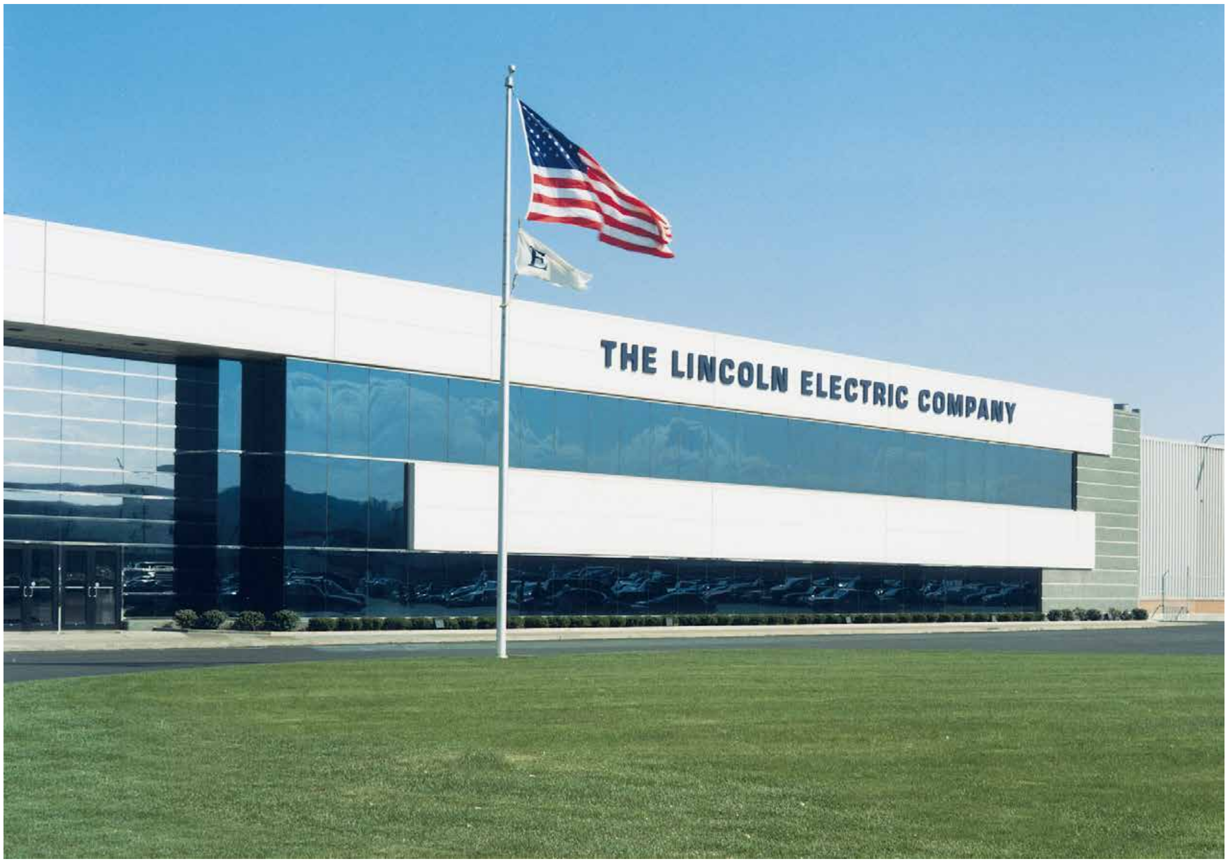
Aluminum GMAW

Gas Metal Arc Welding for Aluminum Guide

LINCOLN ELECTRIC



Lincoln Electric is the world's leading manufacturer of welding equipment and consumables. Our focus is on helping companies make their welding operations more effective, more efficient and more profitable.

We are dedicated to two equally important goals: exceptional quality and exceptional service. Our field support team — with hundreds of field sales engineers and thousands of knowledgeable and responsive Lincoln Electric distributors in countries all over the world — is the largest in the industry. Innovative thinking. A service-first attitude. Fresh approaches to design, manufacturing and packaging. Worldwide strength.

THAT'S LINCOLN ELECTRIC.

Sample defect from spool of competitive product

SuperGlaze "Best in Class"

For superior welding performance, turn to SuperGlaze® aluminum MIG wire from Lincoln Electric. SuperGlaze prevents the problems usually associated with aluminum wire feeding, such as birdnesting, tangling and burnback, to provide a stable arc, great feedability and exceptional control every time you weld! The keys are SuperGlaze's smooth surface finish and consistent chemical composition. What this means for you is a product that produces high quality, exceptionally productive welds.

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As a major supplier of welding wire, Lincoln Electric is the leader in MIG wire manufacturing technology. We carry that same technology and expertise to our aluminum MIG wire manufacturing. Lincoln Electric has the only fully integrated aluminum MIG wire facility in the world. We start from raw primary aluminum and then use state-of-the-art equipment to produce a complete range of aluminum alloys including 1100, 1070, 2319, 4043, 4047, 5087, 5183, 5356, 5554 and 5556. This gives us full control of welding chemistry throughout the process as well as the ability to always deliver product to our customer, regardless of market conditions.

WHAT MAKES SUPERGLAZE STAND OUT FROM THE REST?

Three unique features:

1. A manufacturing process that precisely controls the alloy chemical composition to produce consistent physical characteristics.
2. A proprietary process that gives SuperGlaze a superior surface finish for optimum surface integrity.
3. A technical services team with years of experience dedicated to aluminum welding.

What all this means to you is outstanding welding characteristics, spool to spool, time after time. Lincoln Electric's aluminum MIG wire combined with our advanced MIG welding equipment and help from our technical services team makes aluminum as easy to weld as any other material.

Contents

The use of aluminum as a structural material is fairly recent. In fact, when the Washington Monument was completed in December 1884, it was capped with a 100 oz. pyramid of pure aluminum because aluminum was considered a precious metal.

Aluminum was not widely used at that time because it is a reactive metal. It is never found in its elemental state in nature. Instead, it is always tightly bound with oxygen as aluminum oxide (Al_2O_3), also known as bauxite ore. Although bauxite ore is plentiful, a direct reduction method to produce aluminum from bauxite has yet to be discovered. It was only in 1886, when the American Charles M. Hall and the Frenchman Paul Heroult almost simultaneously (but independently) discovered electrolytic processes for obtaining pure aluminum from aluminum oxide, that aluminum became available in commercial quantities. The processes discovered by Hall and Heroult are still used today, with some modifications. The massive amount of electrical power required to produce aluminum is the main reason for its higher cost relative to steel.

Aluminum is wideley used in numerous applications:

» It conducts electricity and heat almost as well as copper.
» It is widely used in electrical bus bars and other conductors, heat exchangers of all kinds, and cookware.
» It becomes stronger rather than brittle with decreasing temperature, so it has found wide application in cryogenic equipment at temperatures as low as -452°F (-269°C).
» It is very corrosion resistant in most environments, so it has found wide applications in marine and chemical environments.

The characteristics of aluminum alloys that make them attractive as structural materials are their light weight (one third the weight of steel for equal volumes) and their relatively high strength (equal in many cases to that of construction steel grades). This combination has resulted in increased use of aluminum alloys in applications such as passenger automobiles, trucks, over-the-road trailers and railroad cars. Additionally, the structure of most aircraft is fabricated mainly from aluminum alloys, although pieces are most often joined by riveting in these applications.

1.1 WELDING ALUMINUM VS. WELDING STEEL

We often approach welding of aluminum as if it is just shiny steel. Most welders begin by learning how to weld steel, with some moving on to welding aluminum. Most welding equipment is designed to weld steel, with welding of aluminum alloys being an afterthought (this has begun to change).

However, the differences between steel and aluminum mean that you need a specialized approach to welding of aluminum. The balance of this guide will discuss the main differences between welding of aluminum and welding of steel and how to address them.

THE DIFFERENCES BETWEEN WELDING STEEL AND WELDING ALUMINUM CAN BE SUMMED UP IN THREE STATEMENTS:

1. Almost all steels are weldable if you take enough care. There are some aluminum alloys that are just not arc weldable. Fabricators fall into this trap regularly. We'll discuss the weldability of the various alloy families in detail. At this point, let's just say that many aluminum alloys, especially the stronger ones, are not weldable.
2. All steels are heat-treatable. Some aluminum alloys are heat-treatable, but some are not. Even for the heat-treatable aluminum alloys, the heat treatments are totally different from those used for steel. In fact, if you heat up some alloys and quench them, they will become softer instead of harder. Be aware of the differences and act accordingly.
3. When welding steels, you can almost always make a weld that is as strong as the parent material. In aluminum alloys, the weld will rarely be as strong as the parent material. This is usually true for welds in both heat-treatable and nonheat-treatable alloys. The strength difference between the weld or heat affected zone (HAZ) and the parent material is often significant, usually 30% or more.

1.2 METALLURGY

To understand aluminum, we must first understand some basics about aluminum metallurgy. Aluminum can be alloyed with a number of different elements, both primary and secondary, to provide improved strength, corrosion resistance and general weldability.

The primary elements that alloy with aluminum are copper, silicon, manganese, magnesium and zinc. It is important to note that aluminum alloys fall into two classes: heat-treatable or nonheat-treatable.

