisture through the wall of the hose — thus are more likely to cause blowholes.
- Flush out the moisture remained in the shielding gas passage by flowing the shielding gas of 3-5 liter per minute for 15 minutes before welding.
- Control the due point of the shielding gas at the outlet of the welding torch.

(4) How to minimize hydrogen from base metal:
- Remove oxide film and smut from the fusion surfaces of the base metal and tack weld beads with a file, stainless steel brush, or aluminum-use grinder.
- Remove completely machine oil used in groove preparation.
- Use forehand technique for better oxide cleaning action.

3.6.2 Hot cracking

In a case where selection of base metal and filler metal, design of welding joint, welding conditions and welding technique are inappropriate, hot cracking may occur in aluminum and aluminum alloy welds. Hot cracks can occur at various locations and have different designations depending on the location as shown in **Fig. 3.12**. The measures to prevent hot cracking are listed in the following.

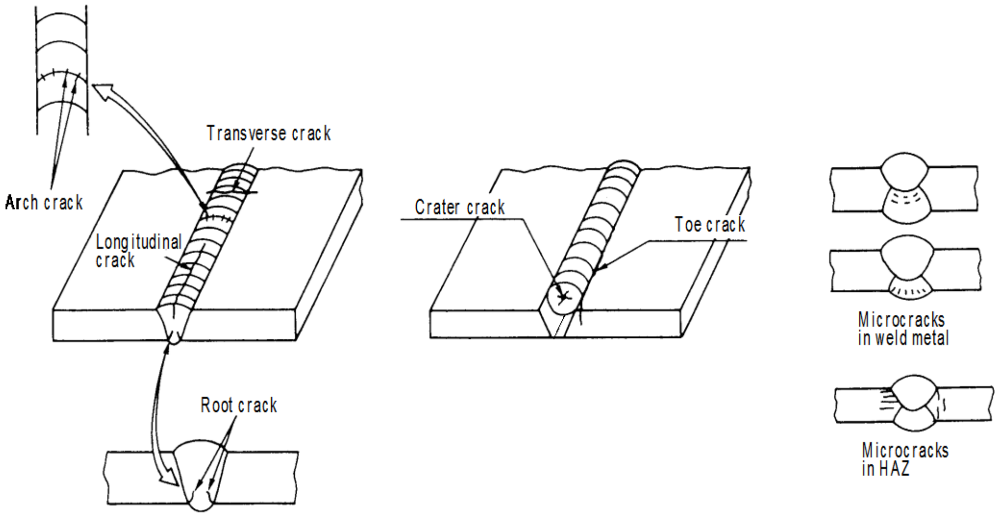


Figure 3.12 *Designations of cracks in aluminum and its alloy welds [Ref. 1]*

(1) Control the root opening in the specified rage. For a wider root opening, use slower welding speeds with lower currents.
(2) Control heat input in the range confirmed by the procedure test. The use of high heat input can particularly cause microcracks in the weld metal.
(3) Use no preheating and control interpass temperatures at 70℃ or lower to prevent microcracks in particular.
(4) Fill up the crater by using the crater treatment technique to prevent crater cracks at the terminal of a bead before cutting the arc.
(5) Minimize the depth of back chipping in double-sided weld joints to minimize heat input into the preceding weld on the opposite side, thereby preventing microcracks in the preceding weld.

Chapter 2

Arc Welding of Copper and Copper Alloys

Contents

Introduction

Copper and copper alloys possess distinctive electrical and thermal conductivity, corrosion resistance, metal-to-metal wear resistance, and aesthetic appearance. Copper offers high electrical and thermal conductivity; therefore, it is widely used for electrical conductors and other electrical equipment. Copper exhibits excellent corrosion resistance against atmosphere, seawater, chemicals, and foods. This is why copper is also used for various applications such as water supply tubes and tanks, chemical containers, brewing equipment, food-processing equipment, and components of ships. Copper alloys possess the electrical and thermal conductivity inferior to copper, and their corrosion resistance varies depending on their chemical compositions. However, they offer higher strength over copper, and therefore they are used for structural components such as water tubing, valves, fittings, heat exchangers, chemical equipment, and bearings.

Copper and its alloys can be joined by welding, brazing, and soldering. The welding processes used for joining copper materials are arc welding, oxyfuel gas welding, laser welding, electron beam welding, ultrasonic welding, resistance welding, flash welding, friction welding, and pressure welding. Among arc welding processes, gas tungsten arc welding (GTAW) and gas shielded metal arc welding with solid wires, referred to as gas metal arc welding (GMAW), are most extensively used due to better performances, although shielded metal arc welding (SMAW) can be used for many non-critical applications.

This textbook discusses various types of copper and copper alloys and their weldability, suitable filler metals, welding procedures, and tips for sound welds and safe practices.

References

[1] Kobe Steel, Ltd. *Welding of Nonferrous Metals and Supper Alloys,* 1969.
[2] The American Welding Society. *Welding Handbook*, 8th Edition, Vol. 3, 1996.
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[7] High Pressure Institute of Japan. *Welding Practices in Cladded Steels.* Sanpo Pub. 1992.
[8] CASTI Metals Red Book. *Nonferrous Metals*, 4th Edition. CASTI Publishing Inc. 2003.
[9] M. Sugiyama. *Nonferrous Metallic Materials*. Corona Publishing Co. 1997.

1. Types and characteristics of copper and copper alloys

Copper offers high electrical and thermal conductivity and excellent corrosion resistance against atmosphere, seawater, chemicals and foods. Copper alloys possess lower electrical and thermal conductivity than copper, and their corrosion resistance varies depending on their chemical compositions. However, copper alloys feature higher strength over copper, and thus are suitable for structural components. Copper and its alloys are available in various forms such as sheets, plates, strips, pipes, tubes, and castings (**Photos 1.1** and **1.2**). This section discusses characteristics of various types of copper and copper alloys that are arc weldable at good or fair degree.

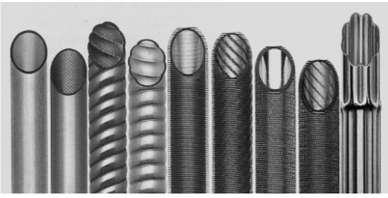


Photo 1.1 *Various heat exchanger tubes made from copper and copper alloys are used for the manufacture of air conditioning, refrigeration, and freezing equipment due to excellent thermal conductivity (Left)*
(Photo source: Kobe Steel's brochure)

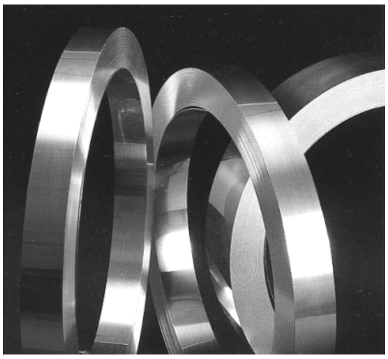


Photo 1.2 *Copper and copper alloy strips are used for the manufacture of IC lead frames, electric terminals, electric connecters, etc. due to excellent electric conductivity (Right)*
(Photo source: Kobe Steel's brochure)

1.1 Copper

Copper products include, as known by common name, electrolytic tough pitch copper, oxygen-free copper, and phosphorous-deoxidized copper. Electrolytic tough pitch copper contains nominally 0.03% oxygen in the form of copper oxide (Cu_2O), which offers excellent electrical and thermal conductivity over other coppers and therefore suits for electric equipment. Oxygen-free copper contains extremely low oxygen. Phosphorous-deoxidized copper contains very low oxygen and high or low amounts of phosphorous. The oxygen content of coppers affects the weldability. The low-oxygen coppers are better weldable and, therefore, are used for welding constructions. The characteristics and usage of coppers are shown in **Tables 1.1** and **1.2** for wrought products.

Table 1.1 *Chemical compositions, features and usage of wrought coppers* (1)

Alloy desig.	Content of main elements (%)		Features and common name	Industrial applications
	Cu	P		
C1020	99.96 min	-	▪ Excellent electrical and thermal conductivity ▪ Excellent malleability and drawability ▪ Good corrosion and weather resistance ▪ Good weldability ▪ Known as "**oxygen-free copper**"	▪ Electric equipment ▪ Chemical equipment
C1100	99.90 min	-	▪ Excellent electrical and thermal conductivity ▪ Excellent malleability and drawability ▪ Good corrosion and weather resistance ▪ Known as "**electrolytic tough pitch copper**"	▪ Electric equipment ▪ Distillation vessels ▪ Building material ▪ Chemical equipment
C1201	99.90 min	0.004 min < 0.015	▪ Good malleability and drawability ▪ Good corrosion and weather resistance ▪ Good heat conductivity ▪ Good weldability ▪ Known as "**deoxidized copper**"	▪ Building material ▪ Chemical equipment ▪ Bath boilers ▪ Water heaters
C1220	99.90 min	0.015-0.040		

Note (1) Excerpted from JIS H 3100:2012 (Copper and Copper Alloy Sheets, Plates and Strips).

Table 1.2 *Tensile properties of wrought coppers* (1)

Alloy desig.	Temper designation and description (2)		Wall thickness (mm)	Tensile strength (N/mm^2)	Elongation (%)
C1020	O	Annealed	0.3-30	195 min	35 min
	½H	Work hardened only	0.3-20	245-315	15 min
C1100	O	Annealed	0.5-30	195 min	35 min
	½H	Work hardened only	0.5-20	245-315	15 min
C1201 C1220	O	Annealed	0.3-30	195 min	35 min
	½H	Work hardened only	0.3-20	245-315	15 min

Note: (1) Excerpted from JIS H 3100:2012 (Copper and Copper Alloy Sheets, Plates and Strips).
(2) As per JIS H 0500:1998 (Glossary of Terms Used in Wrought Copper and Copper Alloys)

1.2 Copper alloys

Copper can be alloyed with many common chemical elements within the limits of solid solution solubility. The principal alloying elements in copper alloys are aluminum, nickel, silicon, tin, and zinc. Also, small quantities of other chemical elements are added to improve mechanical properties, corrosion resistance, or machinability; to provide better response to precipitation hardening heat treatments; or to deoxidize the alloy. Many copper alloys are readily arc weldable but some copper alloys are poor in weldability.

The copper alloys that are used commonly for welding applications are copper-zinc alloys (brass), copper-zinc-tin alloys (naval brass), copper-tin alloys (phosphor bronze), copper-aluminum alloys (aluminum bronze), copper-silicon alloys (silicon bronze), and copper-nickel alloys (cupronickel). The characteristics and usage of these copper alloys are discussed in the following paragraphs.

1.2.1 Copper-zinc alloys (Brass)

Copper alloys in which zinc is the major alloying element are generally called "brasses." Brasses offer good mechanical properties and corrosion resistance. Addition of zinc to copper decreases the melting temperature, density, electrical and thermal conductivity, and modulus of elasticity. On the other hand, zinc additions increase the strength, hardness, ductility, and coefficient of thermal expansion. The color of brass changes from reddish, gold, light gold and yellow, in this order with increasing zinc content. The characteristics and usage of wrought copper-zinc alloys, which are often used for welded equipment, are shown in **Tables 1.3** and **1.4**.

For joining considerations, low-zinc brasses (zinc content 20 percent maximum) have good weldability; however, high-zinc brasses (zinc content greater than 20 percent) have only fair weldability. Selection of a welding filler metal may depend on matching the brass color when joining appearance is important. Leaded brasses feature free-machinability and therefore suit gears and screws; however, they are considered unweldable due to hot-shortness and high crack susceptibility.

Table 1.3 *Characteristics and usage of wrought copper-zinc alloys (Brass)* (1)

Alloy desig.	Content of main elements (%)			Features and common name	Industrial applications
	Cu	Zn	Sn		
C2100	94.0-96.0	Rem	-	▪ Good malleability, drawability and weather proof ▪ Good brightness ▪ Known as "**red brass**"	▪ Building material
C2200	89.0-91.0	Rem	-		
C2300	84.0-86.0	Rem	-		
C2400	78.5-81.5	Rem	-		
C2600	68.5-71.5	Rem	-	▪ Excellent malleability and drawability	▪ Terminal connectors
C2680	64.0-68.0	Rem	-	▪ Good malleability and drawability	▪ Terminal connectors ▪ Electric wiring parts
C2720	62.0-64.0	Rem	-	▪ Good malleability and drawability	▪ Shallow drawn parts
C2801	59.0-62.0	Rem	-	▪ High strength ▪ malleable	▪ Electric wiring parts ▪ Gage board
C4621	61.0-64.0	Rem	0.7-1.5	▪ Good corrosion resistance to seawater ▪ Known as "**naval brass**"	▪ Heat exchanger end plates ▪ Seawater inlets for ships
C4640	59.0-62.0	Rem	0.5-1.0		

Note (1) Excerpted from JIS H 3100:2012 (Copper and Copper Alloy Sheets, Plates and Strips).

Table 1.4 *Tensile properties of wrought copper-zinc alloys (Brass)* (1)

Alloy desig.	Temper designation and description		Wall thickness (mm)	Tensile strength (N/mm^2)	Elongation (%)
C2100	O	Annealed	0.3-30	205 min	33 min
	½H	Work hardened only	0.3-20	265-345	18min
C2200	O	Annealed	0.3-30	225 min	35 min
	½H	Work hardened only	0.3-20	285-365	20 min
C2300	O	Annealed	0.3-3	245 min	40 min
	½H	Work hardened only	0.3-20	305-380	23 min
C2400	O	Annealed	0.3-30	255 min	44 min
	½H	Work hardened only	0.3-20	325-400	25 min
C2600	O	Annealed	0.3-30	275 min	40 min
	½H	Work hardened only	0.3-20	355-440	28 min
C2680	O	Annealed	0.3-30	275 min	40 min
	½H	Work hardened only	0.3-20	355-440	28 min
C2720	O	Annealed	1<, 30 max	275 min	50 min
	½H	Work hardened only	0.3-20	355-440	28 min
C2801	O	Annealed	1<, 30 max	325 min	40 min
	½H	Work hardened only	0.3-20	410-490	15 min
C4621	F	As fabricated	0.8-20	375 min	20 min
			20<, 40 max	345 min	20 min
			40<, 125 max	315 min	20 min
C4640	F	As fabricated	0.8-20	375 min	25 min
			20<, 40 max	345 min	25 min
			40<, 125 max	315 min	25 min

Note (1) Excerpted from JIS H 3100:2012 (Copper and Copper Alloy Sheets, Plates and Strips).

The cast brasses contain 2-41 percent zinc but often have one or more additional alloying elements, including tin, lead, nickel, and phosphorous. Cast alloys are generally not as homogeneous as the wrought products. In addition to the welding complications caused by lead and other alloy elements, the microscopical variation may cause difficulty of welding. Cast alloys without lead are only marginally weldable, and leaded brasses are generally unweldable [Ref. 2].

Cast brasses that have additions of aluminum, ferrous, and manganese are often used for marine propellers because of excellent characteristics of higher strength, better resistance to corrosion and cavitation erosion in seawater. A typical high strength brass (JIS CAC301), also know as cast manganese bronze, contains nominally 57.5%Cu, 37.5%Zn, 1%Al, 1%Fe, and 1%Mn and possesses a minimum tensile strength of 430 N/mm^2 and a minimum elongation of 20%. Such propellers sometimes are subjected to GTAW/GMAW to repair the damages caused by accidents during voyages. For details of this specific casting, refer to JIS H 5120:2009 (Copper and Copper Alloy Castings)

1.2.2 Copper-tin alloys (Phosphor bronze)

Copper-tin alloys are known as phosphor bronze because phosphorous is added during casting as a deoxidizing agent, or is alloyed to improve the wear resistance. In the wrought form, copper-tin alloys are tough, hard and highly fatigue-resistant, particularly in the cold-worked condition. Some very fine precipitation may occur during cold working and this would explain the very high strengths achieved in wrought material [Ref. 2].

Copper-tin alloys tend to be hot-short and to crack during fusion welding. Tin oxidizes when exposed to the atmosphere, and this oxide may reduce weld strength if trapped within the weld metal [Ref. 2].

The characteristics and usage of wrought copper-tin alloys, which are often used for welded equipment, are shown in **Tables 1.5** and **1.6**.

Table 1.5 *Characteristics and usage of wrought copper-tin alloys (Phosphor bronze)* (1)

Alloy desig.	Content of main elements (%)			Features	Industrial applications
	Cu	Sn	P		
C5111	(2)	3.5-4.5	0.03-0.35	▪ Good malleability, fatigue resistance, and corrosion resistance	▪ Springs for electronic/electric equipment ▪ Connectors ▪ Bellows ▪ Sliding bearings, bushes ▪ Diaphragms
C5102	(2)	4.5-5.5	0.03-0.35		
C5191	(2)	5.5-7.0	0.03-0.35		
C5212	(2)	7.0-9.0	0.03-0.35		

Note (1) Excerpted from JIS H 3110:2012 (Phosphor Bronze and Nickel Silver Sheets, Plates and Strips).
(2) Cu+Sn+P: 99.5 min.

Table 1.6 *Tensile properties of wrought copper-tin alloys (Phosphor bronze)* (1)

Alloy desig.	Temper designation and description		Wall thickness (mm)	Tensile strength (N/mm^2)	Elongation (%)
C5111	O	Annealed	0.10-5.0	295 min	38 min
	½H	Work hardened only	0.10-5.0	410-510	12 min
C5102	O	Annealed	0.10-5.0	305 min	40 min
	½H	Work hardened only	0.10-5.0	470-570	15 min
C5191	O	Annealed	0.10-5.0	315 min	42 min
	½H	Work hardened only	0.10-5.0	490-610	20 min
C5212	O	Annealed	0.10-5.0	345 min	45 min
	½H	Work hardened only	0.10-5.0	490-610	30 min

Note (1) Excerpted from JIS H 3110:2012 (Phosphor Bronze and Nickel Silver Sheets, Plates and Strips).

Cast copper-tin alloys can sustain higher tin contents than the wrought tin bronzes, which are limited to about 10%Sn for reasons of workability. Many cast alloys contain less tin than this, along with additions of zinc, nickel, and lead, but alloys with tin contents up to 20% are available. One of the major applications for cast tin bronzes, leaded and unleaded, is as bearing materials [Ref. 8].