Heat-treatable alloys are those that are heat treated to increase their mechanical properties. To heat treat an alloy means heating it at a high temperature, putting the alloying elements into solid solution and then cooling it at a rate that will produce a super saturated solution. The next step in the process is to keep the solution at a lower temperature long enough to allow a controlled amount of precipitation of the alloying elements.

With nonheat-treatable alloys, it is possible to increase strength only through cold working or strain hardening. To do this, a mechanical deformation must occur in the metal structure, producing higher strength and lower ductility and therefore resulting in increased resistance to strain.

1.2.1 ALUMINUM ALLOYS

Just as the American Iron and Steel Institute (AISI) registers steel chemistries and grades, the Aluminum Association (AA) registers alloy designations, chemistries and mechanical properties for aluminum alloys. However, the alloy designation system is totally different from that used for steels. Additionally, different designation systems are used for wrought and cast alloys.

1.2.2 WROUGHT ALLOYS

Wrought alloy designations use a four digit number plus a temper designation, which we will discuss later. Aluminum alloys are broken up into eight “families” depending on the main alloying elements. The aluminum alloy families are shown in Table 1-1, along with their heat-treatability.

Table 1-1: Wrought Alloy Designations

Alloy Family	Main Alloying Elements	Heat -treatable
1xxx	Pure Aluminum	No
2xxx	Copper (sometimes with magnesium)	Yes
3xxx	Manganese (sometimes with magnesium)	No
4xxx	Silicon	No
5xxx	Magnesium	No
6xxx	Magnesium plus silicon	Yes
7xxx	Zinc (sometimes with magnesium & copper)	Yes
8xxx	All others	Normally Yes

Note: The designation 2XXX etc is an industry standard abbreviation used to mean “all alloys in the 2000 series”.

If you have a piece of 6061, it’s clear that it is a wrought alloy (4 digits), it’s heat-treatable, and it contains magnesium and silicon. The second digit of the four shows whether the alloy is the first such alloy registered. If this is the case, the second digit will be “0”, as in 5054. Digits other than “0” indicate that the alloy is a modification of a registered alloy. 5154 would be the first modification of 5054. Alloy 5754 is the seventh modification. The last two digits are assigned arbitrarily by the Aluminum

Association when the alloy is registered. Note that the material designation gives no indication of alloy or weld strength.

1.2.3 CAST ALLOYS

The designation system for cast alloys classified into families is shown in Table 1-2. The families are somewhat different from the designations for wrought alloys. These designations have only three digits, followed by a decimal point and one more digit. For these alloys, the first digit shows the alloy family. The next two digits are arbitrarily assigned. Alloy modifications are indicated by a letter prefix: 356 would be the original version of an alloy, A356 is the first modification, B356 is the second modification, etc. The number following the decimal point designates whether the alloy is produced as a casting of final form or as an ingot for remelting.

Table 1-2: Cast Alloy Designations

Alloy Family	Main Alloying Elements	Heat -treatable
1XX.X	Pure Aluminum	No
2XX.X	Copper (sometimes with magnesium)	Yes
3XX.X	Silicon plus magnesium	Yes
4XX.X	Silicon	Yes
5XX.X	Magnesium	No
6XX.X	Not Used	NA
7XX.X	Zinc	Yes
8XX.X	Tin	No
9XX.X	Other	

1.3 ALLOYING ELEMENTS

Pure Aluminum (1XXX series). Contains no alloying elements and is not heat-treatable. It is used primarily in chemical tanks and pipe because of its superior corrosion resistance. This series is also used in electrical bus conductors because of its excellent electrical conductivity. It is easily welded with 1100 and 4043 filler wires.

Copper (2XXX series) Provides high strength to aluminum. This series is heat-treatable and mainly used in aircraft parts, rivets and screw products. Most 2XXX series alloys are considered poor for arc welding because of their sensitivity to hot cracking. Most of these alloys should not be welded, however, alloys 2014, 2219 and 2519 are easily welded with 4043 or 2319 filler wire. These three alloys are widely used in welded fabrication.

Manganese (3XXX series). Yields a nonheat-treatable series used for general-purpose fabrication and build-up. Moderate in strength, the 3XXX series is used for forming applications including utility and van trailer sheet. Strain hardening will improve it by providing good ductility and improved corrosion properties. Typically welded with 4043 or 5356 filler wire, the 3XXX series is excellent for welding and not prone to hot cracking. Its moderate strengths prevent this series from being used in structural applications.

Silicon (4XXX series). Silicon reduces the melting point of aluminum and improves fluidity. Its principal use is as filler metal. The 4XXX series has good weldability and is considered a nonheat-treatable alloy. Alloy 4047 is often used in the automotive industry because it is very fluid and good for brazing and welding.

Magnesium (5XXX series). When added to aluminum, magnesium has excellent weldability, good structural strength and is not prone to hot cracking. In fact, the 5XXX series has the highest strength of the nonheat-treatable aluminum alloys. It is used for chemical storage tanks and pressure vessels as well as structural applications, railway cars, dump trucks and bridges because of its corrosion resistance.

Silicon And Magnesium (6XXX series). This medium strength, heat-treatable series is primarily used in automotive, pipe, railings and structural extrusion applications. The 6XXX series is prone to hot cracking, but this problem can be overcome by the correct choice of joint and filler metal. Can be welded with either 5XXX or 4XXX series without cracking — adequate dilution of the base alloys with selected filler wire is essential. A 4043 filler wire is the most common for use with this series. 6XXX alloys should never be welded autogenously, as they will crack.

Zinc (7XXX series) Zinc added to aluminum with magnesium and copper produces the highest strength heat-treatable aluminum alloy. It is primarily used in the aircraft industry. The weldability of the 7XXX series is compromised in higher copper grades, as many of these grades are crack sensitive due to wide melting ranges and low solidus melting temperatures. Grades 7005 and 7039 are weldable with 5XXX filler wires. They are widely used for bicycle frames and other extruded applications.

Other (8XXX series). Other elements that are alloyed with aluminum (i.e., lithium) all fall under this series. Most of these alloys are not commonly welded, though they offer very good rigidity and are principally used in the aerospace industry. Filler wire selections for these heat-treatable alloys include the 4XXX series.

In addition to the primary aluminum alloying elements, there are a number of secondary elements, chromium, iron, zirconium, vanadium, bismuth, nickel and titanium. These elements combine with aluminum to provide improved corrosion resistance, increased strength and better heat treatability.

1.4 TEMPER DESIGNATIONS

The information above allows an aluminum alloy to be recognized by its chemistry, but not by the heat treatment or mechanical properties. To show these properties, temper designations are assigned. The complete designation of an alloy might be 6061-T6 or 5083–H114. Most of these designations are different for heat-treatable and nonheat-treatable alloys; however, two common designations apply to all alloys:

» "O" Temper (not zero). When an alloy is given this designation, the supplier has annealed the alloy, typically at 650-750°F (343-300°C), and it is as soft as possible.
» "F" Temper. When an alloy is supplied in this temper, it is supplied "as fabricated". This means the supplier is guaranteeing that the chemistry of the material meets the chemical requirements for the specified alloy, but there are no claims regarding the mechanical properties of the alloy. This temper is often specified by fabricators who subsequently forge or form the supplied material and establish mechanical properties by heat treatment after forming.

To discuss the remainder of the temper designations, we need to discuss the heat-treatable and nonheat-treatable alloys.

1.4.1 NONHEAT-TREATABLE ALLOYS — STRAIN-HARDENED DESIGNATIONS

These alloys cannot be strengthened by heat treatment. However, they can be strengthened by cold working, also called strain hardening. If an aluminum alloy is deformed at elevated temperatures, 600°F (315°C) or higher, little or no strengthening takes place. However, if the alloy is deformed at lower temperatures, it will gain strength. In general:

» The more the alloy is deformed, the stronger it gets. Finally, at some point, the alloy will have no ductility and will fracture.
» The higher the alloy content, the more it will gain strength by being deformed.

Both of these phenomena are shown in Figure 1-1.

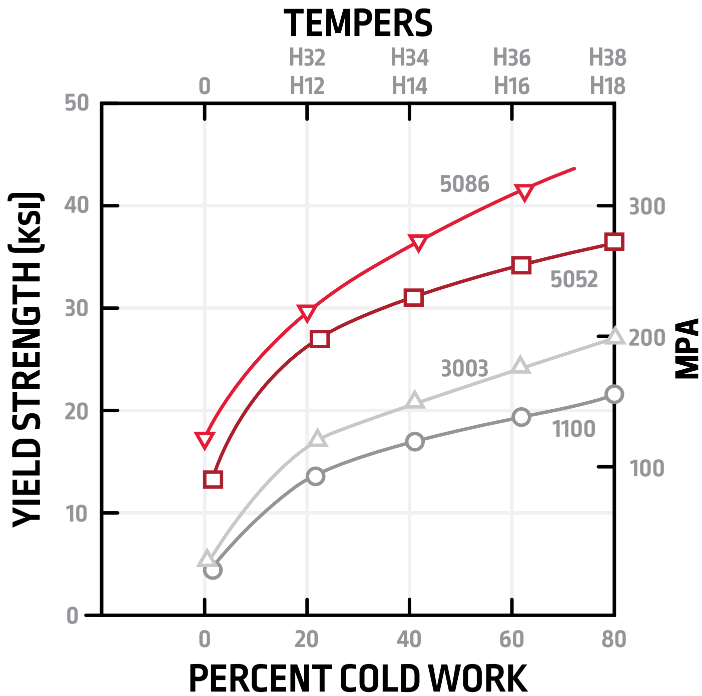


Figure 1-1: Relationship of Yield Strength, Amount of Cold Work and Alloy Content.