1.2.3 Copper-aluminum alloys (Aluminum bronze)

Copper-aluminum alloys called aluminum bronzes, containing 3 to 15 percent aluminum, with or without varying amounts of iron, nickel, manganese, and silicon. There are two types of aluminum bronzes, based on metallurgical structure and response to heat treatment. The first type includes the alpha or single-phase alloys, containing low aluminum of approximately 7 percent or lower, as shown in **Figure 1.1**, which cannot be hardened by heat treatment. The second type, containing from 9.5-11.5 percent aluminum, includes the two-phase, alpha-beta alloys. These two-phase alloys can be strengthened by heat treatment to produce a martensitic structure and tempered to obtain desired mechanical properties. Hardening is accomplished by quenching in water or oil from 843 to 1010°C, followed by tempering at 427 to 649°C [Ref. 2]. The specific heat treatment to be used depends on the composition of the alloy and the desired mechanical properties.

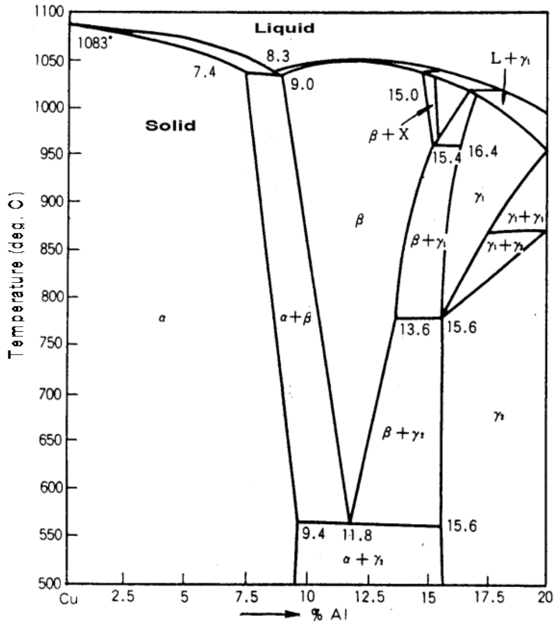


Figure 1.1
An equilibrium phase diagram of Cu-Al alloying system [Ref. 4]

The alpha phase is hot-short; therefore, hot cracking may occur in the heat-affected zone of the weld. In contrast, the beta phase is more ductile at high temperatures, and the $\alpha+\beta$ phase features fine crystal grains, thereby decreasing the hot crack susceptibility. On the other hand, in slow cooling, the beta phase can be susceptible to hot cracking due to the precipitation of very brittle γ_2 phase, although almost no γ_2 phase precipitates in general arc welding because the cooling rate is too high. Additions of nickel, ferrous, and manganese in aluminum bronzes can prevent the γ_2 phase precipitation and, in turn, forms the $\alpha+\kappa$ phase that has higher toughness (κ phase: FeAl, NiAl [Ref. 9]). The two-phase alloys have higher tensile strengths compared to most other copper alloys.

The characteristics and usage of wrought copper-aluminum alloys, which arc often used for welded equipment, are shown in **Tables 1.7** and **1.8**.

Table 1.7 *Characteristics and usage of wrought copper-aluminum alloys (Aluminum bronze)* (1)

Alloy desig.	**Content of main elements (%)** (2)					**Features**	**Industrial applications**
	Cu	**Al**	**Fe**	**Ni**	**Mn**		
C6161	83.0-90.0	7.0-10.0	2.0-4.0	0.5-2.0	0.50-2.0	▪ High strength ▪ Good corrosion resistance particularly to seawater ▪ Good wear resistance	▪ Machine parts ▪ Chemical equipment ▪ Ship parts
C6280	78.0-85.0	8.0-11.0	1.5-3.5	4.0-7.0	0.50-2.0		

Note (1) Excerpted from JIS H 3100:2012 (Copper and Copper Alloy Sheets, Plates and Strips).
(2) Cu+Al+Fe+Ni+Mn: 99.5 min.

Table 1.8 *Tensile properties of wrought copper-aluminum alloys (Aluminum bronze)* (1)

Alloy desig.	**Temper designation and description**		**Wall thickness** (mm)	**Tensile strength** (N/mm^2)	**Elongation** (%)
C6161	F	As fabricated	0.80-50	490 min	30 min
			50<, 125 max	450 min	35 min
	O	Annealed	0.80-50	490 min	35 min
			50<, 125 max	450 min	35 min
	½H	Work hardened only	0.80-50	635 min	25 min
			50<, 125 max	590 min	20 min
C6280	F	As fabricated	0.80-50	620 min	10 min
			50<, 90 max	590 min	10 min
			90<, 125 max	550 min	10 min

Note (1) Excerpted from JIS H 3100:2012 (Copper and Copper Alloy Sheets, Plates and Strips).

The two-phase aluminum bronzes are produced cast in addition to the wrought products. The characteristics of the cast products are similar to those of the wrought products. Two-phase, aluminum bronze castings are often used for marine propellers (**Photo 1.3**) because of excellent characteristics of higher strength, better resistance to corrosion and cavitation erosion in the seawater. A typical aluminum bronze casting (JIS CAC703) for the propellers contains nominally 81.5%Cu, 9.5%Al, 4.5%Fe, and 0.8%Mn and has tensile strengths of 590 N/mm^2 or higher and elongation of 15% or higher. Such propellers sometimes are subjected to GTAW/GMAW to repair the damages caused by accidents during voyages. For details of this specific casting, refer to JIS H 5120:2009 (Copper and Copper Alloy Castings)

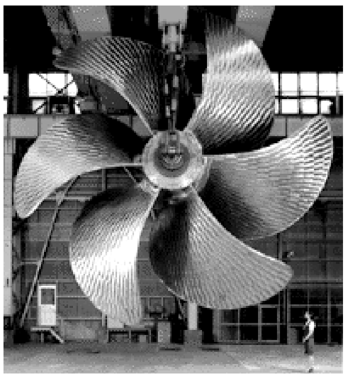


Photo 1.3 *Marine propellers are typical applications for copper alloy castings (Photo courtesy of Nakashima Propeller Co., Ltd., Japan)*

1.2.4 Copper-silicon alloys (Silicon bronze)

Copper-silicon alloys, known as silicon bronze, offer high strength and excellent corrosion resistance, and have good weldability, but are hot-short at elevated temperatures. The characteristics and usage of wrought copper-silicon alloys, which are used for welded equipment, are shown in **Tables 1.9** and **1.10**. **Everdurs 651** and **655** are trade names known as silicon bronzes.

Table 1.9 *Characteristics and usage of wrought copper-silicon alloys (Silicon bronze)*

UNS alloy No.(2)	Content of main elements (%) (1)			Features	Industrial applications
	Cu	Si	Mn		
C65100	Rem.	0.8-2.0	-	▪ High strength and toughness ▪ Good corrosion resistance	▪ Aircraft hydraulic pressure lines ▪ Marine and industrial hardware and fasteners ▪ Heat exchanger tubes
C65500	Rem.	2.8-3.8	0.50-1.3	▪ Higher strength and toughness ▪ Good corrosion resistance	▪ Chemical process equipment ▪ Marine propeller shafts

Note: (1) Excerpted from ASTM B98:2013 (Copper-Silicon Alloy Rod, Bar and Shapes)
(2) The Unified Numbering System per SAE-ASTM: C1xxxx to C7xxxx are wrought copper and copper alloys. C8xxxx to C9xxxx are cast copper and copper alloys. UNS numbers are replacing traditional common and trade names.

Table 1.10 *Tensile properties of wrought copper-silicon alloys (Silicon bronze)* (1)

UNS alloy No.	Temper designation and description		Wall thickness (mm)	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
C65100	O60	Soft anneal	All sizes	275 min	85 min	30 min
	H02	Half-hard	12 max	380 min	140 min	11 min
C65500	O60	Soft anneal	All sizes	360 min	105 min	35 min
	H01	Quarter-hard	All sizes	380 min	165 min	25 min
	H02	Half-hard	50 max	485 min	260 min	20 min

Note (1) Excerpted from ASTM B98:2013 (Copper-Silicon Alloy Rod, Bar and Shapes)

The silicon bronze casting C87300 (nominally 95%Cu, 4%Si, 1%Mn) is used for bearings, bells, pump and valve components, and statuary and art castings. Copper silicon alloy castings also include silicon brasses such as UNS C87600 (nominally 90%Cu, 4%Si, 5.5%Zn), C87610 (nominally 92%Cu, 4%Si, 4%Zn), C87500 (nominally 82%Cu, 4%Si, 14%Zn) and C87800 (nominally 82%Cu, 4%Si, 14%Zn), which find applications similar to those of UNS C87300 [Ref. 8].

1.2.5 copper-nickel alloys (Cupronickel)

Copper and nickel can be completely solid solution in all proportions. Copper-nickel alloys have moderately high tensile strengths that increase with nickel content. Copper-nickel alloys most commonly used in welded fabrication contain 10 and 30 percent nickel and minor alloying elements such as iron, manganese, or zinc, which are known as 90/10 and 70/30 cupronickel. These alloys are ductile, relatively tough, and well resistible to the seawater corrosion. Because of these advantages, cupronickel alloys are used for seawater distillation equipment (**Figure 1.2** and **Photo 1.4**). However, cupronickel alloys are hot-short, as shown in **Figure 1.3,** which can cause cracking in the heat-affected zone; therefore arc welding should be conducted with proper welding procedures.

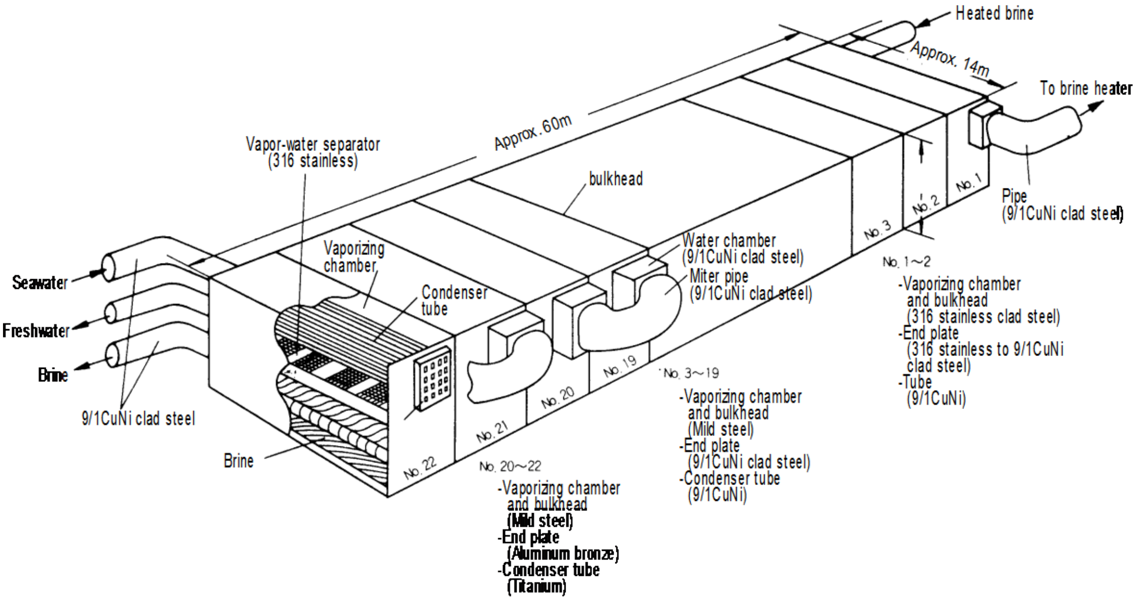


Figure 1.2 *A simplified schematic of multistage-flash unit for desalination of seawater by distillation [Ref. 6]*

Photo 1.4 *A seawater desalination plant*
(Photo courtesy of Hitachizosen Co., Ltd., Japan)

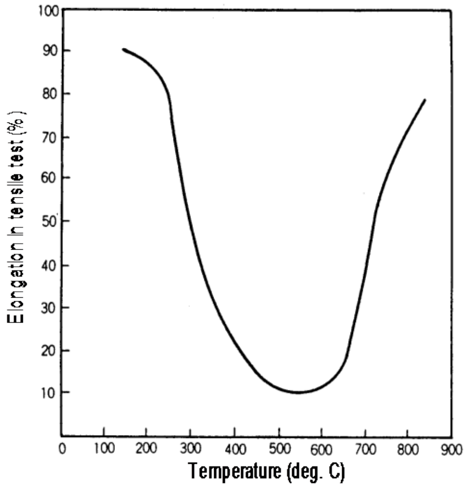


***Figure 1.3** 90/10 cupronickel decreases its ductility at high particular temperatures causing hot short [Ref. 4]*

The characteristics and usage of wrought copper-nickel alloys, which are often used for welded equipment, are shown in **Tables 1.11** and **1.12**.

***Table 1.11** Characteristics and usage of wrought copper-nickel alloys (Cupronickel)* (1)

Alloy desig.	**Content of main elements** (%) (2)				**Features and common name**	**Industrial applications**
	Cu	**Ni**	**Mn**	**Fe**		
C7060	Rem.	9.0-11.0	0.20-1.0	1.0-1.8	▪ Good corrosion resistance particularly to seawater ▪ Suitable for moderately high temperature applications ▪ "**90/10 cupronickel**" for C7060 "**70/30 cupronickel**" for C7150	▪ Heat exchanger end plates and tubes ▪ Condenser tubes (See **Fig. 1.4** below)
C7150	Rem.	29.0-33.0	0.20-1.0	0.40-1.0		

Note (1) Excerpted from JIS H 3100:2012 (Copper and Copper Alloy Sheets, Plates and Strips).
(2) Cu+Ni+Mn+Fe: 99.5 min.

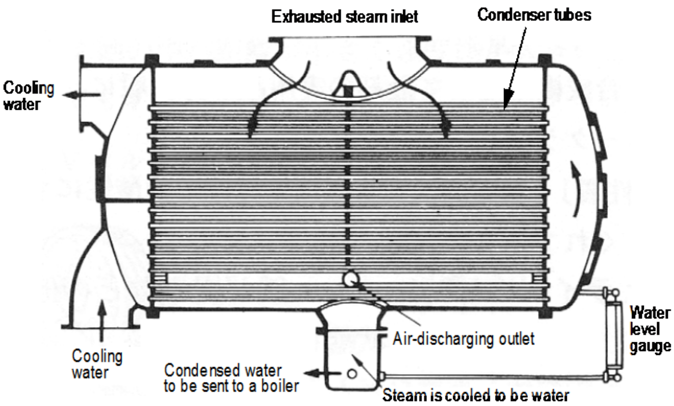


***Figure 1.4** A simplified scheme of condenser*
(Source: Pictorial dictionary of machinery, Jitukyo Shuppan, Japan)

Table 1.12 *Tensile properties of wrought copper-nickel alloys (Cupronickel)* (1)

Alloy design.	Temper designation and description		Wall thickness (mm)	Tensile strength (N/mm^2)	Elongation (%)
C7060	F	As fabricated	0.5-50	275 min	30 min
C7150	F	As fabricated	0.5-50	345 min	35 min

Note (1) Excerpted from JIS H 3100:2012 (Copper and Copper Alloy Sheets, Plates and Strips).

1.3 Physical properties of typical wrought copper and copper alloys

Physical properties of copper and its alloys, important for welding, include melting temperature range, coefficient of thermal expansion, electrical resistivity, and thermal conductivity. The physical properties of typical copper and its alloys that are widely used for welded equipment are listed in **Table 1.13** in comparison with iron, nickel and Monel (nickel-copper alloy). The table data show that when alloying elements are added to copper, electrical resistivity increases (thus electrical conductivity decreases), and thermal conductivity decreases. Specifically, melting range and thermal conductivity governs the weldability of a particular metal.

Table 1.13 *Physical properties of copper and some other metals [Ref. 4]*

Common or trade name	JIS Alloy No.	Melting range (°C)	Specific gravity	Coefficient of thermal expansion at 20-300°C ($\times 10^{-6}$/°C)	Electrical resistivity at 20°C (μΩ・cm)	Thermal conductivity at 20°C (Cal/cm・sec・°C)
Copper	C1020	1083	8.95	16.5	1.67	0.941
90/10 brass	C2200	1045-1020	8.80	18.2	3.9	0.45
70/30 brass	C2600	955-915	8.53	19.9	6.2	0.29
Naval brass	C4621	900-885	8.40	21.2	6.6	0.28
Aluminum bronze	C6161	1045-1037	8.78	17.9	11.3	0.17
Phosphor bronze	C5101	1050-950	8.86	17.8	9.6	0.19
90/10 cupronickel	C7060	1145-1105	8.94	16.7	18.5	0.10
70/30 cupronickel	C7150	1240-1170	8.94	16.2	37.0	0.07
Iron	-	1536	7.87	13	13.0	0.142
Nickel	-	1455	8.89	13.3	9.5	0.145
Monel	-	1350-1300	8.83	13.8	51.0	0.052

2. Filler metals and welding procedures

Copper and its alloys listed in the previous tables are arc weldable to a good or fair degree; however, the inherent physical and metallurgical characteristics of such metals and suitable filler metals should be sufficiently understood in order to obtain successful welding results.

2.1 Types and characteristics of filler metals

Covered electrodes, bare electrode wires and rods are available for welding copper and its alloys to themselves and to other metals. These filler metals are included in JIS Z 3231:2007, *Copper and Copper Alloy Covered Electrodes*; JIS Z 3341:2007, *Copper and Copper Alloy Rods and Wires for Inert Gas Shielded Arc Welding*; AWS A5.6:2008, *Copper and Copper-Alloy Electrodes for Shielded Metal Arc Welding*, and AWS A5.7:2007, *Copper and Copper Alloy Bare Welding Rods and Electrodes*. **Table 2.1** shows nominal chemical compositions of and mechanical property requirements for covered electrodes for SMAW, as per AWS A5.6. **Table 2.2** shows nominal chemical compositions of bare electrode wires and rods for GMAW and GTAW, in accordance with AWS A5.7. **Table 2.3** shows features and typical applications of copper and copper alloy filler metals.