The temper designation for strain hardened alloys is usually made up of two digits, as shown in Table 1-3.

The first digit shows whether the alloy is only strained or whether it has been partially annealed and/or stabilized. The second digit shows how much strain hardening has been put into the alloy. Higher numerical values mean higher strain levels, which means higher yield and tensile strengths.

Table 1-3: "H" Temper Designations	
First Digit Indicates Basic Operations	
H1-	Strain Hardened Only
H2-	Strain Hardened and Partially Annealed
H3-	Strain Hardened and Stabilized
Second Digit Indicates Degree of Strain Hardening	
HX2-	Quarter Hard
HX4-	Half Hard
HX6	Three-Quarters Hard
HX8-	Full Hard
HX9-	Extra Hard

1.4.2 HEAT-TREATABLE ALLOYS

Strain hardened “H” tempers are not used for heat-treatable alloys. Instead, a series of “T” tempers that indicate the heat treatment state are used. A total of (10) tempers exist; T1 through T10. The commonly seen designations are T4 and T6.

Aluminum alloys are heat-treatable because of a phenomenon called precipitation hardening. They do not harden by a martensitic transformation as steel does. In precipitation hardening, one metal can be dissolved in another in a “solid solution,” and solubility generally increases with temperature. For example, just as sugar will dissolve in a cup of tea when heated, copper, zinc or combinations of magnesium and silicon will dissolve in aluminum as it is heated.

When the heat-treatable alloys are heated to approximately 950°F (510°C) and held for a few minutes, all the alloying elements are taken into a solution in the solid aluminum. This is called a “solution heat treatment”. Normally, the alloy is quenched in water after this point to arrive at the T4 temper. Although the T4 temper is substantially stronger than the annealed “O” temper, the primary purpose of quenching is not strengthening by phase transformation. Instead, the quenching serves to keep the alloy additions in solution at room temperature. If the aluminum were cooled slowly from the solution treatment, the alloying additions would re–precipitate and no strengthening would occur.

The tensile and yield strengths of the material will increase for several weeks after the heat treatment and can increase significantly in some alloys. After this initial period, the alloy is stable indefinitely. The customer is generally unaware of this initial strength increase because the aluminum producer doesn’t ship the alloy until the strength has stabilized.

The T4 temper, while stable, does not give the alloy maximum strength. Most alloys are sold in a maximum strength T6 temper. To get from T4 to T6 temper, the material is put in a furnace at a temperature of 325°F to 400°F (163°C to 204°C) and allowed to age 1 to 5 hours. The dissolved alloying elements will form submicroscopic pre-precipitates in the material and produce maximum strength. If this aging heat treatment is carried out at too high a temperature or for too long, the precipitates will get too large and a lower strength, “overaged” condition will result.

Note: This final aging heat treatment is carried out at 400°F (204°C) maximum. The welding heat, which can heat the surrounding material to well over this temperature, can significantly degrade the strength of the heat affected zone (HAZ). This is discussed in more detail on the following page.

As before, it is easiest to discuss the effects of welding on the mechanical properties of aluminum weldments if we discuss nonheat-treatable alloys and heat-treatable alloys separately.

2.1 NONHEAT-TREATABLE ALLOYS

As was discussed earlier, these alloys can be, and often are, strengthened by cold working. Cold worked alloys can have yield and tensile strengths twice those of the annealed "O" temper alloy. These cold worked alloys can be softened back to the "O" temper by annealing at 650-700°F (343-371°C). Since the heat of welding produces temperatures considerably higher than this at the weld fusion line, the result of welding is that the HAZ of welds in nonheat-treatable alloys (i.e., 1XXX, 3XXX, 4XXX, and 5XXX) becomes annealed. Therefore, the strength of the weld joint is always equal to the strength of the "O" temper annealed base material, regardless of what the starting temper of the parent material was. If you weld "O" temper material, the weld will be as strong as the starting parent material. If you weld any material that is strain hardened (i.e., cold worked), the weld will be weaker than the starting material, perhaps significantly weaker.

The HAZ can never become softer then the "O" temper, so excess welding heat input will not make the HAZ softer. It can, however, make the HAZ wider. Normally, this will not further reduce the strength of the welded joint, although other problems can arise due to excessive heat input.

From a practical standpoint, there is no way to regain the strength lost during welding. If the weld is cold worked, it will begin to work harden again. However, this is not usually a practical industrial solution because, in most cases, the weld will not be as strong as the starting cold worked material.

2.2 HEAT-TREATABLE ALLOYS

There is no blanket statement that can be made about the welded strength of heat-treatable alloys. As previously stated, the weld will generally be weaker than the parent material. However, the welded properties will strongly depend on the temper of the material before welding and also on heat treatments performed after welding. Figure 2-1 shows a micro-hardness trace across a weld, starting at the center of the weld. The graph actually shows four curves representing what happens to material in the T4 and T6 tempers in the as-welded (AW) and post-weld heat-treated (PWA) conditions.

Note the following:

1. The HAZ is about 1/2 in. (12.7 mm) wide. The actual width of the HAZ will depend on a number of things, including the welding process used and the thickness of the material. HAZ widths of 1 in. (25.4 mm) are not uncommon in thin materials.
2. The hardness and strength of the weldment is typically lowest in the HAZ. Because of this, strength of the welding filler alloy is not a primary concern when making butt welds. A weld will most often fail in the HAZ.
3. Unlike nonheat-treatable alloys, the hardness (and therefore strength) in the HAZ is not always the same. It depends on the material temper prior to welding and whether the weld is post-weld aged.
    a. The weakest HAZ occurs when the material is welded in the T6 temper and used as-welded.
    b. The HAZ, and therefore the weldment, will actually be slightly stronger if the material is used in the T4 temper and used as welded.
    c. If the weldment in either T4 or T6 material is post-weld aged, the strength of the HAZ can increase significantly. The exact post-weld heat treatment varies with the alloy, but aging at around 400°F (204°C) for about one hour is generally recommended.

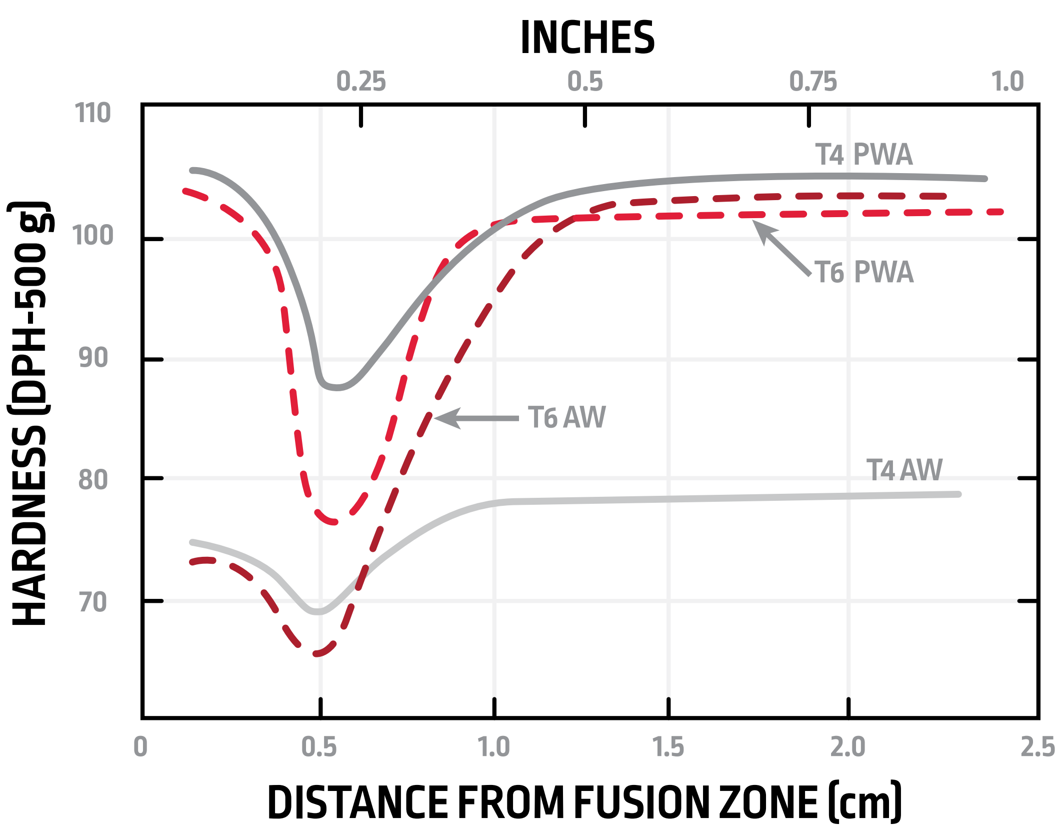


Figure 2-1: Hardness vs Distance for 6061-T4 and T6 in the As-Welded (AW) and Post-Weld Aged (PWA) Conditions

When you fabricate using heat-treatable alloys, you have options that are not available with nonheat-treatable alloys when it comes to recovering some of the strength lost during welding. For instance, since the 6XXX alloys bend more easily and around a smaller radius in the T4 temper than in the T6 temper, these alloys can be bought in the T4 temper, formed easily, welded and then aged. The resulting mechanical properties will be significantly higher than if the material was purchased in the T6 temper.