Table 2.1 *Weld metal chemistry and tensile properties of covered electrodes for copper and its alloys* (1)

AWS class.	Common name	Content of main elements (%) (2)									TS, min (ksi)	El, min (%)
		Cu	Sn	Mn	Fe	Si	Ni	P	Al	Ti		
ECu	Copper	Rem.	-	0.10	0.20	0.10	-	-	0.10	-	25	20
ECuSi	Silicon bronze	Rem.	1.5	1.5	0.50	2.4-4.0	-	-	0.01	-	50	20
ECuSn-A	Phosphor bronze	Rem.	4.0-6.0	-	0.25	-	-	0.05-0.35	0.01	-	35	20
ECuSn-C	Phosphor bronze	Rem.	7.0-9.0	-	0.25	-	-	0.05-0.35	0.01	-	40	20
ECuNi	Copper nickel	Rem.	-	1.00-2.50	0.40-0.75	0.50	19.0-33.0	0.020		0.50	50	20
ECuAl-A2	Aluminum bronze	Rem.	-	-	0.50-5.0	1.5	-	-	6.5-9.5	-	60	20
ECuAl-B	Aluminum bronze	Rem.	-	-	2.5-5.0	1.5	-	-	9.5-11.5	-	65	20
ECuNiAl	Nickel aluminum bronze	Rem.	-	0.50-3.5	3.0-6.0	1.5	4.0-6.0	-	8.0-9.5	-	72	10
ECuMnNiAl	Manganese-nickel aluminum bronze	Rem.	-	11.0-14.0	2.0-4.0	1.5	1.5-3.0	-	6.0-8.5	-	75	15

Note: (1) As per AWS A5.6:2008. (2) Single values are maximum (Pb:0.01 for ECu, 0.02 for the others)

Table 2.2 *Chemistry of bare wires and rods for copper and its alloys* (1)

AWS class.	Common name	Content of main elements (%) (2)									
		Cu	Sn	Mn	Fe	Si	Ni	P	Al	Ti	Zn
ERCu	Copper	≥ 98.0	1.0	0.50	-	0.50	-	0.15	0.01	-	-
ERCuSi-A	Silicon bronze	Rem.	1.0	1.5	0.5	2.8-4.0	-	-	0.01	-	1.0
ERCuSn-A	Phosphor bronze	Rem.	4.0-6.0	-	-	-	-	0.10-0.35	0.01	-	-
ERCuSn-C	Phosphor bronze	Rem.	7.0-9.0	-	0.10	-	-	0.10-0.35	0.01	-	0.20
ERCuNi	Copper nickel	Rem.	-	1.0	0.40-0.75	0.25	29.0-32.0	0.02	-	0.20-0.50	-
ERCuAl-A1	Aluminum bronze	Rem.	-	0.50	-	0.10	-	-	6.0-8.5	-	0.20
ERCuAl-A2	Aluminum bronze	Rem.	-	-	1.5	0.10	-	-	8.5-11.0	-	0.02
ERCuAl-A3	Aluminum bronze	Rem.	-	-	2.0-4.5	0.10	-	-	10.0-11.5	-	0.10
ERCuNiAl	Nickel aluminum bronze	Rem.	-	0.60-2.50	3.0-5.0	0.10	4.0-5.5	-	8.50-9.50	-	0.10
ERCuMnNiAl	Manganese-nickel aluminum bronze	Rem.	-	11.0-14.0	2.0-4.0	0.10	1.5-3.0	-	7.0-8.5	-	0.15

Note: (1) As per AWS A5.7:2007. (2) Single values are maximum (Pb:0.02 for all the classes)

***Table 2.3** Features and typical applications of filler metals*

Common name	AWS class.	Features	Typical applications
Copper	ECu ERCu	▪ Deoxidized with P and Si ▪ Good corrosion resistance but inferior electrical conductivity compared with pure copper	▪ Welding of deoxidized copper and electrolytic tough pitch copper
Silicon bronze	ECuSi ERCuSi-A	▪ Good molten metal fusion due to low thermal conductivity and thus use a lower preheat temperature ▪ Good resistance to chemicals and seawater ▪ Known as "**Everdur**" (Cu-Si-Mn)	▪ Welding of silicon bronze, copper, and brass ▪ Claddings resistible to chemicals and seawater
Phosphor bronze	ECuSn-A ECuSn-C ERCuSn-A	▪ High-phosphorous filler metals precipitate a hard chemical compound (Cu_3P) exhibiting good resistance to mechanical wear	▪ Welding of phosphor bronze, copper, and brass ▪ Overlaying on bearings
Aluminum bronze	ECuAl-A2 ECuAl-B ERCuAl-A1 ERCuAl-A2 ERCuAl-A3	▪ Good resistance to seawater and chemicals ▪ Good resistance to mechanical wear	▪ Welding of aluminum bronze (ERCuAl-A1: for surfacing only) ▪ Repair welding of chemical machinery, cylinders, and marine propellers
Nickel aluminum bronze	ECuNiAl ERCuNiAl	▪ High resistance to corrosion, erosion, and cavitation in salt and brackish water	▪ Welding of wrought or cast nickel-aluminum bronzes
Manganese-nickel aluminum bronze	ECuMnNiAl ERCuMnNiAl	▪ Good resistance to corrosion, erosion, and cavitation	▪ Welding of wrought or cast manganese-nickel-aluminum bronzes
Copper nickel	ECuNi ERCuNi	▪ Excellent resistance to seawater ▪ No preheat is used because of low heat conductivity and hot-shortness	▪ Welding of wrought or cast copper-nickel alloys ▪ Claddings resistible to seawater

Note: This table contents are composed of the information taken separately from the reference documents [Refs.2 and 4] and the Annex (Informative) of the AWS standards of A5.6:2008 and A5.7:2007 in order to study sweepingly the nature of the filler metals grouped by common name; hence, the contents may not necessarily be precise to the individual AWS class filler metal.

2.2 Weldability and welding procedures

Most copper and copper alloys are arc weldable but at a lower degree than in steel. The difficulties in arc welding copper and its alloys can be attributed to the following reasons. First, high thermal conductivity tends to cause insufficient fusion. Second, high thermal expansion is apt to cause distortion and cracking. Third, low melting point can cause slag inclusions in SMAW because the melting temperature of the slag can be higher than that of the weld metal. Forth, the coarse crystal grains of weld metal degrade the mechanical properties. Fifth, added elements such as Pb, Sn, Bi, and P can cause cracking and embrittlement, and Zn vapors can cause insufficient fusion.

2.2.1 Copper

Copper features extremely high heat conductivity (eight times that of steel); therefore, the heat of arc can rapidly be spread from the weld through the base metal. Consequently, sufficient penetration can hardly be obtained and, in turn, insufficient fusion may occur.

The arc welding of strictly-restrained thick work of oxygen-free copper and deoxidized copper tends to cause hot cracking. Blowholes may also occur in copper weld metals, caused by hydrogen dissolved during welding. Electrolytic tough pitch copper that contains a high amount of oxygen has inferior weldability than low-oxygen copper metals because it is more likely to cause hot cracking and blowholes than low-oxygen coppers.

GTAW, GMAW and SMAW can be applied by using the matching filler metals of **ERCu** and **ECu**, respectively. Copper alloy type filler metals such as **ERCuSi-A**, **ERCuSn-A**, **ECuSi**, **ECuSn-A** and **ECuSn-C** are also used where good electrical or thermal conductivity is not a major requirement. Such copper alloy filler metals, unlike the copper type, possess lower heat conductivity and therefore better fusion can be obtained with a lower preheating temperature. However, the electrical resistivity of the silicon- and phosphor-bronze weld metals is higher than that of the copper base metal. GTAW and GMAW can establish higher heat concentration over SMAW, thereby obtaining better fusion and penetration.

In GTAW and GMAW, argon gas is generally used for shielding. The use of helium gas can decrease the minimum preheating temperature. In general, GTAW is suitable for thin metals up to 6 mm, while GMAW is used for thicker metals over 6 mm. The high thermal conductivity of copper requires preheating to achieve complete fusion and adequate joint penetration. Preheat requirements depend on material thickness, the welding process, and the shielding gas as shown in **Figure 2.1**.

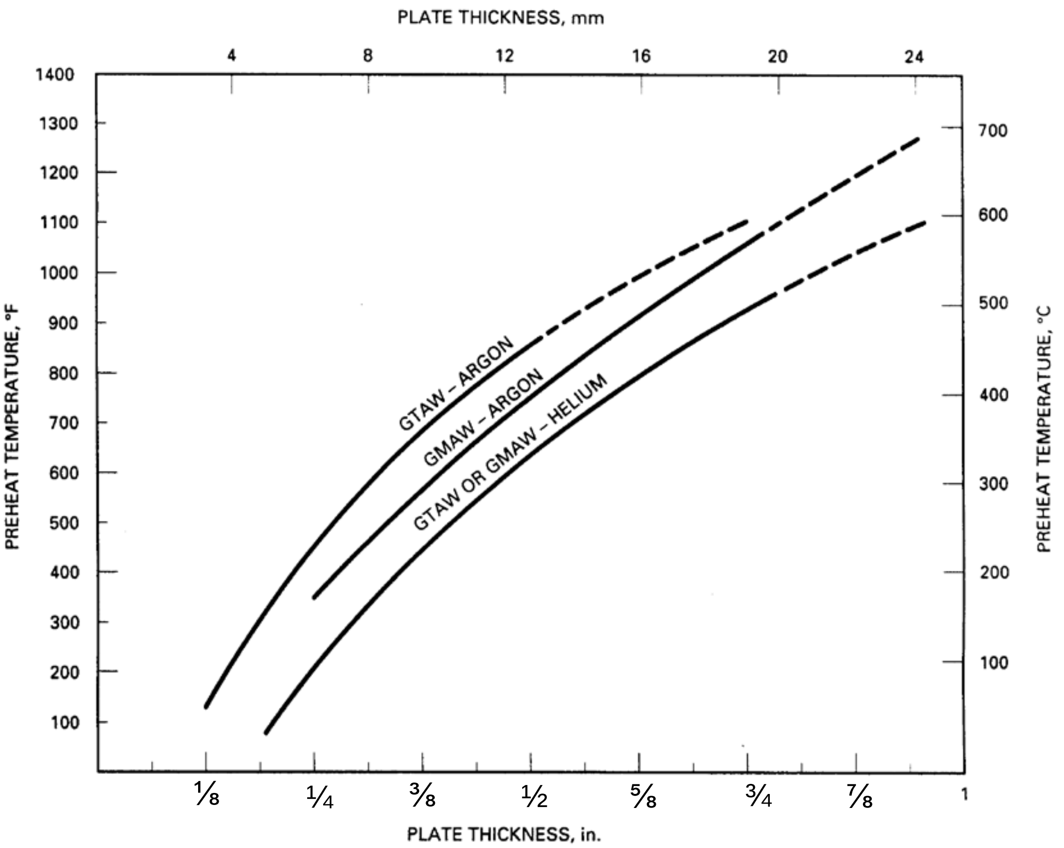


***Figure 2.1** Effects of process, shielding gas, and metal thickness on preheat requirements for welding copper [Ref. 2]*

Figure 2.2 illustrates the effects of preheat temperature on penetration in copper with argon and helium shielding gases. Helium produces a more fluid weld pool that is cleaner, and the risk of oxide entrapment is considerably reduced. Mixtures of argon and helium result in intermediate welding characteristics. A mixture of 75%He-25%Ar produces a good balance between the good penetration of helium and the easier arc starting and greater arc stability of argon.

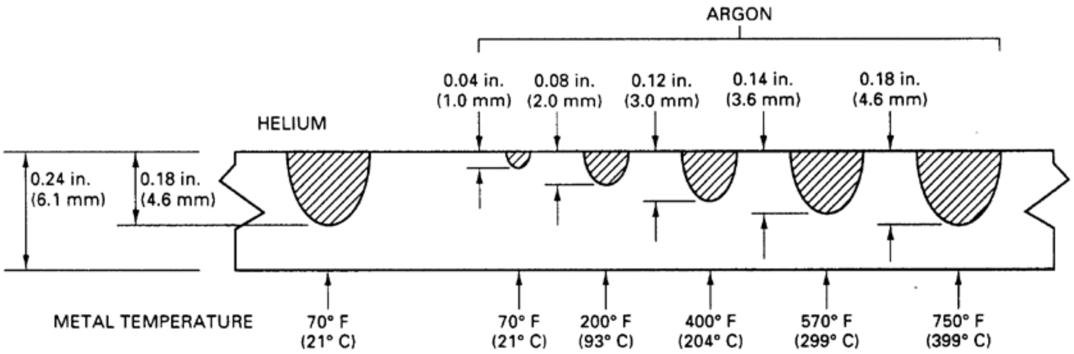


***Figure 2.2** Effects of shielding gas and preheat temperature on weld bead penetration in copper when gas tungsten arc welded with 300A DC at a travel speed of 3.4 mm/sec) [Ref. 2]*

2.2.2 Copper-zinc alloys (Brass)

Since zinc vaporizes from molten brass, zinc fuming is the major problem when welding brasses and is worse for the high-zinc brasses. The zinc vaporization degrades workability and weldability, causing incomplete fusion and blowholes. From these reasons, low zinc brasses have good weldability, and high-zinc brasses only fair weldability.

Recommended welding processes are GTAW and GMAW due to better performance over SMAW. To minimize zinc fuming, GTAW is better than GMAW due to shallower penetration. A compositionally matching filler metal is not available because of the poor workability resulted from the zinc vaporization. Phosphorous bronze filler metals, **ERCuSn-A**, **ECuSn-A** and **ECuSn-C**, provide a good color match with some brasses. Silicon bronze filler metals, **ERCuSi-A** and **ECuSi**, feature lower thermal conductivity and thus can use lower preheating temperatures, and have better fluidity. Aluminum bronze filler metals, **ERCuAl-A2** and **ECuAl-A2**, provide good joint strength for high-zinc brasses. In GTAW and GMAW, argon shielding is normally used. The weldability of brasses with SMAW is not as good as with GTAW and GMAW, and relatively large groove angles are needed for good joint penetration and avoidance of slag entrapment.

Proper preheating temperature depends on the welding process, plate thickness, and the zinc content of the base metal (the preheat temperature can be lowered for the high-zinc brasses), which range from approximately 100 to 350°C. The arc should be directed on the molten weld pool to minimize penetration and thus zinc fuming.

2.2.3 Copper-tin alloys (Phosphor bronze)

Phosphor bronzes have rather wide freezing ranges, solidifying with large, weak dendritic grain structures. Therefore, welding procedures are designed to prevent the tendency of the weld to crack. Hot peening of each layer of multiple-pass welds will reduce welding stresses and the likelihood of cracking.

Recommended welding processes are GMAW for joining large fabrications and thick sections with **ERCuSn-A** filler metal and argon shielding, GTAW for joining sheet metals with **ERCuSn-A** and argon or helium shielding, and SMAW with **ECuSn-A** or **ECuSn-C** covered electrode. Filler metals should be deposited as stringer beads to obtain the best mechanical properties.

Preheating to 150-250°C and maintaining this interpass temperature improve metal fluidity for better usability, but the maximum interpass temperature should not exceed 250°C to avoid hot cracking.

2.2.4 Copper-aluminum alloys (Aluminum bronze)

Single-phase (alpha phase) aluminum bronzes containing 7 percent or lower aluminum are hot-short and, therefore, weldments in these alloys may crack in the HAZ. Two-phase (alpha-beta phase) copper-aluminum alloys containing more than 8 percent aluminum are better weldable because of fine crystal grains of lower crack susceptibility.

In welding copper-aluminum alloys, aluminum oxides (Al_2O_3) tend to cover the joint surfaces and molten weld metal, thereby causing insufficient fusion and slag inclusions. GMAW with DCEP that provides oxide-cleaning action is best suited for welding aluminum bronzes, in which argon shielding is used in most applications. In GTAW, AC current with argon shielding is usually used due to possible oxide-cleaning action. In SMAW, use of a short arc length and stringer beads are recommended, and each bead must be thoroughly cleaned of slag before the next bead is applied to prevent slag inclusions. SMAW, however, should only be used where GMAW or GTAW is inconvenient. Filler metals suitable for aluminum bronzes are **ERCuAl-A1, ERCuAl-A2, ERCuAl-A3, ECuAl-A2,** and **ECuAl-B** for GMAW, GTAW and SMAW, respectively.

Preheat and interpass temperature depends on the thickness of the work and the welding process, which ranges from 100-250°C. Where the thickness of the work is less than 20 mm, preheat may be unnecessary.

2.2.5 Copper-silicon alloys (Silicon bronze)

Silicon bronzes are comparatively better weldable due to their low thermal conductivity (similar to that of steel) and thus low heat loss to the surrounding base metal, good deoxidation of the weld metal by the silicon, and good molten metal fluidity. On the other hand, silicon bronzes are hot short.

GTAW, GMAW and SMAW can be used for welding silicon bronzes by using **ERCuSi-A** and **ECuSi** filler metals, respectively. **ERCuAl-A2** and **ECuAl-A2** may also be used

Preheat is unnecessary. Right after welding finished, apply hot peening for each weld pass to refine the crystal structure, thereby improving mechanical properties. The weldment must be rapidly cooled, interpass temperatures should be 70°C or lower, weaving beads should be minimized, in order to avoid excessive heating, thereby preventing the likelihood of hot cracking.

2.2.6 Copper-nickel alloys (Cupronickel)

Copper-nickel alloys feature low thermal conductivity as steel; thus, their weldability is comparatively good. On the other hand, they are hot-short as shown in Figure 1.3. The hot-shortness can cause cracking in the heat-affected zone of the weld; therefore, heat input should be minimized.

In addition, welding copper-nickel alloys tend to cause blowholes. To prevent blowholes, the Ti-bearing filler metals of **ERCuNi** for GTAW and GMAW and **ECuNi** for SMAW are commonly used for welding both 90/10 and 70/30 cupronickel alloys. The titanium deoxidizes the weld metal to avoid porosity. Autogenous welds or welds without sufficient filler metal addition, therefore, can contain porosity because the base metal contains no titanium. Where a color match is required, a compositionally-matched filler metal should be used. As to compositionally matching filler metals for 90/10 cupronickel, **JIS YCuNi-1** (nominally 90%Cu, 10%Ni) for GTAW and GMAW and **JIS DCuNi-1** (nominally 90%Cu, 10%Ni) for SMAW are available.