Finally, if the right filler alloy is chosen, the finished weldment can be completely heat-treated and the T6 properties restored.

Please note that this requires a re-solution heat treatment, quench and re-aging. This is often practical for small structures, but not for large ones. For example, aluminum bicycle frames are often fabricated in this way.

The HAZ of welds in heat-treatable alloys is significantly different from the HAZ in nonheat-treatable alloys. The strength of the HAZ in heat-treatable alloys can be considerably reduced if excessive heat input is used. Therefore, it is very important not to use excessive preheats [200°F (93°C) maximum is recommended], to carefully monitor interpass temperatures [250°F (121°C) maximum is recommended], and to avoid practices such as wide weave passes, which will result in excessive heat input.

3.1 ALUMINUM FILLER ALLOYS

Most common aluminum filler alloys fall into the 4XXX and 5XXX families, with a few coming from the 1XXX, 2XXX and the casting alloys. The chemical composition of the common aluminum filler alloys is shown in Table 3-1.

A number of characteristics determine the best filler metal choice for a given base material or combination of base materials. Among these are::

- Freedom from hot cracking
- Weld metal ductility
- Weld metal corrosion resistance
- Weld metal shear strength in fillet and lap joints
- Ease of welding (i.e., weldability)
- Filler wire feedability
- Weld color match with parent metal for applications requiring post-weld anodizing

There are a number of filler metal selection charts that have taken these factors into account and give good overall recommendations for filler metal selection. A composite of these charts, which covers most alloy combinations, is shown in Table 3-4 on page 22.

In general, filler alloy recommendations for the various alloy families can be summarized as follows:

1XXX Alloys — These alloys are usually used for their electrical conductivity and/or corrosion resistance. Their sensitivity to hot cracking is very low. They are usually welded using 1100 or 1188 fillers, but matching filler metals are also available for specialized alloys such as 1350. If electrical conductivity of the joint is not of primary importance, 4043 may be used.

2XXX Alloys — Many alloys in this series are not arc weldable. Those that are include 2219, 2014, 2519, 2008 and 2036. Alloy 2319 is a matching filler alloy for 2219 and 2519 and can also be used on the other weldable alloys. Alloys 4043 and 4145, which contain copper, can also be used. Alloy 5XXX fillers should not be used to weld 2XXX parent materials, because cracking will result.

3XXX Alloys — These moderate strength aluminum–manganese alloys are relatively crack resistant and can easily be welded using either 4043 or 5356.

Table 3-1: Wire Chemical Composition for Common Aluminum Wires											
AWS A5.10-99 ASME SFA-5.10 Classification	%Mn	%Si	%Fe	%Mg	%Cr	%Cu	%Ti	%Zn	%Be	%Others(1)	%Al
ER1100 & Alloy 1050	0.05	–	–	–	–	0.05-0.02	–	0.10	–	0.05	99.0
ER2319	0.20-0.40	0.20	0.30	0.02	–	5.8-6.8	0.10-0.20	0.10	(2)	0.05(3)	Balance
ER4043	0.05	4.5-6.0	.08	0.05	–	0.30	0.20	0.10	(2)	0.05	Balance
ER4047	0.15	11.0-13.0	0.8	0.10	–	0.30	–	0.20	(2)	0.05	Balance
Alloy 5052	0.10	0.25	0.40	2.2-2.8	0.15-0.35	0.10	–	0.10	(2)	0.05	Balance
Alloy 5056	0.05-0.20	0.30	0.40	4.5-5.6	0.05-0.20	0.10	–	0.10	(2)	0.05	Balance
Alloy 5154	0.10	0.25	0.40	3.1-3.9	0.15-0.35	0.10	0.20	0.20	(2)	0.05	Balance
ER5183	0.50-1.0	0.40	0.40	4.3-5.2	0.05-0.25	0.10	0.15	0.25	(2)	0.05	Balance
ER5356	0.05-0.20	0.25	0.40	4.5-5.5	0.05-0.20	0.10	0.06-0.20	0.10	(2)	0.05	Balance
ER5554	0.50-1.0	0.25	0.40	2.4-3.0	0.05-0.20	0.10	0.05-0.20	0.25	(2)	0.05	Balance
ER5556	0.50-1.0	0.25	0.40	4.7-5.5	0.05-0.20	0.10	0.05-0.20	0.25	(2)	0.05	Balance
ER5654	0.01	–	–	3.1-3.9	0.15-0.35	0.05	0.05-0.15	0.20	(2)	0.05	Balance

NOTE: Single values are maximum, except aluminum.
(1) Total of "others" shall not exceed 0.15%.
(2) Beryllium shall not exceed 0.0003%.
(3) Vanadium content shall be 0.05 - 0.15% and Zirconium content shall be 0.10 - 0.25%.

4XXX Alloys — These alloys are usually found as welding or brazing fillers. In the rare event you encounter them as parent materials, 4047 is usually the best choice as a filler metal.

5XXX Alloys — These higher strength aluminum–magnesium alloys are the most common structural aluminum sheet and plate alloys. The general rule, except for the alloy 5052, is to choose a 5XXX filler metal with slightly higher magnesium content than the parent material being welded. For all alloys except 5052, 5XXX alloys should not be welded using 4XXX filler alloys. The high Mg content of the parent material, when combined with the high Si content of the 4XXX fillers, will result in a high level of Mg_2Si — a brittle intermetallic compound that will cause the weld to have poor ductility and toughness. In choosing filler alloys for 5XXX alloys, there are several specific recommendations:

5052 — This alloy has just the right amount of Mg content to exhibit a relatively high crack sensitivity. If it is welded with 5052 filler alloy, it will often crack. To avoid the tendency to crack, 5052 is usually welded with a filler alloy of much higher Mg content, such as 5356. The resulting weld metal, which is an alloy of the 5356 and 5052, has a Mg content high enough to be crack resistant. Additionally, the Mg content of 5052 is low enough that it can be successfully welded using 4043.

High Temperature Applications — Al-Mg alloys with Mg content over 3% are unsuitable for service temperatures over 150°F (65°C) because they are susceptible to stress corrosion cracking at higher temperatures. This is true for filler alloys as well and should be taken into account in selecting filler alloys.

5454 — This alloy is a lower Mg alloy specifically developed to be immune to the stress corrosion cracking noted above. Filler alloy 5554 is designed as a matching filler alloy for 5454 and should be used whenever possible.

5083 and 5456 — These high Mg, high strength alloys can be successfully welded using 5356. However, most structural codes require that welds in these alloys have a minimum ultimate tensile strength of 40 ksi (276 MPa). When welded using 5356, welds in these alloys will often fail to meet this requirement. For this reason, 5183 or 5556 are recommended for these alloys.

Table 3-2: Aluminum Product Selection Guide

ER4043	SuperGlaze® 4043
ER4047	SuperGlaze® 4047
ER5183	SuperGlaze® 5183
ER5356	SuperGlaze® 5356
ER5554	SuperGlaze® 5554
ER5556	SuperGlaze® 5556

6XXX Alloys— These Al-Mg-Si alloys are primarily used for extrusion alloys, although they can often be found as sheet and plate as well. The chemistry of these alloys makes them very sensitive to hot short cracking. Autogenous welds (i.e., welds made without adding filler metal) will almost always crack. This is why 6061 filler metal does not exist. If it did, welds made using it would crack. Yet these alloys are readily weldable using either 4043 or 5356 filler metal. Since the chemistry of 4043, Al with 5% Si, or 5356, Al with 5% Mg, is so different from that of 6061, when either is mixed with 6061 the result is a weld with a crack resistant chemistry. In fact, the vast majority of weld cracking in 6XXX alloys is caused by not adding enough crack resistant filler to the weld, leaving it crack sensitive. Weldments that use square butt joint preparations are particularly prone to this problem. The easiest solution is to make a small V preparation instead of a square butt, which allows the welder to add more filler alloy.

Whether to use 4043 or 5356 depends on a number of factors. 4043 is easier for the welder to use, flows better and is more crack resistant. Filler metal 5356 feeds better and yields welds that are stronger (especially in lap welds and fillet welds) and more ductile. 5356 should be used to weld the 6XXX alloys to any of the 5XXX alloys. 4043 should be used to weld the 6XXX alloys to the common 3XXX casting alloys.

7XXX Alloys — Although most of these alloys are not arc-weldable, 7005, 7003 and 7039, display good weldability. These alloys should be welded using 5356.

Figure 3-1: SuperGlaze® Aluminum GMAW Wire

Table 3-3: Comparison of Filler Metals 4043 and 5356

ER4043	ER5356
Smooth Bead, Good Wetting	Black Smut, Distinct Ripples
Lower Column Strength	Best Feedability
Higher Penetration	Lower Penetration
Lower Ductility	Higher Ductility
Lower Tensile	Higher Tensile
More Prone to Porosity	Less Prone to Porosity
Anodizes a Dark Grey	Anodizes with Good Color Match
Much Lower Shear Strength	Higher Shear Strength
Lower Cracking Sensitivity	Higher Cracking Sensitivity
Lower Melting Point	Higher Melting Point
Narrower Melting Range	Wider Melting Range

Table 3-4: Aluminum Filler Alloy Chart

BASE ALLOYS	FILLER ALLOYS	1060 1070 1080 1350						1100						2014 2036						2219 2519					
Characteristics		W	S	D	C	T	M	W	S	D	C	T	M	W	S	D	C	T	M	W	S	D	C	T	M
319.0 333.0 354.0 355.0 C355.0 380.0	2319													B	A	A	A	A	A	B	A	A	A	A	A
	4043/4047	B	A	A	A	A	A	B	A	A	A	A	A	C	C	B	C	A	A	C	C	B	C	A	A
413.0 443.0 444.0 356.0 A356.0 A357.0 359.0	4043/4047	A	A	A	A	A	A	A	A	A	A	A	A	B	B	A	A	A	A	B	B	A	A	A	A
7005 7021 7039 7046 7146 710.0 711.0	4043/4047	A	A	C	A	A		A	A	C	A	A		B	B	A	A	A		B	B	A	A	A	
	5087	B	A	B	A		A	B	A	B	A		A												
	5183	B	A	B	A		A	B	A	B	A		A												
	5356	B	A	A	A		A	B	A	A	A		A												
	5554																								
	5556	B	A	B	A		A	B	A	B	A		A												
	5556A	B	A	B	A		A	B	A	B	A		A												
	5754																								
6061 6070	4043/4047	A	A	C	A	A		A	A	C	A	A		B	B	A	A	A		B	B	A	A	A	
	4643 (1)																								
	5087	B	A	B		A		B	A	B			A												
	5183	B	A	B		A		B	A	B			A												
	5356	B	A	A			A	B	A	A			A												
	5554																								
	5556	B	A	B			A	B	A	B			A												
	5556A	B	A	B			A	B	A	B			A												
	5754																								
6005, 6005A, 6063, 6082 6101, 6151, 6201,6351, 6951	4043/4047	A	A	C	A	A		A	A	C	A	A		B	B	A	A	A		B	B	A	A	A	
	4643 (1)																								
	5087	B	A	B			A	B	A	B			A												
	5183	B	A	B			A	B	A	B			A												
	5356	B	A	A			A	B	A	A			A												
	5554																								
	5556	B	A	B			A	B	A	B			A												
	5556A	B	A	B			A	B	A	B			A												
	5754																								
5454 5754	5087	B	A	B	B		A	B	A	B	B		A												
	5183	B	A	B	B		A	B	A	B	B		A												
	5356	B	A	A	B		A	B	A	A	B		A												
	5554	C	A	A	A	A	A	C	A	A	A	A	A												
	5556	B	A	B	B		A	B	A	B	B		A												
	5556A	B	A	B	B		A	B	A	B	B		A												
	5754	C	A	A	A	A	A	C	A	A	A	A	A												
511.0, 512.0, 513.0, 514.0, 535.0 5154, 5254	5087	B	A	B	B		A	B	A	B	B		A												
	5183	B	A	B	B		A	B	A	B	B		A												
	5356	B	A	A	B		A	B	A	A	B		A												
	5554	C	A	A	A		A	C	A	A	A		A												
	5556	B	A	B	B		A	B	A	B	B		A												
	5556A	B	A	B	B		A	B	A	B	B		A												
	5754	C	A	A	A		A	C	A	A	A		A												
5086, 5056	5087	A	A	B	A		A	A	A	B	A		A												
	5183	A	A	B	A		A	A	A	B	A		A												
	5356	A	A	A	A		A	A	A	A	A		A												
	5554																								
	5556	A	A	B	A		A	A	A	B	A		A												
	5556A	A	A	B	A		A	A	A	B	A		A												
	5754																								
5083, 5456	5087	A	A	B	A		A	A	A	B	A		A												
	5183	A	A	B	A		A	A	A	B	A		A												
	5356	A	A	A	A		A	A	A	A	A		A												
	5554																								
	5556	A	A	B	A		A	A	A	B	A		A												
	5556A	A	A	B	A		A	A	A	B	A		A												
	5754																								
5052, 5652	4043/4047	A	B	C	A	A		A	B	C	A	A													
	5087	B	A	B			A	B	A	B			A												
	5183	B	A	B			A	B	A	B			A												
	5356	B	A	A			A	B	A	A			A												
	5554																								
	5556	B	A	B			A	B	A	B			A												
	5556A	B	A	B			A	B	A	B			A												
	5754																								
5005, 5050	1100	C	B	A	A	A	A	C	B	A	A	A	A												
	4043/4047	A	A	C	A	A		A	A	C	A	A													
	5087	C	A	B			B	C	A	B			B												
	5183	C	A	B			B	C	A	B			B												
	5356	C	A	B			B	C	A	B			B												
	5556	C	A	B			B	C	A	B			B												
	5556A	C	A	B			B	C	A	B			B												
3004	1100	D	B	A	A	A	A	D	B	A	A	A	A												
	4043/4047	A	A	C	A	A		A	A	C	A	A													
	5087	C	A	B			B	C	A	B			B												
	5183	C	A	B			B	C	A	B			B												
	5356	C	A	B			B	C	A	B			B												
	5554																								
	5556	C	A	B			B	C	A	B			B												
	5556A	C	A	B			B	C	A	B			B												
	5754																								
3003 ALCLAD 3003	1100	B	B	A	A	A	A	B	B	A	A	A	A												
	4043/4047	A	B	B	A	A		A	A	B	A	A		B	A	A	A	A		B	A	A	A	A	
2219 2519	2319													B	A	A	A	A	A	A	A	A	A	A	A
	4043/4047	B	A	A	A	A		B	A	A	A	A		B	C	B	C	A		B	C	B	C	A	
2014 2036	2319													C	A	A	A	A	A	2319					
	4043/4047	B	A	A	A	A		B	A	A	A	A		B	C	B	C	A		4043/4047					
1100	1100	B	B	A	A	A	A	B	B	A	A	A		1100											
	4043/4047	A	A	B	A	A		A	A	B	A	A		4043/4047											
1060 1070 1080 1350	1100	B	B	A	A	A	B	1100																	
	4043/4047	A	A	B	A	A		4043/4047																	