Preheat is unnecessary. Interpass temperature should be as low as 100°C or lower and a stringer-bead technique with a minimized arc length is recommended to overcome the hot-shortness and prevent the likelihood of porosity.

2.2.7 Dissimilar metal combinations

Copper and copper alloy welding joints often consist of dissimilar metals in various constructions such as oil refinery, chemical synthetic and power generation equipment from the standpoint of design requirements including strength, corrosion resistance, and material cost. Dissimilar metal welding is involved in overlaying of copper or copper alloy weld metals on carbon steel substrates, joining copper or copper alloy and either carbon steel, stainless steel, or nickel-based alloy, and joining clad steels. In such dissimilar metal welding, specific considerations in terms of metallurgy are necessary to get successful results for specific dissimilar metal combinations. The following paragraphs discuss such metallurgy considerations for three categories of base metals to be welded with copper or copper alloys: carbon steel, stainless steel and nickel-based alloy, and clad steel.

(1) Carbon steel

The melting point of copper and copper alloys ranges from approximately 900 to 1200°C depending on the type of copper and copper alloy, while that of carbon steel is approximately 1500°C. Such a considerable difference in melting point can cause very little penetration in the carbon steel base metal when welding with a copper alloy filler metal.

Part of the molten copper or copper alloy weld metal can infiltrate into the austenite grain boundaries of the heat-affected zone of the carbon steel base metal when heated at high temperatures, which is known as "copper infiltration." **Photo 2.1** shows a typical copper infiltration occurred at the interface between carbon steel and 90/10 cupronickel weld metal. The copper infiltration may cause microcracks in the side bend testing of the weld at room temperature. Where the copper infiltration must be prevented, a buttering technique may be used to deposit a buffer layer on the carbon steel base metal by using a nickel filler metal (**ENi-1**, **ERNi-1**) or nickel-based alloy filler metal (**ENiCu-7**, **ERNiCu-7**) known as a Monel (nominally 65%Ni, 35%Cu); subsequently, copper or copper alloy weld metal is deposited. However, such nickel and Monel filler metals contain small amounts of titanium to prevent porosity in the weld metal. This titanium may cause microcracks in the copper or copper alloy filling passes. Therefore, the welding procedure should thoroughly be examined in advance.

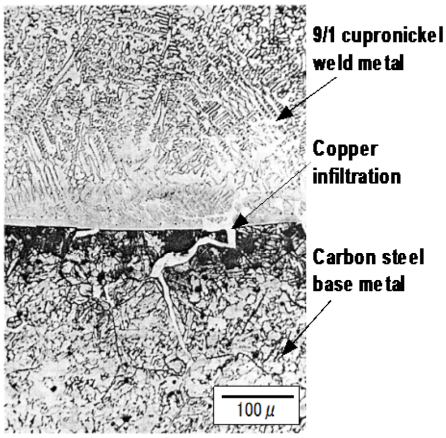


***Photo 2.1** The typical copper infiltration occurred at the interface between carbon steel base metal and 90/10 cupronickel weld metal [Ref. 5]*

Copper and iron mix completely in the liquid state but have limited mutual solubility in the solid state. Therefore, as the temperature decreases the copper-iron alloy precipitates γ-Fe and, at room temperature, the Cu-Fe alloy becomes two-phase (α-Cu and α-Fe) solid solution as shown in **Photo 2.2**. The carbon contained in the Cu-Fe alloy condenses in the iron because carbon and copper cannot mix as a solid solution, and thereby the precipitated iron becomes brittle, high-carbon compounds known as "free iron" and "hard spot." Consequently, the corrosion resistance and crack resistibility of the weld metal become inferior. In order to improve this problem, the following procedures are often used with copper or copper alloy filler metals.

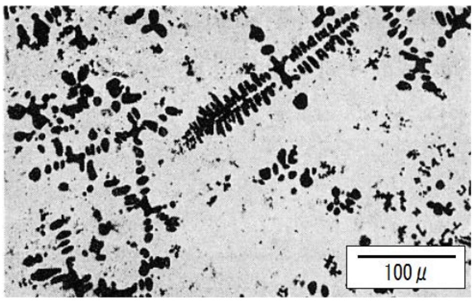


***Photo 2.2** Microstructure of a 10%Fe-Cu alloy (Bright area: Cu; Dark area: Fe) [Ref. 1]*

a) Minimize the dilution from the carbon steel base metal by using a buttering technique with low welding currents. As to welding processes, GTAW, SMAW and pulsed GMAW are recommended.

b) Use an appropriate number of multiple layers for overlaying the carbon steel substrate to eliminate the detrimental effect of iron. **Figure 2.3** shows that two or three layers are needed to eliminate the effect of dilution in SMAW.

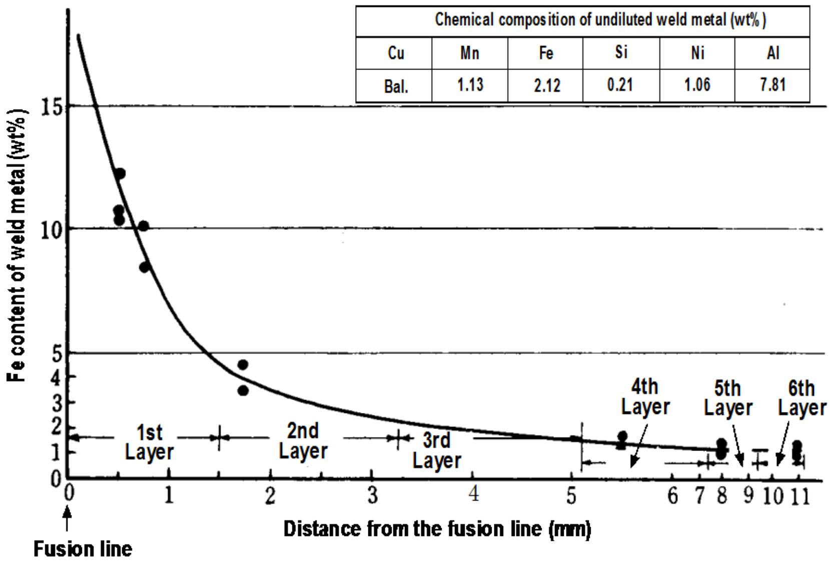


Figure 2.3 *Transition of the Fe content of the SMAW aluminum bronze weld metal (JIS DCuAlNi) deposited on a carbon steel base metal, as a function of the distance from the fusion line [Ref. 1]*

(2) Stainless steel and nickel-based alloy

In addition to the problems of insufficient fusion and copper infiltration like the case of carbon steel, the copper or copper alloy weld metal increases chromium content due to the dilution from the base metal of stainless steel or nickel-based alloy (e.g. Inconel containing nominally 76%Ni, 16%Cr, and 8%Fe), thereby increasing its susceptibility to cracking. To overcome this problem, buttering the base metal with a nickel (**ENi-1**, **ERNi-1**) or nickel-based alloy filler metal (**ENiCu-7**, **ERNiCu-7**) is generally used prior to the filling pass welding with a copper or copper alloy filler metal.

In contrast, nickel-based filler metals may be used with the specific buttering technique as shown in **Figure 2.4**. Significant differences in melting temperature ranges of ENiCrFe-2 weld metal (Approx. 1340-1430°C) and 90/10 cupronickel base metal (1145-1105°C) can result in liquation cracking of the base metal with the lower melting temperature in the following mechanism.

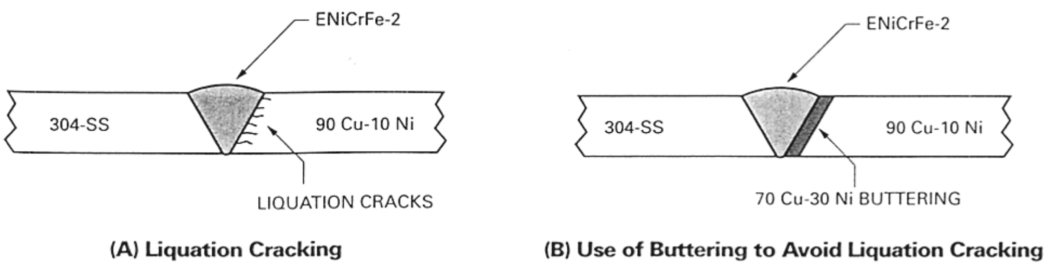
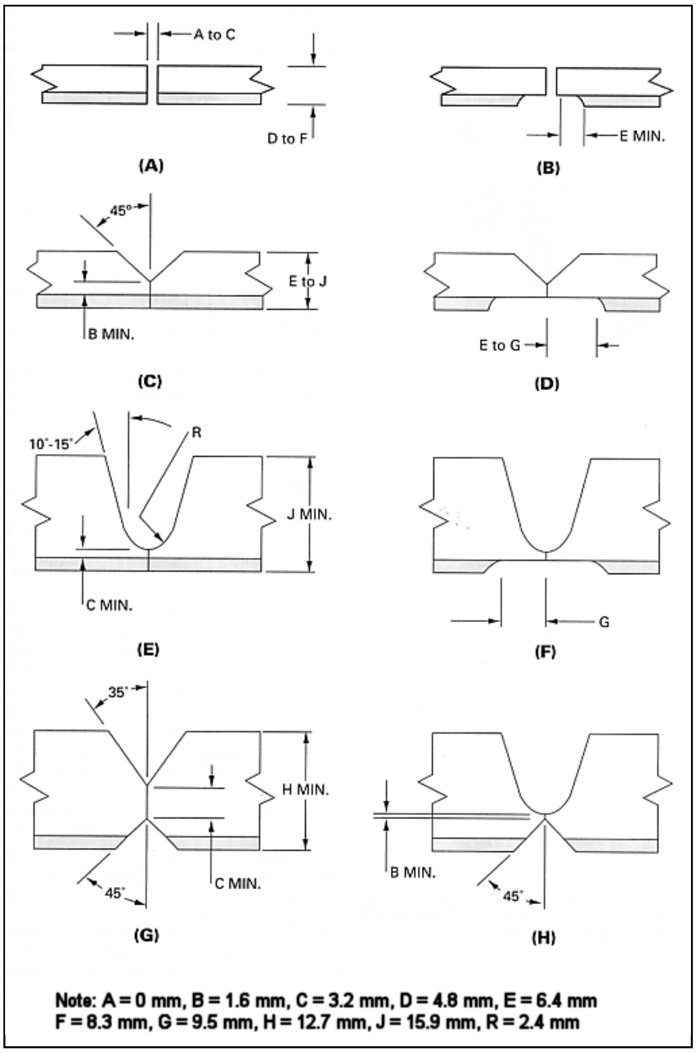


Figure 2.4 *Liquation cracking may be avoided by buttering with an intermediate melting temperature weld metal [Ref. 3]*

Solidification and contraction of the weld metal with the higher melting temperature will induce stresses in the 90/10 cupronickel base metal while it is a weak, partially solidified condition. This problem may be solved by depositing one or more layers of 70/30 cupronickel filler metal of intermediate melting temperature (1240-1170°C) range on the face of the lower melting range base metal. The weld is then made between the buttered face and 304-type stainless steel. The buttering layer serves to reduce the effect of the melting temperature differential.

(3) Clad steel

A variety of carbon or low-alloy steel forms can be clad with copper or copper alloy to protect them in harsh environments, usually to provide better corrosion or erosion resistance. Copper or copper alloy clad steels are produced mainly by explosion cladding and roll cladding [Ref. 7]. Because of the benefits of good electric conductivity and corrosion resistance, copper clad (deoxidized copper, and oxygen-free copper) steels are used for electric field linear accelerators, alcohol production tanks, and food processing equipment. Copper alloy clad (90/10 cupronickel, 70/30 cupronickel, aluminum bronze, and naval brass) steels are used for end plates of seawater heat exchangers, equipment for seawater desalination plants, and chemical synthetic equipment, due to excellent resistance to seawater corrosion and erosion.



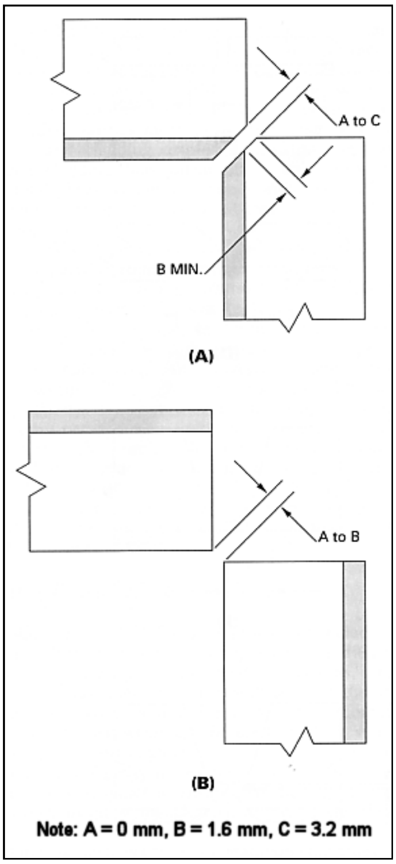


***Figure 2.5** Butt joint designs for welding clad steels from both sides (Left) and corner joint designs for welding clad steels from both sides (Above) [Ref. 3]*

Suitable joint designs for clad steels are shown in **Figure 2.5**. Cladding thickness is generally 10 to 20 percent of the total thickness for most applications [Ref. 3]. As shown in **Figure 2.6**, the base steel is welded first with a steel filler metal. The first pass of carbon steel weld metal must not penetrate into the clad metal because dilution by copper or copper alloy metals can embrittle or crack the steel weld metal. **Table 2.4** shows variations of welding procedures for the 90/10 cupronickel cladding shown in Figure 2.6. The procedures A, B and D using a nickel filler metal (**ERNi-1**) or nickel-copper filler metal (**ERNiCu-7**) for the first layer prevent the free iron precipitation in the subsequent 90/10 cupronickel filling pass weld metal and the copper infiltration into the heat-affected zone of the steel. The procedure C using a 90/10 cupronickel filler metal (**JIS YCuNi-1**) in the first layer causes the free-iron precipitation and copper infiltration but they are so little that there is no detrimental effect in terms of the ductility of the weld in the bending tests.

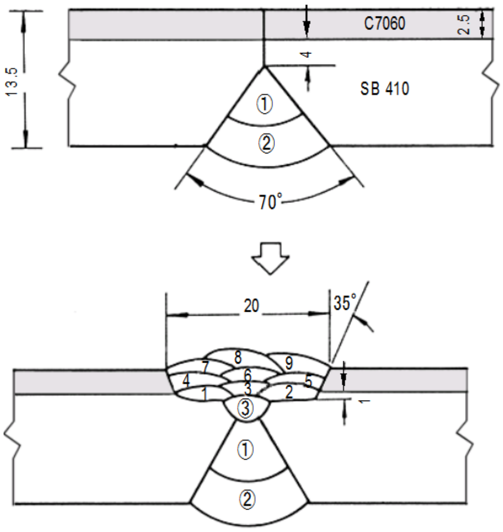


Figure 2.6 *Groove preparations and weld pass sequence in welding of 90/10 cupronickel clad steel [Ref. 6]*

- *①-②: SMAW with an E7016 filler metal*
- *③: SMAW with an E7016 filler metal after gouging the cladded side of the joint*
- *1-3: GTAW with an ERNi-1, ERNiCu-7 or JIS YCuNi-1 filler metal*
- *4-9: GTAW or pulse GMAW with a YCuNi-1 filler metal*

Table 2.4 *Welding procedures for 90/10 cupronickel clad metal [Ref. 6]*

Procedure	1st layer			2nd and 3rd layers			Current (A)	Ar gas flow rate (liter/min)	Interpass temp.(1) (°C)
	Process	Filler metal	Pass No.	Process	Filler metal	Pass No.			
A	GTAW	ERNi-1 (2.4Φ)	3	GTAW	YCuNi-1 (2.4Φ)	3	150-170	10-15	150 max
B	GTAW	ERNiCu-7 (2.4Φ)	3	GTAW	YCuNi-1 (2.4Φ)	3	150-170	10-15	150 max
C	GTAW	YCuNi-1(2) (2.4Φ)	3	GTAW	YCuNi-1 (2.4Φ)	3	150-170	10-15	150 max
D	GTAW	ERNi-1 (2.4Φ)	3	GMAW(3)	YCuNi-1 (1.6Φ)	2	150-200	10-30	150 max

Note: (1) No preheating
(2) JIS YCuNi-1: 90%Cu-10%Ni
(3) 100-c/s pulsed GMAW

In the welding of clad steels cladded with other copper and copper alloys, the welding procedures shown in **Table 2.6** in the following section may be used.

2.3 Summarized welding procedures

The base metal and filler metal combinations recommended for welding compositionally matching base metals are shown in **Table 2.5**, and those for welding dissimilar base metals are shown in **Table 2.6**, in accordance with the metallurgical considerations discussed in Section 2.2.