BASE ALLOYS	FILLER ALLOYS	3003 ALCLAD 3003						3004						5005 5050						5052 5652					
Characteristics		W	S	D	C	T	M	W	S	D	C	T	M	W	S	D	C	T	M	W	S	D	C	T	M
319.0 333.0 354.0 355.0 C355.0 380.0	2319																								
	4043/4047	B	B	A	A	A	A	B	B	A	A	A	A	B	B	A	A	A	A	A	A	A	A	A	A
413.0 443.0 444.0 356.0 A356.0 A357.0 359.0	4043/4047	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	A	A	A	A
7005 7021 7039 7046 7146 710.0 711.0	4043/4047	A	B	C	A	A		A	D	C	B	A		A	B	C	B	A		B	D	C	B	A	
	5087	B	A	B	A		A	B	A	B	A		A	B	A	B	A		A	A	A	B	A		A
	5183	B	A	B	A		A	B	A	B	A		A	B	A	B	A		A	A	A	B	A		A
	5356	B	A	A	A		A	B	B	A	A		A	B	A	A	A		A	A	B	A	A		A
	5554							C	C	A	A	A	A	C	A	A	A	A	A	B	C	A	A	A	A
	5556	B	A	B	A		A	B	A	B	A		A	B	A	B	A		A	A	A	B	A		A
	5556A	B	A	B	A		A	B	A	B	A		A	B	A	B	A		A	A	A	B	A		A
	5754							C	C	A	A	A	A	C	A	A	A	A	A	B	C	A	A	A	A
6061 6070	4043/4047	A	B	C	A	A		A	D	C	A	A		A	B	C	A	A		A	D	C	A	A	
	4643 (1)																								
	5087	B	A	B			A	B	A	B			A	B	A	B			A	B	A	B	C		B
	5183	B	A	B			A	B	A	B			A	B	A	B			A	B	A	B	C		B
	5356	B	A	A			A	B	B	A			A	B	A	A			A	B	B	A	C		A
	5554																			C	C	A	B	A	B
	5556	B	A	B			A	B	A	B			A	B	A	B			A	B	A	B	C		B
	5556A	B	A	B			A	B	A	B			A	B	A	B			A	B	A	B	C		B
	5754																			C	C	A	B	A	B
6005, 6005A, 6063, 6082 6101, 6151, 6201,6351, 6951	4043/4047	A	B	C	A	A		A	D	C	A	A		A	B	C	A	A		A	D	C	A	A	
	4643 (1)																								
	5087	B	A	B			A	B	A	B			A	B	A	B			A	B	A	B	C		B
	5183	B	A	B			A	B	A	B			A	B	A	B			A	B	A	B	C		B
	5356	B	A	A			A	B	B	A			A	B	A	A			A	B	B	A	C		A
	5554																			C	C	A	B	A	B
	5556	B	A	B			A	B	A	B			A	B	A	B			A	B	A	B	C		B
	5556A	B	A	B			A	B	A	B			A	B	A	B			A	B	A	B	C		B
	5754																			C	C	A	B	A	B
5454 5754	5087	B	A	B	B		A	B	A	B	B		A	B	A	B	B		A	A	A	A	B		A
	5183	B	A	B	B		A	B	A	B	B		A	B	A	B	B		A	A	A	A	B		A
	5356	B	A	A	B		A	B	B	A	B		A	B	A	A	B		A	A	B	A	B		A
	5554	C	A	A	A	A	A	C	C	A	A	A	A	C	A	A	A	A	A	C	C	A	A	A	A
	5556	B	A	B	B		A	B	A	B	B		A	B	A	B	B		A	A	A	B	B		A
	5556A	B	A	B	B		A	B	A	B	B		A	B	A	B	B		A	A	A	B	B		A
	5754	C	A	A	A	A	A	C	C	A	A	A	A	C	A	A	A	A	A	C	C	A	A	A	A
511.0, 512.0, 513.0, 514.0, 535.0 5154, 5254	5087	B	A	B	B		A	B	A	B	B		A	B	A	B	B		A	A	A	B	B		B
	5183	B	A	B	B		A	B	A	B	B		A	B	A	B	B		A	A	A	B	B		B
	5356	B	A	A	B		A	B	B	A	B		A	B	A	A	B		A	A	B	A	B		A
	5554	C	A	A	A		A	C	C	A	A		A	C	A	A	A		A	C	C	A	A		B
	5556	B	A	B	B		A	B	A	B	B		A	B	A	B	B		A	A	A	B	B		B
	5556A	B	A	B	B		A	B	A	B	B		A	B	A	B	B		A	A	A	B	B		B
	5754	C	A	A	A		A	C	C	A	A		A	C	A	A	A		A	C	C	A	A		B
5086, 5056	5087	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A
	5183	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A
	5356	A	A	A	A		A	A	B	A	A		A	A	A	A	A		A	A	B	A	A		A
	5554																			C	C	A	A		A
	5556	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A
	5556A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A
	5754																			C	C	A	A		A
5083, 5456	5087	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A
	5183	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A
	5356	A	A	A	A		A	A	B	A	A		A	A	A	A	A		A	A	B	A	A		A
	5554																			C	C	A	A		A
	5556	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A
	5556A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A
	5754																			C	C	A	A		A
5052, 5652	4043/4047	A	B	C	A	A		A	B	C	A	A		A	B	C	A	A		A	D	C	B	A	
	5087	B	A	B			A	B	A	B			A	B	A	B			A	A	A	B	C		B
	5183	B	A	B			A	B	A	B			A	B	A	B			A	A	A	B	C		B
	5356	B	A	A			A	B	A	A			A	B	A	A			A	A	B	A	C		A
	5554																			C	C	A	A	A	B
	5556	B	A	B			A	B	A	B			A	B	A	B			A	A	A	B	C		B
	5556A	B	A	B			A	B	A	B			A	B	A	B			A	A	A	B	C		B
	5754																			C	C	A	A	A	B
5005, 5050	1100	C	C	A	A	A	A							B		A	A	A	A	1100					
	4043/4047	A	B	C	A	A		A	B	C	A	A		A	B	D	A	A		4043/4047					
	5087	C	A	B	C		B	B	A	B			A	B	A	C			B	5087					
	5183	C	A	B	C		B	B	A	B			A	B	A	C			B	5183					
	5356	C	A	B	C		B	B	A	A			A	B	A	B			B	5356					
	5556	C	A	B	C		B	B	A	B			A	B	A	C			B	5556					
	5556A	C	A	B	C		B	B	A	B			A	B	A	C			B	5556A					
3004	1100	C	C	A	A	A	A							1100											
	4043/4047	A	B	C	A	A		A	B	D	A	A		4043/4047											
	5087	C		B	C		A	B	A	C	C		A	5087											
	5183	C		B	C		A	B	A	C	C		A	5183											
	5356	C	A	B	C		A	B	B	B	C		A	5356											
	5554							C	C	A	B	A	A	5554											
	5556	C		B	C		A	B	A	C	C		A	5556											
	5556A	C		B	C		A	B	A	C	C		A	5556A											
	5754							C	C	A	B	A	A	5754											
3003 ALCLAD 3003	1100	B	B	A	A	A	A	1100																	
	4043/4047	A	A	B	A	A		4043/4047																	
2219 2519	2319	2319																							
	4043/4047	4043/4047																							
2014 2036	2319																								
	4043/4047																								
1100	1100																								
	4043/4047																								
1060 1070 1080 1350	1100																								
	4043/4047																								

5083 5456 W	S	D	C	T	M	5086 5056 W	S	D	C	T	M	511.0 512.0 513.0 514.0 535.0 5154 5254 W	S	D	C	T	M	5454 5754 W	S	D	C	T	M	6005 6005A 6063 6082 6101 6151 6201 6351 6951 W	S	D	C	T	M	6061 6070 W	S	D	C	T	M	7005 7021 7039 7046 7146 710.0 711.0 W	S	D	C	T	M	413.0 443.0 444.0 356.0 A356.0 A357.0 359.0 W	S	D	C	T	M	319.0 333.0 354.0 355.0 C355.0 380.0 W	S	D	C	T	M	Filler
																																																B	A	A	A	A	A	2319
A	A	A	A	A	A	A	A	A	A		A	A	A	A	A		A	A	A	A	A	A	A	B	B	A	A	A	A	B	B	A	A	A	A	B	B	A	A	A	A	B	B	A	A	A	A							4043/4047

5083 5456 W	S	D	C	T	M	5086 5056 W	S	D	C	T	M	511.0 512.0 513.0 514.0 535.0 5154 5254 W	S	D	C	T	M	5454 5754 W	S	D	C	T	M	6005 6005A 6063 6082 6101 6151 6201 6351 6951 W	S	D	C	T	M	6061 6070 W	S	D	C	T	M	7005 7021 7039 7046 7146 710.0 711.0 W	S	D	C	T	M	413.0 443.0 444.0 356.0 A356.0 A357.0 359.0 W	S	D	C	T	M	Filler
																								A	B	A	A	A	A	A	B	A	A	A	A	A	B	B	A	A	A	A	B	A	A	A	A	4043/4047

5083 5456 W	S	D	C	T	M	5086 5056 W	S	D	C	T	M	511.0 512.0 513.0 514.0 535.0 5154 5254 W	S	D	C	T	M	5454 5754 W	S	D	C	T	M	6005 6005A 6063 6082 6101 6151 6201 6351 6951 W	S	D	C	T	M	6061 6070 W	S	D	C	T	M	7005 7021 7039 7046 7146 710.0 711.0 W	S	D	C	T	M	Filler
																								A	D	C	B	A		A	D	C	B	A		B	D	C	B	A		4043/4047
A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	5087
A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	5183
A	B	A	A		A	A	B	A	A		A	A	B	A	A		A	A	B	A	A		A	A	B	A	A		A	A	B	A	A		A	A	B	A	A		A	5356
												B	C	A	A		A	B	C	A	A	A	A	B	C	A	A	A	A	B	C	A	A	A	A	B	C	A	A	A	A	5554
A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	5556
A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	A	A	B	A		A	5556A
												B	C	A	A		A	B	C	A	A	A	A	B	C	A	A	A	A	B	C	A	A	A	A	B	C	A	A	A	A	5754

5083 5456 W	S	D	C	T	M	5086 5056 W	S	D	C	T	M	511.0 512.0 513.0 514.0 535.0 5154 5254 W	S	D	C	T	M	5454 5754 W	S	D	C	T	M	6005 6005A 6063 6082 6101 6151 6201 6351 6951 W	S	D	C	T	M	6061 6070 W	S	D	C	T	M	Filler
																								A	C	B	A	A		A	C	B	A	A		4043/4047
																								A	C	B	A	A		A	C	B	A	A		4643 (1)
A	A	B	A		A	A	A	B	A		A	B	A	B	C		B	B	A	B	C		A	B	A	A	C		A	B	A	A	C		B	5087
A	A	B	A		A	A	A	B	A		A	B	A	B	C		B	B	A	B	C		A	B	A	A	C		A	B	A	A	C		B	5183
A	B	A	A		A	A	B	A	A		A	B	B	A	C		A	B	B	A	C		A	B	A	A	C		A	B	B	A	C		A	5356
B	C	A	A		A	B	C	A	A		A	C	C	A	B		B	C	C	A	A	A	A	C	B	A	B	B	A	C	B	A	B	B	B	5554
A	A	B	A		A	A	A	B	A		A	B	A	B	C		B	B	A	B	C		A	B	A	A	C		A	B	A	A	C		B	5556
A	A	B	A		A	A	A	B	A		A	B	A	B	C		B	B	A	B	C		A	B	A	A	C		A	B	A	A	C		B	5556A
B	C	A	A		A	B	C	A	A		A	C	C	A	B		B	C	C	A	A	A	A	C	B	A	B	B	A	C	B	A	B	B	B	5754

5083 5456 W	S	D	C	T	M	5086 5056 W	S	D	C	T	M	511.0 512.0 513.0 514.0 535.0 5154 5254 W	S	D	C	T	M	5454 5754 W	S	D	C	T	M	6005 6005A 6063 6082 6101 6151 6201 6351 6951 W	S	D	C	T	M	Filler
A	B	C	A			A	B	C	A			A	B	C	A			A	B	C	B	A		A	C	B	A	A		4043/4047
																								A	C	B	A	A		4643 (1)
A	A	B	A		A	A	A	B	A		A	B	A	B	C		A	B	A	B	C		A	B	A	A	C		A	5087
A	A	B	A		A	A	A	B	A		A	B	A	B	C		A	B	A	B	C		A	B	A	A	C		A	5183
A	A	A	A		A	A	A	A	A		A	B	A	A	C		A	B	A	A	C		A	B	A	A	C		A	5356
B	A	A	A		A	B	A	A	A		A	C	A	A	B		A	C	A	A	A	A	A	C	B	A	B	B	A	5554
A	A	B	A		A	A	A	B	A		A	B	A	B	C		A	B	A	B	C		A	B	A	A	C		A	5556
A	A	B	A		A	A	A	B	A		A	B	A	B	C		A	B	A	B	C		A	B	A	A	C		A	5556A
B	A	A	A		A	B	A	A	A		A	C	A	A	B		A	C	A	A	A	A	A	C	B	A	B	B	A	5754