Table 2.5 *A guide to the correct welding procedures for individual base metals*

Base metal classification			Filler metal classification per AWS (EXXX)/JIS (YXXX)			Preheating temp. (GTAW)
Common name	JIS class	UNS No.	GTAW	GMAW	SMAW	
Oxygen-free copper	C1020	C10200	ERCu ERCuSi-A ERCuSn-A	ERCu ERCuSi-A ERCuSn-A	ECu ECuSi ECuSn-A	300-500°C (200-450)
Deoxidized copper	C1201 C1220	C12000 C12200				
Red brass	C2100 C2200 C2300 C2400	C21000 C22000 C23000 C24000	ERCuSi-A ERCuSn-A ERCuAl-A2	ERCuSi-A ERCuSn-A ERCuAl-A2	ECuSi ECuSn-A ECuAl-A2	250-350°C (150-300)
Brass	C2600 C2680 C2720 C2801	C26000 C26800 C27200 C28000	ERCuSi-A ERCuAl-A2	ERCuSi-A ERCuAl-A2	ECuSi ECuAl-A2	250-350°C (150-300)
Naval brass	C4621 C4640	C46200 C46400	ERCuSi-A ERCuAl-A2	ERCuSi-A ERCuAl-A2	ECuSi ECuAl-A2	200-300°C (100-250)
Phosphor bronze	C5111 C5102 C5191 C5212	C51000 C51000 C51900 C52100	ERCuSn-A	ERCuSn-A	ECuSn-A	200-250°C (150-200)
Aluminum bronze	C6161 C6280	C61600 C62800	ERCuAl-A2	ERCuAl-A2	ECuAl-A2	150-250°C (100-200)
Silicon bronze	-	C65100 C65500	ERCuSi-A	ERCuSi-A	ECuSi	No need
Cupronickel	C7060 C7150	C70600 C71500	ERCuNi YCuNi-1 (1)	ERCuNi YCuNi-1 (1)	ECuNi	No need

Note: (1) For 90/10 cupronickel (C7060, C70600) only

Table 2.6 *A guide to the correct welding procedures for individual combinations of dissimilar metals* (1)

Metal (B) \ Metal (A)	Cupronickel	Aluminum bronze	Phosphor bronze	Silicon bronze	Brass	Copper
Carbon steel	F4, B3, P0	F3, B1, P4	F2, B1, P3	F1, B1, P0	F1, B2, P2 F3, B2, P2	F1, B2, P1 F0, B3, P1
Copper	F4, B1, P1	F3, B1, P1	F2, B1, P1	F1, B1, P1	F1, B2, P1	
Brass	F4, B1, P2	F3, B1, P2	F2, B1, P2	F1, B1, P2		
Silicon bronze	F4, B0, P0	F1, B0, P4	F2, B0, P3			
Phosphor bronze	F2, B0, P3	F2, B0, P3				
Aluminum bronze	F3, B0, P4					

Note: (1) Refer to the index in the following table. The preheat information (P1-P4) is for a metal that uses a higher temperature than does the other of a particular combination of dissimilar metals.

Index	Filler metal classification			Index	Buttering (1)	Index	Preheat (2)
	GTAW	GMAW	SMAW				
F0	ERCu	ERCu	ECu	B0	No need	P0	No need
F1	ERCuSi-A	ERCuSi-A	ECuSi	B1	On metal (B)	P1	200-500°C for copper
F2	ERCuSn-A	ERCuSn-A	ECuSn-A	B2	On both metals (A) and (B)	P2	100-350°C for brass
F3	ERCuAl-A2	ERCuAl-A2	ECuAl-A2	B3	On metal (B) with ERNi-1, ERNiCu-7, ENi-1, or ENiCu-7	P3	150-250°C for P-bronze
F4	ERCuNi	ERCuNi	ECuNi			P4	100-250°C for Al-bronze

Note: (1) One-layer buttering with the specified individual filler metals
(2) The exact temperature depends on the welding process and base metal thickness.

2.4 Tips for successful welding and safe practices

Most copper and copper alloys can be joined by arc welding. Such welding processes that use inert gas shielding and have better arc concentration as GTAW and GMAW are generally preferred, although SMAW can be used for many non-critical applications. However, specific considerations are needed to get successful results, as stated in the following.

(1) Welding joint preparation

Recommended welding joint designs for copper and copper alloys are shown in **Figure 2.7**, which are appropriate for GTAW, SMAW and GMAW. These joint designs have larger groove angles than those used for steel. The larger groove angles are required to provide adequate fusion and penetration for copper and copper alloys that have high thermal conductivity. The welding joint faces and adjacent surfaces should be cleaned and made free of oil, grease, dirt, paint, and oxides prior to welding, by means of abrasive methods or degreasing with suitable solvent.

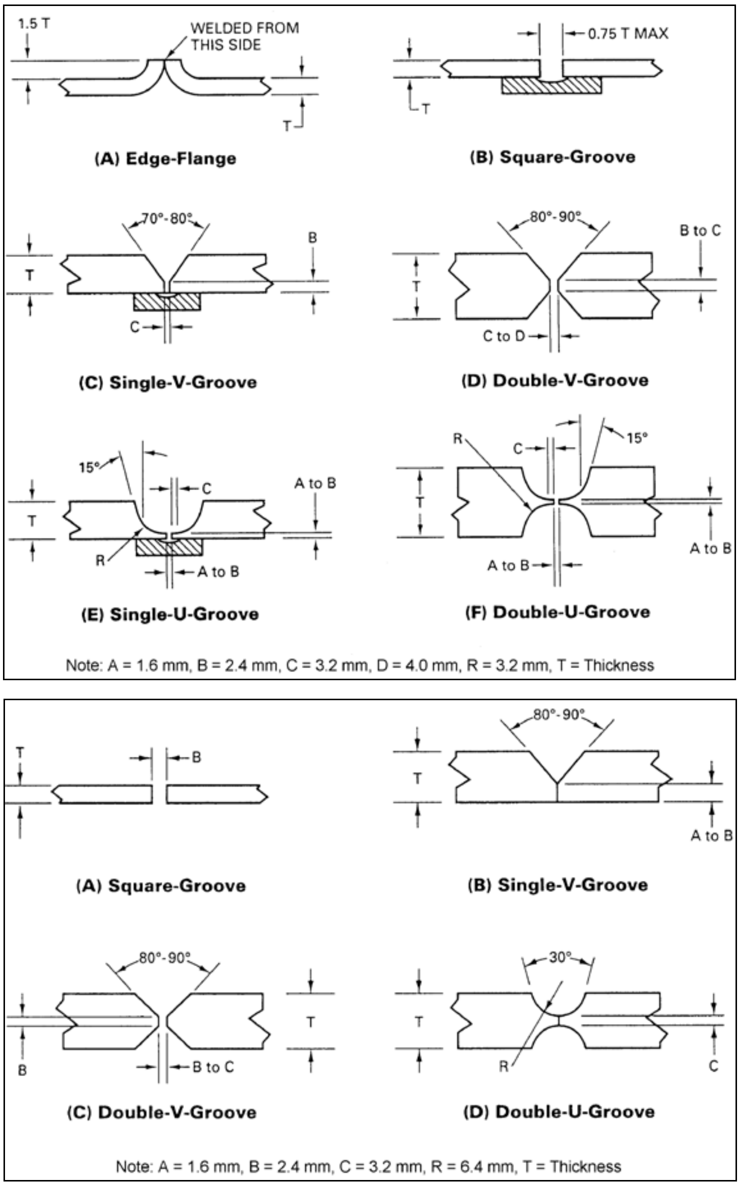


Figure 2.7 *Joint designs for GTAW and SMAW (Above) and GMAW (Bottom) of copper and copper alloys [Ref. 2]*

(2) Power sources and deposition techniques

In GTAW of copper and copper alloys, DCEN currents are generally used with thoriated tungsten electrodes in argon gas shielding. Aluminum bronzes, however, tend to generate aluminum oxides (Al_2O_3) on their surfaces by oxidation in the atmosphere. The aluminum oxide on the surface of the base metal can cause insufficient fusion in the weld. This weld imperfection can be prevented by using AC currents with a pure tungsten electrode and argon gas shielding in GTAW due to the arc cleaning action and better capacity of the tungsten electrode. In addition to argon gas shielding, helium and a mixture of argon and helium are also used, in which better penetration or faster travel can be provided with DCEN currents. Helium produces a more fluid weld pool that is cleaner, and the risk of oxide entrapment is considerably reduced. Pulsed current improves weld bead shape and workability in positions other than flat. Stringer beads or narrow weave beads should be used because wide oscillation of the arc exposes each edge of the weaving bead to the atmosphere.

GMAW uses DCEP currents with argon gas shielding for most joining and surfacing applications, while a 75% argon-25% helium mixture is helpful when welding thick sections where increased welding heat and penetration are required. The filler metal should be deposited by stringer beads or narrow weave beads using spray transfer. Wide electrode weaving may result in oxidation at bead edges. Minimum conditions for spray transfer with copper and copper alloy filler metals are shown in **Table 2.7**. Pulsed current improves weld bead shape and operability for welding in positions other than flat.

Table 2.7 *Approximate GMAW conditions for spray transfer with copper and copper alloy filler metal and argon shielding [Ref. 2]*

Filler metal			Minimum welding current	Arc voltage	Filler wire feed
Common name	AWS class.	Dia. (mm)	(A)	(V)	(mm/s)
Copper	ERCu	0.9	180	26	146
		1.1	210	25	106
		1.6	310	26	63
Aluminum bronze	ERCuAl-A2	0.9	160	25	125
		1.1	210	25	110
		1.6	280	26	78
Silicon bronze	ERCuSi-A	0.9	165	24	178
		1.1	205	26-27	125
		1.6	270	27-28	80
Cupronickel	ERCuNi	1.6	280	26	74

SMAW filler metals are used with DCEP currents. Use of a short arc length and stringer or narrow weave beads is recommended. To prevent inclusions, each bead must be thoroughly cleaned of slag before the next bead is applied.

(3) Peening

Peening can be defined as the mechanical working of metals using impact blows. Peening is accomplished by repeated hammer blows to the surface of the metal. The blows may be administered manually, as with a hammer, or with pneumatic tools. Peening stretches the surface of the solid metal, thus reducing contraction stresses, thereby reducing the likelihood of cracking. The stretched, thus plastically deformed, area can be recrystallized to become fine structure by the heat of the succeeding weld passes.

In peening copper and copper alloy welds, peen each bead while it is still hot immediately after completion of each weld pass and removal of slag. Peening should be done with repeated, moderate blows using a peening hammer with round-nose, or square-nose. The force of peening should be sufficient to deform the weld metal to an extent that the weld ripples are completely removed but without rupturing the weld.

(4) Postweld heat treatment

Postweld heat treatment (PWHT) of copper and copper alloys may involve stress relieving, annealing, or precipitation hardening. PWHT may be required if the base metal can be strengthened by a heat treatment or if the service environment can cause stress-corrosion cracking. Copper alloys that include the high-zinc brasses and some aluminum bronzes are considered susceptible to stress-corrosion cracking.

Stresses induced in weldments can lead to premature failure of the welding construction in certain corrosive environments. Such welding stresses can be relieved by heating the weldment to specified temperatures after welding. Typical stress relieving temperatures for some copper alloys are given in **Table 2.8**. Heating time must be adequate for the entire weldment to reach a specified temperature. The weldment is usually held for at least one hour at the stress relief temperature and then slowly cooled. Weldments thicker than 25.4 mm must be held for longer periods, usually for 1 hour per 25.4 mm of thickness.

***Table 2.8** Typical stress-relieving temperatures for weldments of copper alloys [Ref. 2]*

Common name	UNS No.	Temperature	
Red brass	C23000	550°F	288°C
Naval brass	C46400-C46700	500	260
Aluminum bronze	C61400	650	343
Silicon bronze	C65500	650	343
Cupronickel	C70600-C71500	1000	538

Copper alloys that respond to precipitation hardening include some high coppers, some copper-aluminum alloys, and copper-nickel castings containing beryllium or chromium. If precipitation-hardenable alloys are not postweld heat treated, the hardness in the weld area will vary as a result of aging or overaging caused by the welding heat.

(5) Safe practices [Ref. 2]

Copper and a number of alloying elements in copper alloys (arsenic, beryllium, cadmium, chromium, lead, manganese, and nickel) have low or very low permissible exposure limits. Therefore, special ventilation precautions are required when welding or grinding copper or copper alloys to assure the level of contaminants in the atmosphere is below the limit allowed for human exposure. These precautions may include local exhaust ventilation, respiratory protection, or both. Welding copper and its alloys containing appreciable amounts of beryllium, cadmium, or chromium may present health hazards to welders and coworkers. Exposure to welding fumes containing these elements may cause adverse health effects.

Copper and zinc fume and dust can cause irritation of the upper respiratory tract, nausea, and metal fume fever. They may also cause skin irritation and dermatitis as well as eye problems. Cadmium and beryllium fume are toxic when inhaled.

Good personal hygiene should be practiced, particularly before eating. Food and beverages should not be stored or consumed in the work area. Contaminated clothing should be changed.

Chapter 3

Arc Welding of Nickel and Nickel Alloys

Contents

Introduction

Nickel and nickel alloys possess superior corrosion resistance and excellent low- and high-temperature mechanical properties, the applications of which can be seen in various chemical process equipment and high-temperature service machinery that are operated in severe environments where stainless steels may be damaged. Uses of commercial purity nickel are relatively limited; however, an enormous range of nickel alloys is available. The typical applications of nickel alloys include various components of gas turbines, jet aircraft engines, organic and inorganic chemical equipment, oil refineries, ethylene plants, hydrogen production plants, and hydrogen chlorides removal equipment for coal and oil-fired power plants.

Nickel and its alloys can be joined by welding, brazing, and soldering. The welding processes used generally for joining nickel and its alloys are arc welding, electron beam welding, and resistance welding. Among arc welding processes, the gas tungsten arc welding (GTAW) process is most extensively used due to better performances, although shielded metal arc welding (SMAW), gas shielded metal arc welding with solid wires (referred to as GMAW) and flux-cored wires (referred to as FCAW) and submerged arc welding (SAW) are also used for many non-critical applications.

This textbook discusses various types of nickel and nickel alloys and their weldability, suitable filler metals and welding procedures for SMAW, GTAW, GMAW, and FCAW together with tips for sound welds and safe practices.

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1. Types and characteristics of nickel and nickel alloys

Nickel and nickel alloys (specific superalloys that contain Ni as one of the main elements are also included) offer excellent ductility, formability, resistance to oxidation and corrosion, and high temperature strength, which find applications in various chemical equipment and high temperature service machinery. High purity nickels are more resistant to chemicals such as caustic soda, while nickel-based alloys are superior in tensile strength and corrosion resistance in the high temperature and severe corrosive environments where stainless steels cannot withstand. Nickel and its alloys are available in various forms such as plates, sheets, strips, pipes, tubes, bars, and castings. This section discusses characteristics of various types of nickel and its alloys that are weldable at good or fair degrees.

1.1 Nickel

Nickel offers high strength and excellent malleability. Because of good hot and cold workability, a variety of nickel products such as forgings, rods, plates, pipes, wires and castings are available. Nickel exhibits excellent corrosion resistance against seawater, sulfuric acid, hydrochloric acid and caustic soda, but is likely to be corroded by chlorine with much water vapor, sulfur dioxide and ammonia.

Table 1.1 shows the chemical and mechanical properties of typical commercially pure nickels. Alloy 200 and the low-carbon version, alloy 201, are most widely used where welding is involved. Of these, the low-carbon alloy 201 is preferred for applications involving the service exposure to temperatures above 315°C, because of its increased resistance to graphitization at elevated temperatures. This graphitization is the result of excess carbon being precipitated in the intergranular area in the temperature range of 315-760°C when alloy 200 is held there for extended time.

Major applications for the two alloys are food processing equipment, caustic handling equipment, laboratory crucibles, chemical shipping drums, and electrical and electronic parts.

Table 1.1 *Chemical and mechanical properties of commercially pure nickels [Ref. 2][Ref. 5]* (1)

Alloy type	Common alloy name	UNS (2) No.	Content of main elements (%) (3)						T.S. (MPa)	El. (%)
			Ni	C	Fe	Cu	Mn	Si		
200	Nickel 200	N02200	99.0 min	0.15	0.40	0.25	0.35	0.35	380 min	40 min
201	Nickel 201	N02201	99.0 min	0.02	0.40	0.25	0.35	0.35	345 min	40 min

Note: (1) Mechanical properties are the ASTM requirements for plates.
(2) UNS No.: The Unified Numbering System per SAE-ASTM
(3) Single values are maximum.

1.2 Nickel alloys

Because nickel has wide solubility for a number of other metals, many different commercial alloys are available. However, alloying elements have different influences on the microstructure and properties; i.e., some produce solid solution strengthening, some form carbide or nitride particles within the nickel-base solid solution matrix, some form brittle intermetallic phases which are detrimental to properties, and some form precipitates, e.g. $Ni_3(Al,Ti)$, which provide useful precipitation hardening. The solid-solution strengthened alloys are most extensively used because they are readily weldable. This textbook concentrates on such nickel alloys strengthened by solid-solution hardening as nickel-copper alloys, nickel-chromium alloys, nickel-iron-chromium alloys, nickel-molybdenum alloys, and nickel-chromium-molybdenum alloys. Additions of aluminum, chromium, cobalt, copper, iron, molybdenum, titanium, tungsten, and vanadium contribute to solid solution strengthening.

1.2.1 Nickel-copper alloys

Alloy 400 is the typical alloy of this group, which is commonly used. This alloy has high strength and toughness together with excellent resistance to sea or brackish water, chlorinated solvents, glass etching agents, sulfuric acids, and many other acids and alkalis. Like nickels, however, the alloys tend to be corroded by chlorine with much water vapor, sulfur dioxide and ammonia. The chemical and mechanical properties of the alloy are shown in **Table 1.2**.

Typical applications for Monel metals are seawater desalination equipment, salt manufacturing equipment, and petroleum distillation tower.

Table 1.2 *Chemical and mechanical properties of nickel-copper alloys [Ref. 2][Ref. 5]* (1)

Alloy type	Common alloy name	UNS No.	Content of main elements (%) (2)						T.S. (MPa)	El. (%)
			Ni	C	Fe	Cu	Mn	Si		
400	Monel 400	N04400	63.00-70.00	0.3	2.50	Rem	2.00	0.50	485 min	35 min

Note: (1) Mechanical properties are the ASTM requirements for plates.
(2) Single values are maximum.

1.2.2 Nickel-chromium alloys

Nickel-chromium-iron and nickel-chromium-cobalt-molybdenum alloys are included in this alloy group. Common nickel-chromium-iron alloys include alloys 600, 601 and 690. A typical nickel-chromium-cobalt-molybdenum alloy is alloy 617. **Table 1.3** shows chemical and mechanical properties of these alloys.

Alloy 600 is most widely used, which has good corrosion resistance at elevated temperatures along with good high-temperature strength. Because of its resistance to chloride-ion stress-corrosion cracking, it finds wide uses at all temperatures and has excellent room temperature and cryogenic properties. Alloy 600 finds applications in furnace components, such as muffles and baskets, as well as in chemical and food processing equipment.

Alloy 601 exhibits outstanding oxidation and scaling resistance at temperatures up to 1200°C and extends the temperature range achieved with alloy 600 through the addition of 1.4% aluminum.

Alloy 617 is a nickel-chromium-cobalt-molybdenum alloy with an exceptional combination of metallurgical stability, strength, and oxidation resistance at high temperatures, as well as corrosion resistance in aqueous environments. This alloy is used in gas turbine applications and in the petrochemical and thermal processing industries.

Alloy 690, with 30% chromium, has even better resistance to stress-corrosion cracking. This alloy finds uses based on its resistance to nitric acid or mixtures of nitric and hydrofluoric acid, as well as high temperatures in sulphur-bearing gases.

Table 1.3 *Chemical and mechanical properties of nickel-chromium alloys [Ref. 2][Ref. 5]* (1)

Alloy type	Common alloy name	UNS No.	Content of main elements (%) (2)											T.S. (MPa)	El. (%)
			Ni	C	Cr	Mo	Fe	Co	Cu	Al	Ti	Mn	Si		
600	Inconel 600	N06600	72.0 min	0.15	14.00-17.00	-	6.00-10.00	-	0.50	-	-	1.00	0.50	550 min	30 min
601	Inconel 601	N06601	58.0-63.0	0.1	21.0-25.0	-	Rem.	-	1.0	1.0-1.7	-	1.0	0.50	550 min	30 min
617	Inconel 617	N06617	44.5 min	0.05-0.15	20.0-24.0	8.0-10.0	3.00	10.0-15.0	0.50	0.80-1.50	0.60	1.00	1.00	655 min	35 min
690	Inconel 690	N06690	58.0 min	0.05	27.0-31.0	-	7.0-11.0	-	0.50	-	-	0.50	0.50	586 min	30 min

Note: (1) Mechanical properties are the ASTM requirements for plates.
(2) Single values are maximum.

1.2.3 Nickel-iron-chromium alloys

Alloys 800, 800H, 800HT, and 825 are included in this alloy group. Alloys 800, 800H, and 800HT are used for process piping, heat exchanger and vessel bodies. Alloy 800 is generally used for applications at temperatures below about 620°C and Alloys 800H and 800HT at higher temperatures.

Alloy 825 is used in corrosive environments under 540°C because of their resistance to reducing acids and to chloride-iron stress-corrosion cracking. Some environments in which alloy 825 is particularly useful are sulfuric acid, phosphoric acid, sulfur-containing flue gases, sour gas and oil wells, and seawater.

The chemical composition and mechanical properties of these alloys are shown in **Table 1.4**.

Table 1.4 *Chemical and mechanical properties of nickel-iron-chromium alloys [Ref. 2][Ref. 5]* (1)

Alloy type	Common alloy name	UNS No.	Content of main elements (%) (2)										T.S. (MPa)	El. (%)
			Ni	C	Cr	Mo	Fe	Cu	Al	Ti	Mn	Si		
800	Incoloy 800	N08800	30.0-35.0	0.10	19.0-23.0	-	Rem	0.75	0.15-0.60	0.15-0.60	1.5	1.0	520 min	30 min
800H	Incoloy 800H	N08810	30.0-35.0	0.05-0.10	19.0-23.0	-	Rem.	0.75	0.15-0.60	0.15-0.60	1.5	1.0	450 min	30 min
800HT	Incoloy 800HT	N08811	30.0-35.0	0.06-0.10	19.0-23.0	-	39.5 min	0.75	0.15-0.60	0.15-0.60	1.5	1.0	450 min	30 min
825	Incoloy 825	N08825	38.0-46.0	0.05	19.5-23.5	2.5-3.5	Rem	1.5-3.0	0.2	0.6-1.2	1.0	0.5	586 min	30 min

Note: (1) Mechanical properties are the ASTM requirements for plates.
(2) Single values are maximum.

1.2.4 Nickel-molybdenum alloys

The principle alloys in this group are Alloys B-2, B-3, and N. As shown in **Table 1.5**, they contain 16-28% molybdenum and lesser amounts of chromium and iron. Alloys B-2 and B-3 have good resistance to hydrochloric acid and other nonoxidizing acids. However, the chromium level is too low to permit the formation of a protective chromium oxide film, so that the alloys are not corrosion resistant in oxidizing environments. In contrast, Alloy N with a higher amount of chromium has good oxidation resistance to hot fluoride salts in the temperature range of 704-871°C.

Table 1.5 *Chemical and mechanical properties of nickel-molybdenum alloys [Ref. 2][Ref. 5] (1)*

Alloy type	Common alloy name	UNS No.	Content of main elements (%) (2)												T.S. (MPa)	El. (%)
			Ni	C	Cr	Mo	Fe	Co	Al	Ti	Cu	W	Mn	Si		
B-2	Hastelloy B-2	N10665	Rem	0.02	1.0	26.0-30.0	2.0	1.0	-	-	-	-	1.0	0.10	760 min	40 min
B-3	Hastelloy B-3	N10675	65 min	0.01	1.0-3.0	27.0-32.0	1.0-3.0	3.0	0.50	0.20	0.20	3.0	3.0	0.10	760 min	40 min
N	Hastelloy N	N10003	Rem	0.04-0.08	6.0-8.0	15.0-18.0	5.0	0.20	0.50	-	0.35	0.50	1.00	1.00	690 min	40 min

Note: (1) Mechanical properties are the ASTM requirements for plates.
(2) Single values are maximum (additionally, 0.20%Cb, 0.20%Ta, 0.20%V, 0.10%Zr for Alloy B-3; 0.010%B, 0.50%V for Alloy N)

1.2.5 Nickel-chromium-molybdenum alloys

Included in this group are Alloys C-22, C-276, C-4, G-30, X, 625, and 686. They are designed primarily for corrosion resistance at room temperature, as well as for resistance to oxidizing and reducing atmospheres at elevated temperatures. **Table 1.6** shows chemical and mechanical properties of these alloys.

Alloy C-22 has superior corrosion resistance in oxidizing acid chlorides and wet chlorine. It also has good resistance to pitting, crevice corrosion, and stress corrosion cracking, and finds uses in the pulp and paper industry, petrochemical industry and in pollution control equipment.

Alloy C-276 has good resistance to seawater corrosion as well as to pitting and crevice corrosion. It is used in the equipment for chemical processing, pollution control and waste treatment.

Alloy C-4 resists the formation of grain-boundary precipitates in the weld heat-affected zone, thus making it suitable for most chemical process applications in the as-welded condition. This alloy has excellent resistance to stress-corrosion cracking and to oxidizing atmospheres up to 1038°C. This alloy also has exceptional resistance to a wide variety of chemical process environments. These include hot contaminated mineral acids, solvents, chlorine and chlorine-contaminated media (organic and inorganic), dry chlorine, formic and acetic acids, acetic anhydride, and seawater and brine solutions [referred to HAYNES' brochure of Hastelloy C-4].

Alloy G-30, with 30% chromium, has superior resistance to commercial phosphoric acids and many highly oxidizing acids. Its use is growing in the fertilizer industry for acid evaporators.

Alloy X has excellent strength and oxidation resistance up to 1200°C. It has also been found to be exceptionally resistant to stress-corrosion cracking in petrochemical applications. It is used for components of furnaces and aircraft engines and in the petrochemical industry.

Alloy 625 has additions of 9% molybdenum and 4% niobium, which enhance its room and high-temperature strength and corrosion resistance. The molybdenum improves its resistance to pitting corrosion in chloride-bearing environments. The niobium contributes to weldability by tying up the carbon as niobium carbides thereby avoiding the formation of chromium carbides whose presence at grain boundaries can lead to intergranular corrosion as in the sensitization of stainless steel.

Alloy 686 offers good resistance to reducing media due to its high nickel and oxidizing media due to its high chromium. Molybdenum and tungsten aid resistance to localized corrosion such as pitting. Low carbon helps minimize grain boundary precipitation to maintain corrosion resistance in the heat-affected zones of welded joints. Resistance to general, pitting and crevice corrosion increases with the alloying (Cr + Mo + W) content. This alloy is used for resistance to aggressive media in chemical processing, pollution control, pulp and paper manufacture, and waste management applications.

Table 1.6 *Chemical and mechanical properties of nickel-chromium-molybdenum alloys [Ref. 2][Ref. 5]* (1)(2)

Alloy type	Common alloy name	UNS No.	Content of main elements (%)											T.S. (MPa)	El. (%)
			Ni	C	Cr	Mo	Fe	Co	Ti	Mn	Si	W	V		
C-22	Hastelloy C-22	N06022	Rem	0.015	20.0-22.5	12.5-14.5	2.0-6.0	2.5	-	0.50	0.08	2.5-3.5	0.35	690 min	45 min
C-276	Hastelloy C-276	N10276	Rem	0.02	14.5-16.5	15.0-17.0	4.0-7.0	2.5	-	1.0	0.08	3.0-4.5	0.35	690 min	40 min
C-4	Hastelloy C-4	N06455	Rem	0.015	14.0-18.0	14.0-17.0	3.0	2.0	0.70	1.0	0.08	-	-	690 min	40 min
G-30	Hastelloy G-30	N06030	Rem	0.03	28.0-31.5	4.0-6.0	13.0-17.0	5.0	Cu: 1.0-2.4	1.5	0.8	1.5-4.0	Cb: 0.30-1.50	586 min	30 min
X	Hastelloy X	N06002	Rem	0.05-0.15	20.5-23.0	8.0-10.0	17.0-20.0	0.5-2.5	-	1.00	1.00	0.20-1.0	-	655 min	35 min
625	Inconel 625	N06625	Rem	0.10	20.0-23.0	8.0-10.0	5.0	Al: 0.40	0.40	0.50	0.50	-	Cb: 3.15-4.15	758 min	30 min
686	Inconel 686	N06686	Rem	0.010	19.0-23.0	15.0-17.0	5.0	-	0.02-0.25	0.75	0.08	3.0-4.4	-	690 min	45 min

Note (1) Mechanical properties are the ASTM requirements for plates.
(2) Chemistry of N06686 is as per ASTM B575-06 (

1.3 Physical properties of typical nickel and nickel alloys

Pure nickel has a face-centered cubic (fcc) crystal structure at all temperatures, and this is also true of most nickel alloys. Physical properties such as melting point, coefficient of thermal expansion and thermal conductivity are useful information when considering the welding performance of a particular metal. **Table 1.7** shows the physical properties of nickel and nickel alloys in comparison with 304-type austenitic stainless steel and carbon steel.

The melting temperatures of nickel and its alloys are lower than that of carbon steel. Nickel alloys possess lower melting temperatures than nickel and 304-type stainless steel. The coefficient of thermal expansion of nickel and its alloys are lower than that of 304-type stainless steel and are close to that of carbon steel, and therefore lesser degrees of welding distortion can be expected in welding nickels and nickel alloys than in welding 304-type stainless steels. The thermal conductivity of nickel is higher than that of carbon steel, and therefore the heat of arc can be dispersed quicker in welding nickels than in welding 304-type stainless and carbon steels. Nickel alloys exhibit low thermal conductivity similar to that of 304-type stainless steel. This is why nickel alloys provide good wettability with the weld pool, like austenitic stainless steels.

Table 1.7 *Physical properties of Ni and Ni-alloys in relation to stainless and carbon steel [Ref. 2]*

Alloy type	**Density** (g/cm^3)	**Melting range** (°C)	**Coefficient of thermal expansion at 21-93°C** (μm/m/°C)	**Thermal conductivity at 21°C** (W/m°K)
200	8.88	1435-1446	13.3	70
400	8.83	1298-1348	13.9	20
600	8.41	1354-1412	13.3	14
800	7.94	1357-1385	14.2	11
N	8.85	1301-1398	11.5	11
C-276	8.94	1265-1343	11.3	11
304-type stainless steel	7.93 (1)	1370-1450 (1)	17.3 (0-100°C) (1)	16.2 (at 100°C) (2)
Carbon steel	7.86 (1)	1492-1520 (1)	11.7 (0-100°C) (1)	51.0 (at 100°C) (2)

Note (1) Source: Kobe Steel's Welding Electrodes Handbook.
(2) Source: CASTI Metals Black Book.

2. Filler metals and welding procedures

Solid-solution nickel and nickel alloys used for welding constructions have comparatively good weldability, and most of the alloys use gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), gas metal arc welding (GMAW), and flux cored arc welding (FCAW). However, some alloys use only GTAW to prevent hot cracking. To obtain successful welding results, choice of filler metal and control of welding procedure are essential.

2.1 Types and characteristics of filler metals

Cover electrodes, solid wires/rods, and flux-cored wires are available for welding nickel and nickel alloys. The filler metals for SMAW, GTAW, GMAW, and FCAW are specified in various standards: e.g. JIS Z 3224:2010 (Nickel and Nickel-Alloy Covered Electrodes), JIS Z 3334:2011 (Nickel and Nickel-Alloy Rods, Solid Wires and Strip Electrodes for Welding), AWS A5.11:2010 (Nickel and Nickel-Alloy Welding Electrodes for Shielded Metal Arc Welding), AWS A5.14:2011 (Nickel and Nickel-Alloy Bare Welding Electrodes and Rods), and AWS A5.34:2013 (Nickel-Alloy Electrodes for Flux Cored Arc Welding).

Table 2.1 shows the main chemical and mechanical properties of SMAW filler metals selected from AWS A5.11. **Table 2.2** shows the main chemistry of GTAW and GMAW wires and rods selected from AWS A5.14. The chemical and mechanical properties of FCAW weld metals excerpted from AWS A5.34 are shown in **Table 2.3**. For more details, refer to the individual AWS standards. In general the filler metals are designed so that the main chemical composition of weld metal resembles that of the applicable base metal. However, the major chemical elements may be higher in the filler metal than in the base metal to diminish the effects of dilution by the base metal for similar and dissimilar metal joints. In addition, the filler metal chemistry is adjusted fine to satisfy weldability requirements such as adequate porosity resistance, micro-crack resistance and mechanical properties. Normally, Al, Ti, Mn and Nb are added to deoxidize and denitrify the weld metal.

Table 2.4 shows intended applications for individual AWS filler metal classifications for SMAW, GTAW, GMAW, and FCAW for only the nickel and nickel alloys discussed above.

Table 2.1 *Chemical and mechanical properties of Ni and Ni-alloy weld metals by SMAW* (1)

AWS class.	**Content of main elements** (%) (2)														T.S. min (ksi)	El. min (%)
	C	Mn	Fe	Si	Cu	Ni	Co	Al	Ti	Cr	Nb	Mo	V	W		
ENi-1	0.10	0.75	0.75	1.25	0.25	92.0 min	-	1.0	1.0-4.0	-	-	-	-	-	60	20
ENiCu-7	0.15	4.00	2.5	1.5	Rem	62.0-69.0	-	0.75	1.0	-	-	-	-	-	70	30
ENiCrFe-1	0.08	3.5	11.0	0.75	0.50	62.0	-	-	-	13.0-17.0	1.5-4.0(3)	-	-	-	80	30
ENiCrFe-2	0.10	1.0-3.5	12.0	0.75	0.50	62.0	(0.12)	-	-	13.0-17.0	0.5-3.0(3)	0.5-2.5	-	-	80	30
ENiCrFe-3	0.10	5.0-9.5	10.0	1.0	0.50	59.0 min	(0.12)	-	1.0	13.0-17.0	1.0-2.5(3)	-	-	-	80	30
ENiCrFe-7	0.05	5.0	7.0-12.0	0.75	0.50	Rem	(0.12)	0.50	0.50	28.0-31.5	1.0-2.5	0.5	B: 0.005	Zr: 0.020	80	30
ENiMo-7	0.02	1.75	2.25	0.2	0.50	Rem	1.0	-	-	1.0	-	26.0-30.0	-	1.0	100	25
ENiMo-10	0.02	2.0	1.0-3.0	0.2	0.50	Rem	3.0	-	-	1.0-3.0	-	27.0-32.0	-	3.0	100	25 min
ENiCrMo-2	0.05-0.15	1.0	17.0-20.0	1.0	0.50	Rem	0.50-2.50	-	-	20.5-23.0	-	8.0-10.0	-	0.2-1.0	95	20
ENiCrMo-3	0.10	1.0	7.0	0.75	0.50	55.0 min	(3)	-	-	20.0-23.0	3.15-4.15	8.0-10.0	-	-	110	30
ENiCrMo-4	0.02	1.0	4.0-7.0	0.2	0.50	Rem	2.5	-	-	14.5-16.5	-	15.0-17.0	0.35	3.0-4.5	100	25
ENiCrMo-7	0.015	1.5	3.0	0.2	0.50	Rem	2.0	-	0.70	14.0-18.0	-	14.0-17.0	-	0.5	100	25
ENiCrMo-10	0.02	1.0	2.0-6.0	0.2	0.50	Rem	2.5	-	-	20.0-22.5	-	12.5-14.5	0.35	2.5-3.5	100	25
ENiCrMo-11	0.03	1.5	13.0-17.0	1.0	1.0-2.4	Rem	5.0	-	-	28.0-31.5	0.3-1.5	4.0-6.0	-	1.5-4.0	85	25
ENiCrMo-14	0.02	1.0	5.0	0.25	0.50	Rem	-	-	0.25	19.0-23.0	-	15.0-17.0	-	3.0-4.4	100	30
ENiCrCoMo-1	0.05-0.15	0.3-2.5	5.0	0.75	0.50	Rem	9.0-15.0	-	-	21.0-26.0	1.0	8.0-10.0	-	-	90	20

Note: (1) Excerpted from AWS A 5.11:2010.
(2) Single values are maximum. Bracketed values apply when specified by the purchaser.
(3) Ta: 0.30% max, when specified by the purchaser.