5083 5456 W	S	D	C	T	M	5086 5056 W	S	D	C	T	M	511.0 512.0 513.0 514.0 535.0 5154 5254 W	S	D	C	T	M	5454 5754 W	S	D	C	T	M	Filler
A	A	B	B		A	A	A	B	B		A	A	A	B	B		A	A	A	B	B		A	5087
A	A	B	B		A	A	A	B	B		A	A	A	B	B		A	A	A	B	B		A	5183
A	B	A	B		A	A	B	A	B		A	A	B	A	B		A	A	B	A	B		A	5356
B	C	A	A		A	B	C	A	A		A	B	C	A	A		A	B	C	A	A	A	A	5554
A	A	B	B		A	A	A	B	B		A	A	A	B	B		A	A	A	B	B		A	5556
A	A	B	B		A	A	A	B	B		A	A	A	B	B		A	A	A	B	B		A	5556A
B	C	A	A		A	B	C	A	A		A	B	C	A	A		A	B	C	A	A	A	A	5754

5083 5456 W	S	D	C	T	M	5086 5056 W	S	D	C	T	M	511.0 512.0 513.0 514.0 535.0 5154 5254 W	S	D	C	T	M	Filler
A	A	B	A		A	A	A	B	A		A	A	A	B	B		B	5087
A	A	B	A		A	A	A	B	A		A	A	A	B	B		B	5183
A	B	A	A		A	A	B	A	A		A	A	B	A	B		A	5356
B	C	A	A		A	B	C	A	A		A	B	C	A	A		B	5554
A	A	B	A		A	A	A	B	A		A	A	A	B	B		A	5556
A	A	B	A		A	A	A	B	A		A	A	A	B	B		A	5556A
B	C	A	A		A	B	C	A	A		A	B	C	A	A		B	5754

5083 5456 W	S	D	C	T	M	5086 5056 W	S	D	C	T	M	Filler
A	A	B	A		A	A	A	B	A		A	5087
A	A	B	A		A	A	A	B	A		A	5183
A	B	A	A		A	A	B	A	A		A	5356
												5554
A	A	B	A		A	A	A	B	A		A	5556
A	A	B	A		A	A	A	B	A		A	5556A
												5754

5083 5456 W	S	D	C	T	M	Filler
A	(Z)	B	A		A	5087
A	(Z)	B	A		A	5183
A		A	A		A	5356
						5554
A	A	B	A		A	5556
A	A	B	A		A	5556A
						5754

Filler
4043/4047
5087
5183
5356
5554
5556
5556A
5754

How to Use

1. Select base alloys to be joined.
2. Find the block where the column and row intersect.
3. This block contains horizontal rows of letters (A, B, C or D) representative of the alloy directly across from them in the filler alloy box at the end of each row. The letters in each line give the A-to-D rating of the characteristics listed at the top of each column – W, S, D, C, T and M (see Legend at right for explanation of each letter).
4. Analyze the weld characteristics afforded by each filler alloy. You will find that you can "trade off" one characteristic for another until you find the filler that best meets your needs.

Example

When joining base alloys 3003 and 1100, find the intersecting block. Note that filler alloy 1100 provides an (A) rating for ductility (D), corrosion resistance (C), performance at elevated temperatures (T), and color match after anodizing (M), and a (B) rating for ease of welding (W) and strength (S). However, if ease of welding and shear strength are important, and ductility and color match can be sacrificed slightly, then filler alloy 4043 can be used.

SYMBOL	CHARCTERISTIC
W	Propensity for weld cracking. "A" indicates little tendency for weld cracking. "D" indicates severe tendency for weld cracking
S	Shear strength - applicable particularly to fillet welds.
D	Ductility of the finished weld
C	Resistance to corrosion in ambient temperature fresh or salt water
T	Recommended for service at Suitability for long term expoure to temperatures above 150 degrees F
M	Color match between the weld and the parent material after anodizing
A, B, C, & D are relative ratings in decreasing order of merit. The ratings have relative meaning only within a given block.	

Aluminum Filler Alloy Chart

Preparation for welding includes storage and handling of aluminum prior to welding, methods for making the weld preparation and methods for cleaning prior to welding. While not strictly “welding preparation”, methods for backgouging and interpass cleaning will be included in this section.

4.1 STORAGE OF ALUMINUM AND ALUMINUM WIRE PRIOR TO WELDING

Improper storage of aluminum and aluminum wire prior to welding makes preparation for welding much more costly at best. At worst, it can result in welds of inadequate quality.

It is well known that all aluminum alloys form an oxide coating immediately upon exposure to air. This coating is extremely thin, approximately 100-150 Angstroms (one millionth of a centimeter) thick. Because it is so thin, it is not visible to the naked eye. When stored at ambient temperatures and relative humidity levels of 70% or below, the oxide thickness increases extremely slowly. It is safe to say that aluminum and aluminum wires stored under these conditions will be usable for a couple of years. Plus, the reverse polarity arc tends to strip off the oxides. Therefore, if aluminum is stored in a dry area, oxide removal prior to welding will be very easy or unnecessary.

However, if aluminum is subjected to temperatures above 200°F (93°C) and/or very high humidity levels, the thickness of the oxide layer can increase rapidly. Because of this, the following guidelines are suggested:

- Aluminum wire that has ever become wet should be scrapped. Boxes of wire where the cardboard box has become wet on the inside should be discarded.
- Aluminum wire should be stored inside, if possible.
- Wire should be stored in the original box and any plastic interior bag it came in.
- It is helpful to store wire in a closed cabinet that is heated to approximately 20°F (-6°C) above the ambient temperature to reduce relative humidity. This can be done simply by mounting an electrical fixture with a low wattage bulb inside the cabinet and letting the bulb burn continuously.
- Wire that will not be used for two (2) days or more should be dismounted from the wire feeder, returned to its original packaging and stored properly.

Aluminum wire that is stored in accordance with the above recommendations will be usable, with no deterioration in performance, for at least two (2) years. Wire older than this should be discarded.

Oxides on an aluminum plate can be removed by power wire brushing, sanding, grinding or chemical etching; however, please note that proper storage will prevent the formation of oxides. Aluminum should be stored indoors in a dry environment.

If stored outside, it should be securely covered to keep it dry. Under no circumstances should it be stored uncovered with one plate lying flat on top of another. This will allow water to "wick" in between the plates from the edges. If this happens, thick hydrated oxide will form very quickly on the plate surfaces, making it difficult to pry the two plates apart.

4.2 WELDING PREPARATION

Even the hardest aluminum alloy is much softer than a high speed steel or carbide cutting tool. While specialized tools are available to cut aluminum, aluminum is easily cut using circular saws, radial arm saws, and the like. End preparations can be put on pipe or tube using woodworking routers. The general rule is "if it will cut wood, it will cut aluminum."

Mechanical methods of weld preparation are as follows:

Machining

Machining of weld preparations can be performed using a variety of tools. Milling machines, bed planers and shapers are commonly used with carbide cutting tools. It is recommended that any machining be performed dry, i.e., without any cutting lubricants. Lubricants are either oil (hydrocarbon) or water-based. If lubricants are used, the residue must be removed before welding. If not removed, excessive porosity will result.

Sawing

Both band and circular saws are commonly used to make weld preparations. Higher blade speeds and coarser teeth are required than when cutting steel. Recommended blade surface speeds are 8000 surface feet per minute (sfpm) for circular saws and 5000 sfpm for band saws. Band saw blades should have no more than 4 teeth per inch. If circular saws are used, the cut quality can be good enough so that no further preparation is necessary. Band saws usually leave a coarse surface that must be sanded or grinded.

Grinding and Sanding

The use of grinding and/or sanding to form weld preparations was discouraged in the past because organic binders in the disc often left behind organic residues that caused weld porosity. Today, there are a number of grinding and sanding discs specifically formulated for aluminum. These can give excellent results for forming weld preparations on aluminum.

Shearing

Shearing is very useful to cut sheets or plates to size, but the edge quality is rarely acceptable for welding. It is relatively rough and has many crevices that can trap oils, greases and the like. It is recommended that you smooth the edge by machining, grinding or sanding after shearing.

Routers & Carbide Burrs

You can use routers for repairs and back-gouging. If using an air powered router, ensure that there is a dryer on the line to prevent moisture from getting on the work-piece. When using for repair work or back gouging, make sure that the material is removed to sound metal.