Table 2.2 *Chemical compositions of GTAW/GMAW bare wires and rods for Ni and Ni-alloys* (1)

AWS class.	**Content of main elements** (%) (2)													
	C	Mn	Fe	Si	Cu	Ni	Co	Al	Ti	Cr	Nb	Mo	V	W
ERNi-1	0.15	1.0	1.0	0.75	0.25	93.0 min	-	1.5	2.0-3.5	-	-	-	-	-
ERNiCu-7	0.15	4.0	2.5	1.25	Rem	62.0-69.0	-	1.25	1.5-3.0	-	-	-	-	-
ERNiCr-3	0.10	2.5-3.5	3.0	0.50	0.50	67.0 min	(0.12)	-	0.75	18.0-22.0	2.0-3.0	-	-	-
ERNiCrFe-5	0.08	1.0	6.0-10.0	0.35	0.50	70.0 min	(0.12)	-	-	14.0-17.0	1.5-3.0	-	-	-
ERNiCrFe-7 (3)	0.04	1.0	7.0-11.0	0.50	0.30	Rem	-	1.10	1.0	28.0-31.5	0.10	0.50	-	-
ERNiCrFe-11	0.10	1.0	Rem	0.50	1.0	58-63.0	-	1.0-1.7	-	21.0-25.0	-	-	-	-
ERNiFeCr-1	0.05	1.0	22.0 min	0.50	1.5-3.0	38.0-46.0	-	0.20	0.6-1.2	19.5-23.5	-	2.5-3.5	-	-
ERNiMo-2	0.04-0.08	1.0	5.0	1.0	0.50	Rem	0.20	-	-	6.0-8.0	-	15.0-18.0	0.50	0.50
ERNiMo-7	0.02	1.0	2.0	0.10	0.50	Rem	1.0	-	-	1.0	-	26.0-30.0	-	1.0

(Continued)

Table 2.2 (Cont.) *Chemical compositions of GTAW/GMAW bare wires and rods for Ni and Ni-alloys* (1)

AWS class.	Content of main elements (%) (2)													
	C	**Mn**	**Fe**	**Si**	**Cu**	**Ni**	**Co**	**Al**	**Ti**	**Cr**	**Nb**	**Mo**	**V**	**W**
ERNiMo-10 (4)	0.01	3.0	1.0-3.0	0.10	0.20	65.0 min	3.0	0.50	0.20	1.0-3.0	0.20	27.0-32.0	0.20	3.0
ERNiCrMo-2	0.05-0.15	1.0	17.0-20.0	1.0	0.50	Rem	0.5-2.5	-	-	20.5-23.0	-	8.0-10.0	-	0.2-1.0
ERNiCrMo-3	0.10	0.50		0.50	0.50	58 min	-	0.40	0.40	20.0-23.0	3.15-4.15	8.0-10.0	-	-
ERNiCrMo-4	0.02	1.0	4.0-7.0	0.08	0.50	Rem	2.5	-	-	14.5-16.5	-	15.0-17.0	0.35	3.0-4.5
ERNiCrMo-7	0.015	1.0	3.0	0.08	0.50	Rem	2.0	-	0.70	14.0-18.0	-	14.0-18.0	-	0.50
ERNiCrMo-10	0.015	0.50	2.0-6.0	0.08	0.50	Rem	2.5	-	-	20.0-22.5	-	12.5-14.5	0.35	2.5-3.5
ERNiCrMo-11	0.03	1.5	13.0-17.0	0.80	1.0-2.4	Rem	5.0	-	-	28.0-31.5	0.30-1.50	4.0-6.0	-	1.5-4.0
ERNiCrMo-14	0.01	1.0	5.0	0.08	0.50	Rem	-	0.50	0.25	19.0-23.0	-	15.0-17.0	-	3.0-4.4
ERNiCrCoMo-1	0.05-0.15	1.0	3.0	1.0	0.50	Rem	10.0 15.0	0.8-1.5	0.60	20.0-24.0	-	8.0-10.0	-	-

Note: (1) Excerpted from AWS A 5.14:2011.
(2) Single values are maximum. Bracketed values apply when specified by the purchaser.
(3) Al+Ti: 1.5% max. (4) Ni+Mo: 94.0-98.0%, Ta: 0.02% max, Zr: 0.10% max.

Table 2.3 *Chemical and mechanical properties of Ni and Ni-alloy weld metals by GMAW (with FCW)* (1)

AWS class.	Content of main elements (%) (2)													T.S.	El.
	C	**Mn**	**Fe**	**Si**	**Cu**	**Ni**	**Co**	**Ti**	**Cr**	**Nb(3)**	**Mo**	**V**	**W**	min (ksi)	min (%)
ENiCr3T	0.10	2.5-3.5	3.0	0.50	0.50	67.0	(0.10)	0.75	18.0-22.0	2.0-3.0	-	-	-	80	25
ENiCrMo3T	0.10	0.50	5.0 (1.0)	0.50	0.50	58.0 min	(0.10)	0.40	20.0-23.0	3.15-4.15	8.0-10.0	-	-	100	25
ENiCrMo4T	0.02	1.0	4.0-7.0	0.2	0.50	Rem	2.5	-	14.5-16.5	-	15.0-17.0	0.35	3.0-4.5	100	25

Note: (1) Excerpted from AWS A 5.34:2013.
(2) Single values are maximum. Bracketed values apply when specified by the purchaser.
(3) Ta: 0.30% max when specified by the purchaser.

Table 2.4 *Typical intended applications for individual AWS filler metal classifications* (1)

AWS classification		Typical applicable alloys	
SMAW	**GTAW/GMAW (FCW)**	**Type of alloy**	**UNS No. and Proprietary alloy**
ENi-1	ERNi-1	Pure nickel	N02200, N02201
ENiCu-7	ERNiCu-7	Ni-Cu	N04400
ENiCrFe-1 ENiCrFe-2 ENiCrFe-3	ERNiCr-3 (ENiCr3T) ERNiCrFe-5	Ni-Cr-Fe	N06600
ENiCrFe-7	ERNiCrFe-7	Ni-Cr-Fe	N06690
-	ERNiCrFe-11	Ni-Cr-Fe-Al	N06601
-	ERNiFeCr-1	Ni-Fe-Cr-Mo-Cu	N08825
-	ERNiMo-2	Ni-Mo	N10003
ENiMo-7	ERNiMo-7	Ni-Mo	N10665
ENiMo-10	ERNiMo-10	Ni-Mo	N10665, N10675
ENiCrMo-2	ERNiCrMo-2	Ni-Cr-Mo	N06002
ENiCrMo-3	ERNiCrMo-3 (ENiCrMo3T)	Ni-Cr-Mo	N06625
		Ni-Fe-Cr	N08800
ENiCrMo-4	ERNiCrMo-4 (ENiCrMo4T)	Ni-Cr-Mo	N10276
ENiCrMo-7	ERNiCrMo-7	Ni-Cr-Mo	N06455
ENiCrMo-10	ERNiCrMo-10	Ni-Cr-Mo	N06022
ENiCrMo-11	ERNiCrMo-11	Ni-Cr-Mo	N06030
ENiCrMo-14	ERNiCrMo-14	Ni-Cr-Mo	N06686, N06625, N10276, N06022
ENiCrCoMo-1	ERNiCrCoMo-1	Ni-Cr-Co-Mo	N06617

Note: (1) Excerpted from the annexes of AWS A5.11:2010, A5.14:2011, and A5.34:2013 only for the filler metals mentioned in the previous sections of this chapter.

2.2 Weldability and welding procedures

Nickel and nickel alloys can be arc welded commonly by SMAW, GTAW, GMAW and FCAW with suitable filler metals, though some alloys use only GTAW to overcome a lesser degree of weldability. The weldability can be affected by several factors; i.e. wrought alloys surpass castings, fine grain alloys are superior to coarse grain alloys, and annealed alloys are better than age- or work-hardened alloys. The suitable filler metal normally has the chemical composition similar to the base metal, but some base metal uses a specific filler metal to prevent hot cracking in the weld metal and to improve corrosion resistance to a specific environment.

Nickel and its alloys, like austenitic stainless steel, have an austenitic face centered cubic (fcc) crystal structure and exhibit no structural transformation in the solidification process, thereby causing high susceptibility to hot cracking in arc welding. The Ni-Cr-Fe and Ni-Fe-Cr alloys, like some austenitic stainless steels, can exhibit carbide precipitation in the weld heat-affected zone, though in most environments such sensitization does not impair corrosion resistance in nickel-based alloys as it does in the austenitic stainless steel. This is because many alloys have an addition of titanium or niobium to stabilize carbon. Porosity in the weld metal may be a problem, which can generally occur associated with oxidation of carbon and dissolved nitrogen in arc welding. Virtually all filler metals for nickel and nickel alloys contain such elements as Mn, Al, Ti and Nb to deoxidize and denitrify the weld metal to avoid porosity. However, excessive amounts of oxygen and nitrogen entrapped in the weld metal can cause blowholes.

Precipitation-hardenable alloys generally contain higher amounts of Al and Ti to improve the elevated temperature strength. With this type of alloy, SMAW can result in degraded weld metal mechanical properties and inter-bead slag adhesion, while high-heat-input GMAW can cause strain-age cracking in the heat-affected zone of the base metal. Therefore, GTAW is generally used in the annealed (solid solution treated) condition, and the completed fabrication is age-hardened with postweld heat treatment. Such complicated welding procedures including preweld annealing and postweld age-hardening should be conducted by consulting the suppliers of the base metal and filler metal to be used.

The following sections discuss the weldability of widely used solid solution alloys and the proper welding procedures for general applications by the type of alloy.

2.2.1 Nickel

Pure nickel metals, typically Nickel 200 (UNS N0200) and Nickel 201 (UNS 0201), feature comparatively low susceptibility to hot cracking and can be welded with similar filler metals, typically ENi-1 and ERNi-1, modified with Al and Ti to avoid porosity. GTAW is common due to better weldability.

2.2.2 Nickel-copper alloys

Nickel copper alloys, typically Monel 400 (UNS 04400) are readily joined by arc welding. Filler metals, usually ENiCu-7 and ERNiCu-7, differ somewhat from the base metal in the chemical composition, containing Al and Ti to improve strength and to eliminate porosity in the weld metal. To prevent hot cracking, heat input and interpass temperature should be kept lower. GTAW and SMAW are common.

2.2.3 Nickel-chromium alloys

Examples of nickel-chromium alloys are Inconel 600 (UNS N06600), 601 (UNS N06601), 617 (UNS N06617), and 690 (UNS N06690), all of which possess outstanding weldability by SMAW, GTAW, GMAW, and FCAW in the use of matching filler metals. ENiCrFe-1, ENiCrFe-2, ENiCrFe-3, ERNiCr-3, ENiCr3T, and ERNiCrFe-5 are all suitable for Alloy 600. ERNiCrFe-11 is used for Alloy 601. ENiCrCoMo-1 and ERNiCrCoMo-1 are matching filler metals for Alloy 617. ENiCrFe-7 and ERNiCrFe-7 are suited for Alloy 690. However, the weld crater tends to contain hot cracks, and thick sections are likely to contain microcracks; therefore, heat input and interpass temperature should be kept lower.

2.2.4 Nickel-iron-chromium alloys

Incoloy 800 (UNS N08800), 800H (UNS N08810), 800HT (UNS N08811) and 825 (UNS N08825) are well known proprietary alloys. Inconel type filler metals such as ENiCrFe-2 and ERNiCr-3 are commonly used for Alloys 800, 800H and 800HT. For Alloy 825, a matching filler metal of ERNiFeCr-1 is available but ENiCrMo-3 and ERNiCrMo-3, and ENiCrMo3T are usually used. Heat input and interpass temperature should be kept lower to prevent hot cracking.

2.2.5 Nickel-molybdenum alloys

This type of alloy exhibits comparatively good weldability in the use of similar composition filler metal. Hastelloy B2 (UNS N10665), B-3 (UNS N10675) and N (UNS N10003) are well known proprietary alloys. These alloys can be welded with matching filler metals: ENiMo-7 and ERNiMo-7 for Alloy B-2, ENiMo-10 and ERNiMo-10 for Alloy B-3, and ERNiMo-2 for Alloy N. GTAW is more common.

2.2.6 Nickel-chromium-molybdenum alloys

This type of alloy has relatively good weldability in the use of similar composition filler metal. Hastelloy C-22 (UNS N06022), C-276 (UNS N10276), C-4 (UNS N06455), G-30 (UNS N06030), X (UNS N06002), Inconel 625 (UNS N06625), and Inconel 686 (UNS N06686) are proprietary alloys. These alloys can be welded with matching filler metals: ENiCrMo-10 and ERNiCrMo-10 for Alloy C-22; ENiCrMo-4, ERNiCrMo-4, and ENiCrMo4T for Alloy C-276; ENiCrMo-7 and ERNiCrMo-7 for Alloy C-4; ENiCrMo-11 and ERNiCrMo-11 for Alloy G-30; ENiCrMo-2 and ERNiCrMo-2 for Alloy X; ENiCrMo-3, ERNiCrMo-3, and ENiCrMo3T for Alloy 625; and ENiCrMo-14 and ERNiCrMo-14 for Alloy 686. GTAW is more common.

2.2.7 Dissimilar metal combinations

Nickel and nickel alloys offer excellent corrosion resistance against various acids and alkaline solutions, but they are very expensive materials. Therefore, they are often used by overlaying, cladding and lining onto carbon steel, low-alloy steel and stainless steel, where corrosion resistance is the essential requirement. In this case, dissimilar metal welding is involved in overlaying nickel and nickel alloy weld metals on the base metal, joining clad steels, and affixing liners onto the substrate. In such dissimilar metal welding, specific considerations in terms of metallurgy are necessary to get successful results. The following paragraphs discuss metallurgy considerations and welding procedures including filler metal selection.

(1) Dilution by steel

Nickel and its alloys can be welded to steels using appropriate nickel-based filler metals since the nickel-based weld metal can tolerate dilution with the steel, thereby maintaining its stable single solid solution structure. However, excessive dilution with the steel can cause detrimental effects on the quality of the nickel-based weld, e.g. increased Fe, C, Si, S and P can cause hot cracking, and increased Fe can reduce corrosion resistance. Therefore, dilution should be minimized by using relatively-shallow-penetration GTAW or SMAW with lower currents when welding a joint of nickel-based alloy and steel with a nickel-based filler metal. This is the same in the case of overlaying a nickel-based weld metal on the steel base metal.

(2) Filler metal selection

Suggested nickel-based filler metals for the SMAW/GTAW of nickel-based alloy to carbon steel, low-alloy steel or stainless steel are given in **Table 2.5**. Where two or more filler metals are given for a particular dissimilar metal combination, the choice depends upon the specific application.

Table 2.5 *A reference to filler metals for welding nickel-based alloys to steels* (1)

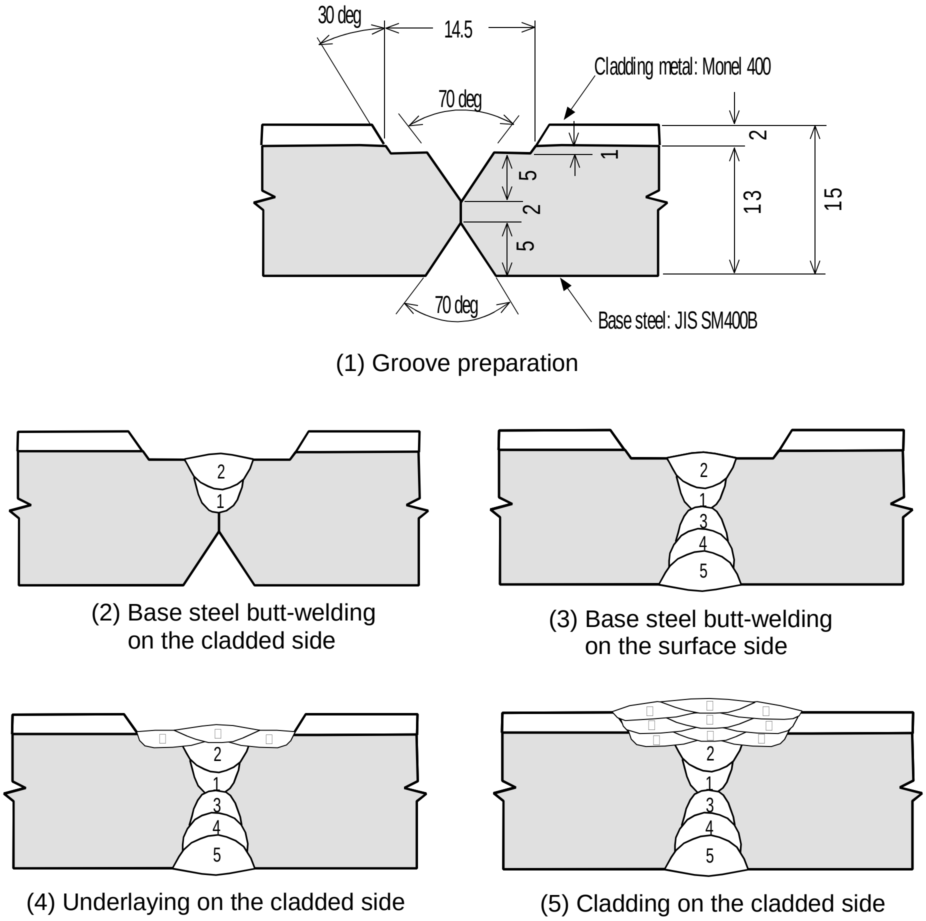
Alloy type	Proprietary alloy	UNS No.	Welding process	AWS class filler metals for each combination of base metals	
				Carbon or low-alloy steel	Stainless steel
200	Nickel 200	N02200	SMAW	ENi-1, ENiCrFe-1, 2, or 3	ENi-1, ENiCrFe-1, -2, or -3
			GTAW	ERNi-1, ERNiCr-3	ERNi-1, ERNiCr-3
400	Monel 400	N04400	SMAW	ENi-1, ENiCu-7, ENiCrFe-1	ENiCrFe-1, 2, or 3
			GTAW	ERNi-1, ERNiCu-7, ERNiCr-3	ERNiCr-3
600	Inconel 600	N06600	SMAW	ENiCrFe-1, -2, or -3	ENiCrFe-1, -2, or -3
			GTAW	ERNiCr-3	ERNiCr-3,
800	Incoloy 800	N08800	SMAW	ENiCrFe-1, -2, or -3	ENiCrFe-1, -2, or -3
			GTAW	ERNiCr-3	ERNiCr-3,
625	Inconel 625	N06625	SMAW	ENiCrFe-2, ENiCrMo-3 or -10	ENiCrFe-2, ENiCrMo-3 or -10
			GTAW	ERNiCr-3, ERNiCrMo-3 or -10	ERNiCr-3, ERNiCrMo-3 or -10
825	Incoloy 825	N08825	SMAW	ENiCrMo-3, ENiCrFe-2 or -3	ENiCrMo-3 or -10
			GTAW	ERNiCrMo-3, ERNiCr-3	ERNiCrMo-3 or -10
B-2	Hastelloy B-2	N10665	SMAW	ENiMo-7, ENiCrMo-10	ENiMo-7, ENiCrMo-10
			GTAW	ERNiMo-7, ERNiCrMo-3 or -10	ERNiMo-7, ERNiCrMo-3 or -10
C-276	Hastelloy C-276	N10276	SMAW	ENiCrMo-4 or -10	ENiCrMo-4 or -10
			GTAW	ERNiCrMo-3 or -4	ERNiCrMo-3 or -4
C-4	Hastelloy C-4	N06455	SMAW	ENiCrMo-7 or -10	ENiCrMo-7 or -10
			GTAW	ERNiCrMo-3, -7 or -10	ERNiCrMo-3, -7 or -10
C-22	Hastelloy C-4	N06022	SMAW	ENiCrMo-3 or -10	ENiCrMo-3 or -10
			GTAW	ERNiCrMo-3 or -10	ERNiCrMo-3 or -10

Note (1) Developed by referring to Refs. 3 and 7, HAYNES' brochure, Nickel Development Institute's guidelines, and Kobe Steel's brochure

(3) Clad steel

Nickel and nickel alloys — Nickel, Monel, Inconel and Hastelloy — are used as cladding metal mainly due to their excellent corrosion resistance. Nickel-based alloy clad steels can be produced by explosion cladding, roll cladding and overlay welding; and explosion and roll cladding processes are mainly used [Ref. 4]. Nickel-based alloy clad steels are extensively used for chemical process equipment, nuclear power plants, salt manufacturing plants and offshore line pipes.

In welding nickel-based alloy clad steels, the base steel is welded first with a steel filler metal as shown in **Figure 2.1**. The filler metal for welding the cladded side can be selected by referring to **Table 2.5** according to the type of the base steel and cladding metal. Particularly, the first layer — dissimilar metal welding — on the cladded side must be carefully welded with minimized dilution, as discussed the above.



Welding procedure	Pass No.	Process	Filler metal
Butt welding	1 thru 5	SMAW	E7016
Underlaying	① thru ③	GTAW	ERNiCu-7
Cladding	④ thru ⑨	GTAW	ERNiCu-7

Figure 2.1 *An example of welding procedure for clad steel*

(4) Lining

To provide steel structures with corrosion resistance, nickel and nickel alloy sheet or strip, generally 1.6 mm thick or heavier, is affixed to the interior of the steel structures such as tanks and vessels by SMAW, GTAW, GMAW, and FCAW with filler metals matching or over-alloying the alloy sheet to be lined. This process is referred to as "alloy lining" or "wallpapering." The lining, however, should be limited to applications where service pressure and temperature fluctuations are negligible; if not, the fluctuations can cause premature failure of the lining due to the fatigue forces on the attachment welds, induced by thermal and mechanical stresses between the lining and the steel substrate.

Figure 2.2 shows typical joints for alloy lining. The shingle joint method (A) is the least expensive, fastest to apply, and most tolerant to fit up. Shingle joints have the disadvantage of the possibility of a direct leak path, which can allow contents to spread widely under the lining. Flue-gas desulfurization equipment is an example of application for this type of lining. The three-bead method (B) offers an ease of fitting but requires more welding and has a greater tendency to iron dilution, especially in the first layer. The batten strip method (C) applies the strip to cover the joints, which provides optimum corrosion resistance. This method is generally used in the chemical process industry.

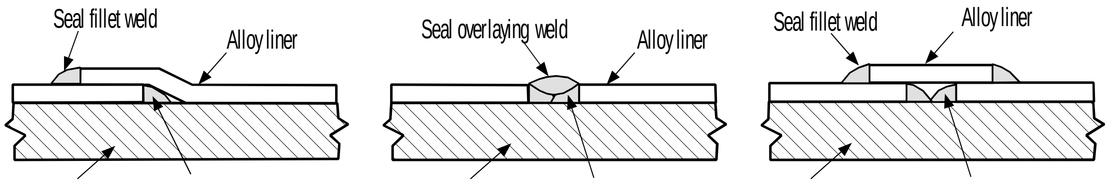


Figure 2.2 *Typical joints for alloy lining*

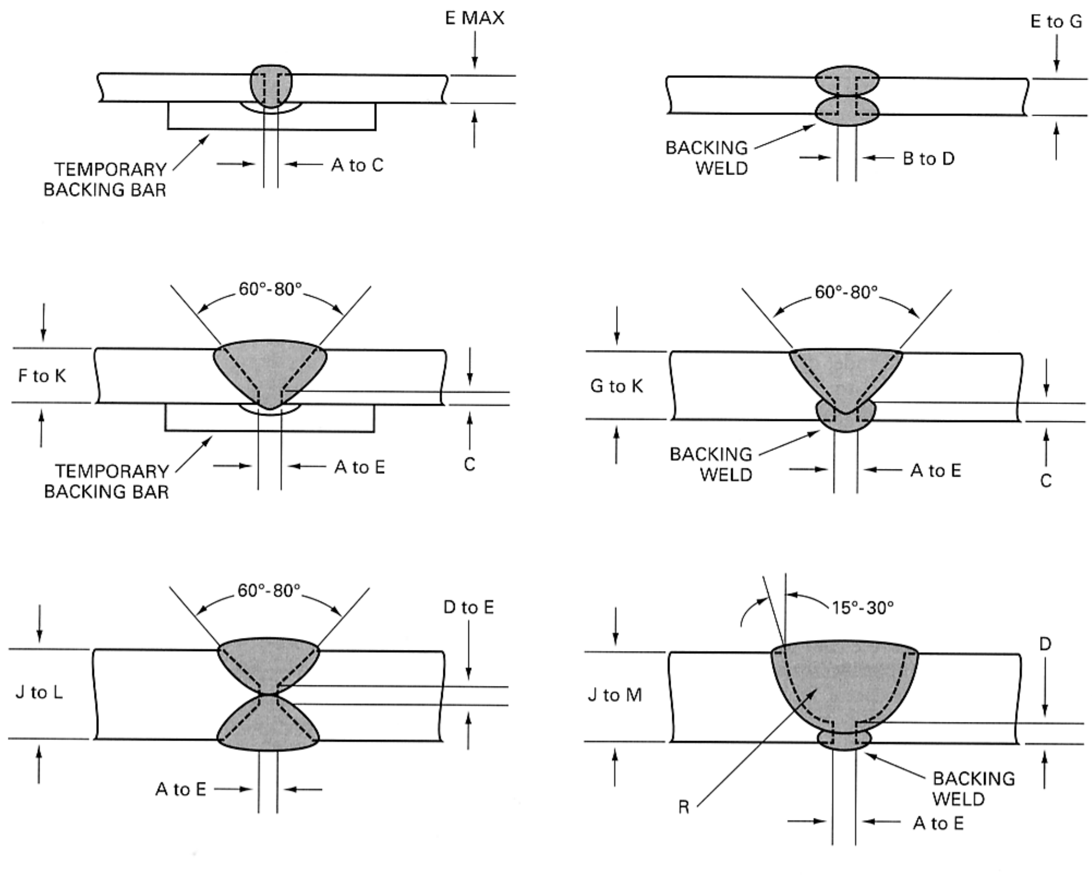
2.3 Tips for successful welding and safe practices

Most of the solid-solution nickel and nickel alloys, except high-silicon castings, can be arc welded by SMAW, GTAW, GMAW, and FCAW. GTAW is the most widely used process due to better weldability. However, specific considerations based on the characteristics of nickel and nickel alloys must be taken to obtain successful results, as discussed in the following.

(1) Joint preparation

The most significant characteristic of nickel and its alloys is the sluggish nature of molten weld metal, which does not spread easily, requiring accurate metal placement by the welder within the welding groove. This is why wider groove angles are used. Secondly, the force of arc is weaker, resulting in the less depth of fusion in nickel-based alloys than in carbon steels. The smaller depth of fusion makes it necessary to use a narrower root face. Based on these specific characteristics, the various joint designs are suggested as shown in **Figure 2.3.** The backing bar (usually copper) is to assist in bead shape on the root side.

In addition to such dimensional requirements, the weld surfaces must be prepared clean without oil, grease, paint, and other sulfur- and lead-bearing substances to prevent hot cracking of the weld metal. Cleaning should be by vapor or solvent degreasing and by brushing with stainless steel — not mild steel — brushes.



Note: A = 0 in. (0 mm); B = 1/32 in. (0.8 mm); C = 1/16 in. (1.6 mm); D = 3/32 in. (2.4 mm); E = 1/8 in. (3.2 mm); F = 3/16 in. (4.8 mm); G = 1/4 in. (6.4 mm); H = 5/16 (7.9 mm); J = 1/2 (12.7 mm); K = 5/8 (15.9 mm); L = 1 1/4 in. (31.8 mm); M = 2 in. (50.8 mm); R = 3/16 to 5/16 in. (4.8 to 7.9 mm).

Figure 2.3 *Suggested designs for arc-welded butt joints in nickel and nickel alloys [Ref. 2]*

(2) SMAW techniques

Most of the covered electrodes for nickel and nickel alloys are recommended to use with direct current electrode positive (DCEP) electrical characteristics for better performance, although some proprietary electrodes can also be used with alternating current. Nickel and nickel-alloy molten weld metals are sluggish with lower fluidity. Therefore, the welder may need to weave the electrode so that the weld pool wets the groove sidewalls to prevent incomplete fusion, but the weaving should not be wider than, as per Ref. 2, three times (1.5 times for Ni-Mo alloys) the electrode core diameter to reduce the risk of hot cracking and porosity in the weld. When the welder is ready to break the arc the weld crater should be treated to form a smaller, slightly convex contour to prevent crater cracking (solidification cracking). When restarting the arc to join the preceding bead, use the backstep technique to prevent the starting porosity. All starts and craters should be strictly inspected and, if necessary, they should be grounded to sound weld. Complete slag removal from all welds is recommended because the slag can accelerate corrosion both in aqueous and high temperature environments.

(3) GTAW techniques

Power supplies equipped with high frequency start, pre-purge and post-purge, and upslope and down-slope controls are recommended. The common polarity is direct current electrode negative (DCEN). In manual GTAW welds, the shielding gas is usually high purity argon for the torch shielding and back purging. For the tungsten electrode, 2% thoriated electrode is used due to longer life. Arc stability is best when the tungsten electrode is ground to a flattened point. As shown for the point geometry recommended in **Figure 2.4**, cone angles of 30 to 60 degrees with a small flat apex are generally used. The point geometry, however, should be designed for the particular application, varying from sharp to flat. The shape of the electrode tip has an effect on the depth of fusion and bead width, with all other welding conditions being equal. The welding torch should be held essentially perpendicular to the workpiece for better shielding effect; if it is inclined too much, air may be drawn into the shielding gas and cause porosity in the weld metal with some nickel alloys. To ensure better shielding effect and minimize heat input, stringer technique is usually employed. During welding, the tip of the welding filler wire should always be held under the shielding gas to prevent oxidation of the hot welding filler wire.

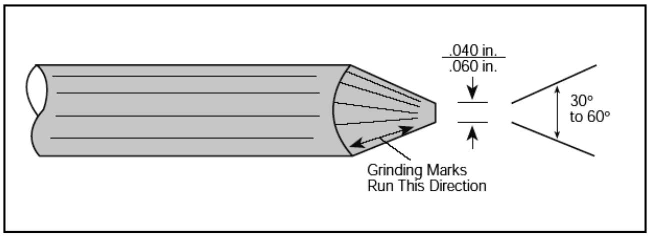


Figure 2.4 *Recommended shape of a tungsten electrode tip for welding Hastelloy alloys (Source: HAYNES International, Fabrication of Hastelloy Corrosion-Resistant Alloys)*

In the manual GTAW process, the amount of filler metal added — thus conversely the amount of base metal melted — may vary considerably depending on welder technique. For this reason, welder training and qualification is very important in terms of the dilution control.

(4) GMAW and FCAW techniques

GMAW uses solid wires, and FCAW uses flux-cored wires for filler metal. The recommended polarity is DCEP with, normally, constant-potential power sources. With a solid wire, the dominant mode of metal transfer is spray transfer, but short circuiting and pulsed spray welding are also widely employed depending on the welding position and joint thickness. For shielding the weld zone, solid wires normally use argon or argon mixed with helium. The addition of helium is believed to be beneficial for obtaining wider and flatter beads and less depth of fusion. The optimum shielding gas will vary with, primarily, the type of metal transfer used for better performance, as shown in **Table 2.6**. In contrast, gas shielded FCAW normally uses 75-80%Ar/Balance CO_2. Still, some proprietary filler metals may use shielding gases with specific compositions.

Table 2.6 *Typical shielding gas for GMAW in nickel and its alloys* [(1)]

Metal transfer mode	Typical shielding gas composition
Spray	100% Argon
Pulsed spray	Argon + 15-25% Helium
Short-circuiting	Argon + 25-50% Helium

Note (1) Developed referring to Ref. 2 and Fabrication of Hastelloy Corrosion-Resistant Alloys, HAYNES International

In manipulating the welding torch, the torch should be kept virtually perpendicular to the joint for better shielding effect. Some slight inclination is permissible to allow the visibility for manual welding; however, excessive displacement can result in aspiration of the surrounding atmosphere into the shielding gas, thereby causing porosity or heavily oxidized welds.

(5) Heat input control

High heat input during welding reduces the cooling speed of the weld, thereby causing some degree of annealing and grain growth in the heat-affected zone (HAZ) of nickel and its alloys. High heat input may result in excessive constitutional liquation and carbide precipitation. The liquation of the interface between weld metal crystals can be opened — thus cracked — by the contraction stresses induced by solidification of the weld metal, which is referred to as the solidification cracking that is often observed in the weld metal and its crater. The liquation occurred in the grain boundaries of a solid weld metal or base metal can be opened or cracked by the restraint stresses of the weldment, which is called the reheat cracking that is often recognized in the heat-affected zone of the base metal. Both cracks are also referred to as hot cracking. Low-melting-point chemical compounds (e.g. Ni_2S_2: 645°C; Ni_2P: 880°C; FeS: 988°C; Fe_2P: 1050°C; FeSi: 1200°C — Ref. 7) and metals (e.g. Pb, Bi and their alloys) are believed to be the principal causes of the inter-crystal and inter-granular liquation. On the other hand, the carbide precipitation, which can occur in the grain boundaries heated in the 500-850°C range [Ref. 6], can be a detrimental effect on the corrosion resistance of the weld.

In order to minimize heat input, the welding current should be lower, the arc length shorter, and the weaving width smaller.

(6) Preheat and interpass temperature control

Preheat is not usually required or recommended in arc welding of nickel and its alloys. However, if the base metal is cold, heating to about 16°C or above [Ref. 2] avoids condensed moisture that could cause weld porosity. However, excessive preheat can cause grain growth if cold-worked base metal is brought above its recrystallization temperature. In addition, to reduce the risk of hot cracking and minimize the carbide precipitation, the weld should be cooled faster by controlling preheat and interpass temperatures. A preheat and interpass temperature of 150°C max is widely used, although 90°C max [Ref. 2] is recommended for some corrosion-resistant alloys.

(7) Porosity considerations

Porosity is one of the problems encountered in welding nickel and its alloys. To prevent the occurrence of porosity in the weld metal, (1) shielding gas must possess sufficient qualities with low amounts of impurity, (2) welding technique must be correct to protect the weld pool from the atmosphere, and (3) the equipment for GTAW, GMAW, and FCAW must be maintained free from shielding gas contamination and turbulence.

Porosity can be caused by hydrogen, oxygen and nitrogen in the weld metal. Nickel and nickel alloys can dissolve a high amount of hydrogen in molten state, and even in solid state, they can dissolve a high amount of hydrogen about three times that in low carbon steel. Therefore, hydrogen alone seldom causes porosity. On the other hand, molten nickel can dissolve a high amount of oxygen (1.18% at 1720°C) but the solubility reduces to 1/20 (0.06% at 1470°C) when it solidifies. Such an excessive amount of oxygen oxidizes the molten nickel to produce NiO. Then NiO can react with hydrogen ($NiO + H_2 \rightarrow Ni + H_2O$) in the nickel to produce water vapors, thereby causing porosity. Oxygen can also combine with carbon in the molten nickel to produce CO, which causes porosity. On the other hand, nitrogen cannot produce stable nitrides with nickel; therefore, it causes porosity [Ref. 1]. To prevent porosity, the use of correct filler metal and welding procedure is essential.

(8) Safe practices [Ref. 2]

Compounds of chromium, including hexavalent chromium, and of nickel may be found in fumes from welding processes. The specific compounds and concentrations will vary with the welding processes and the compositions of the base and filler metals; hence, consult the manufacturers Material Safety Data Sheets (MSDS) for the products being used. Immediate effects of overexposure to welding fumes containing chromium and nickel are similar to the effects produced by fumes of other metals. The fumes can cause symptoms such as nausea, headaches, and dizziness. Some persons may develop a sensitivity to chromium or nickel that can result in dermatitis or skin rash.

The fumes and gases should not be inhaled, and the face should be kept out of the fumes. Sufficient ventilation or exhaust at the arc, or both, should be used to keep fumes and gases away from the welder's breathing zone and the general area. In some cases, natural air movement will provide enough ventilation. Where ventilation may be questionable, air sampling should be used to determine if corrective measures should be applied.

Nickel and chromium must be considered possible carcinogens under the Occupational Safety and Health Act (OSHA 29CFR1910.1200) of the USA. Long-term exposure without proper ventilation to welding fumes, gases, and particulate may have long-term effects of skin sensitization, neurological damage, and respiratory disease such as bronchial asthma, lung fibrosis, or pneumoconiosis.

Use local exhaust when cutting, grinding, or welding nickel or nickel alloys. Exposures to fumes, gases, and dusts generated in welding should not exceed permissible exposure limits. Confined spaces require special attention. Wear correct eye, ear, body, and respiratory protection.