Water-Jet Cutting

Water jet cutting utilizes high pressure water with the addition of an abrasive garnet. Water pressures can reach 100 kilopounds per square inch (ksi), and the velocity of the water can reach speeds above Mach 3 or 2283 mph. Temperatures only reach 195˚F, which allows the aluminum to be cut without causing liquation cracking. This process can cut aluminum up to up to 9.25 in. thick in certain applications. There are, however, limitations to the process. Cutting speeds are relatively slow, especially when compared to plasma arc cutting. For example, water-jet cutting speeds may be as slow as 3.8 inches per minute (ipm) on 1.5 in. thick material using 90 ksi water pressure for a good-quality cut. In addition, waterjet cutting systems are generally expensive and not portable.

Thermal Cutting Technologies

While aluminum can't be cut using oxyfuel cutting equipment, it can easily be cut using plasma and laser cutting equipment. Heat-treatable alloys are prone to form micro cracks due to liquation cracking, which can extend back from the cut edge as far as 1/8 in. (3.2 mm). Therefore, laser or plasma cut edges in heat-treatable alloys should be machined to remove the edge before welding.

Plasma Cutting

You can produce an acceptable quality cut on aluminum 1.5 in. thick using a 400A power source with a travel speed of 35 inches per minute (ipm).

Laser Cutting

Because of the high reflectivity and high conductivity of aluminum, laser cutting isn't as effective as other methods of preparation; therefore, solid state laser cutting gives the best result when cutting aluminum. This process is typically limited to materials 3/8 in. (9.5 mm) thick.

4.3 PRE-WELD CLEANING

Once the weld preparation is formed, it must be cleaned before the weld joint is fit together. Cleaning consists of removing any contaminants. These contaminants are as follows:

> Whichever method you use, you must degrease the part to be welded before performing any of the oxide removal procedures outlined below. Otherwise, the oils and greases will be spread by the oxide removal and will be difficult to remove.

(1) Oils and Greases

Removal of oils and greases can be performed in one of several ways. First, you can wipe with a clean rag saturated with a degreasing solvent. This method is effective; however, the use of many solvents has been severely curtailed in recent times due to environmental concerns. Second, mild alkaline solutions make good degreasers. The part to be degreased can be sprayed with these solutions or dipped into a tank containing them. Since such cleaners are usually water based, it is important to thoroughly dry the part after degreasing. Third, you may use an acid based cleaning solution for cleaning aluminum. These are usually effective. However, all are acidic and some contain hydrofluoric acid, so you must be cautious when using and discarding them. Again, since these solutions contain water, you must dry the piece thoroughly before welding.

(2) Excess Oxides

Once you have removed the oils and greases, you may remove the oxides in several ways. The most common way is to use a stainless steel wire brush. The brush should be clean and not previously used on materials other than aluminum. The brush should be relatively flexible and used with light pressure in order to avoid unnecessarily roughening the surface of the aluminum.

You can also remove oxides by immersing the part in a strong alkaline solution. However, these solutions are very corrosive and can etch the surface of the aluminum; therefore, be sure to use extreme caution.

In some industries, especially the aerospace industry, final oxide removal is performed just before the joint is fitted together. This is accomplished by mechanically removing the oxide using a steel scraper (identical to those used in woodworking) or by draw filing. Once the cleaning is performed, the joint is fit together as soon as possible. This is an effective method of oxide removal. However, it is time consuming, costly and primarily used in industries where the demand for extremely high quality overrides the additional cost.

4.4 INTERPASS CLEANING

The surface of a weld usually has areas of oxides and weld “smut”. This gray to black colored smut is composed of aluminum oxide and magnesium oxide. We recommend that you remove the smut and oxides before depositing another weld pass; otherwise, they can cause lack of fusion defect.

The easiest way to remove these oxides is to use a wire brush, either manual or power driven. The wire brush should be clean and used only on aluminum. It should be flexible and used with light pressure.

4.5 BACKGOUGING

When making a double-sided weld, it is necessary to remove the metal on the back side to sound metal before depositing the back side weld. If you neglect to do this and make the backside weld with no preparation, lack of fusion will often result. The usual geometry for the backgouged seam is a V preparation with a 60° included angle and a 1/8 in. (3.2 mm) radius at the base. There are a number of ways to perform this backgouging:

(1) Air Arc or Plasma Arc Gouging

Either of these processes can be used successfully. However, they rely on the skill and steadiness of the operator to obtain a uniform backgouge. In addition, they usually require cleaning up with a grinding disk before welding. This is especially true of air arc gouging, which leaves carbon deposits in the gouged groove. If the carbon isn’t removed, porosity on the backside weld can result.

(2) Grinding

A thin 1/8 in. (3.2 mm) grinding disk on edge can be used for backgouging. Again, it takes a great deal of skill to produce a uniform gouge.

(3) Machining

The best way to get a uniform backgouge is to mount the weld in a milling machine and machine the backgouge. Unfortunately, this usually isn’t practical. However, a number of manufacturers supply a pneumatically powered circular saw mounting a 4 in. (102 mm) diameter milling cutter. This milling cutter is ground to have a tooth form with a 60° V with a 1/8 in. (3.2 mm) tip radius. The depth of the backgouge is determined by setting the cutting depth of the saw. It is relatively easy to set up a straightedge to guide the saw so that you get a straight backgouge.

(4) Chipping

Although not used very often, a pneumatic chipping hammer with the appropriate chisel can be an effective way to backgouge. The problem with this method is the extremely high noise level produced. An advantage of this method is that it’s easy to regulate the cutting depth: when you reach sound metal, you’ve reached the correct cutting depth.

5.1 PROPERTIES OF ALUMINUM

The engineering use of wrought and cast aluminum base materials continues to increase because of the basic properties of this unique material. The more prominent features of aluminum and its alloys are as follows:

- Aluminum is lightweight. Its weight is about one third that of steel. A cubic inch of aluminum weighs 0.098 lbs/in^3 compared to steel, which weighs 0.283 lbs/in^3.
- Aluminum has a wide range of strength properties that vary from 13,000 psi tensile strength for pure aluminum up to 90,000 psi tensile strength for the strongest heat-treatable aluminum alloys.
- Aluminum provides excellent corrosion resistance in many environments. The thin refractory oxide that forms on the surface of aluminum provides a protective barrier.
- Aluminum is an excellent conductor of heat. It is up to five times more thermally conductive than steel.
- Aluminum is reflective of radiant heat, and the surface finish of aluminum is frequently used to take advantage of this feature.
- Aluminum is widely available in either extruded shapes or wrought sheet in an equally wide range of alloy compositions.
- Aluminum is widely available as a die cast base material.

For welding purposes, an important consideration for welding aluminum is its thermal conductivity. This property has an important facet: To compensate for the high rate of thermal conductivity, aluminum requires the use of higher energy modes of metal transfer. Axial spray and pulsed spray are the two recommended GMAW modes of metal transfer for aluminum. The use of the lower energy forms of metal transfer, such as short circuiting transfer, will usually result in incomplete fusion defects.

5.2 MODES OF METAL TRANSFER

When welding aluminum base material, it is important to note that the thermal conductivity of the aluminum base material is five times higher than it is for carbon steel, and because of this the lower energy modes of metal transfer are unable to provide sufficient melting of the base material to ensure good fusion. More specifically, short circuiting transfer is not recommended for welding aluminum.

Axial spray and pulsed spray metal transfers are the preferred metal transfer modes for aluminum. Each of these is capable of providing the required energy levels for base metal melting to ensure good fusion.

Table 5-1 shows the typical axial spray transfer transition currents for specific aluminum electrode diameters (note that argon gas is the shielding gas associated with the transition currents). In those cases where helium additions are made to the argon, the required watt energy level (current x voltage) to achieve the transition to axial spray will have to increase. Axial spray is the highest energy transfer mode for GMAW, and aluminum requires the use of higher energy modes of transfer to compensate for the higher thermal conductivity. Because of these two central facts, axial spray is generally applied to aluminum base materials 0.125 in. (3.2 mm) or greater in thickness.

Table 5-1: Axial Spray Transition Current

Aluminum Electrode Diameter		Shielding Gas	Transition Current
Inches	mm		
0.030	0.8	100% Argon	70 Amps
0.035	0.9	100% Argon	90 Amps
0.047	1.2	100% Argon	130 Amps
0.062	1.6	100% Argon	180 Amps

For many years, we were limited to these transition currents shown in Table 5-1 as a minimum for GMAW of aluminum. This meant that GMAW could be used for welding relatively thick aluminum sections but couldn't be used for welding thin aluminum because the current was too high.

Pulsed Spray Welding (GMAW-P)

The invention of pulsed spray power supplies was the key to welding thin aluminum. In GMAW-P, the welding current is pulsed between a peak current that is higher than the transition current and a much lower background current (see Figure 5-1). This means that we can use GMAW-P to weld at average currents far below the transition current for the wire being used. In axial spray mode, by contrast, filler wire is transferred across the arc at the peak current, and no wire is transferred at the background current. GMAW-P is the preferred mode of metal transfer for materials 0.125 in. (3.2 mm) and thinner because the average current is lower in magnitude for GMAW-P than for axial spray transfer. GMAW-P is able to join thin and thick sections of aluminum. GMAW-P has the following advantages when used for welding aluminum when compared to axial spray transfer:

- Lower heat input – less distortion
- Ability to handle poor fit-up
- Ability to handle thinner materials

» Lower heat input of GMAW-P reduces the size of the heat affected zone
» Out-of-position welding is greatly enhanced

Please consult Table 6-3 on page 61 for recommended GMAW-P parameters.

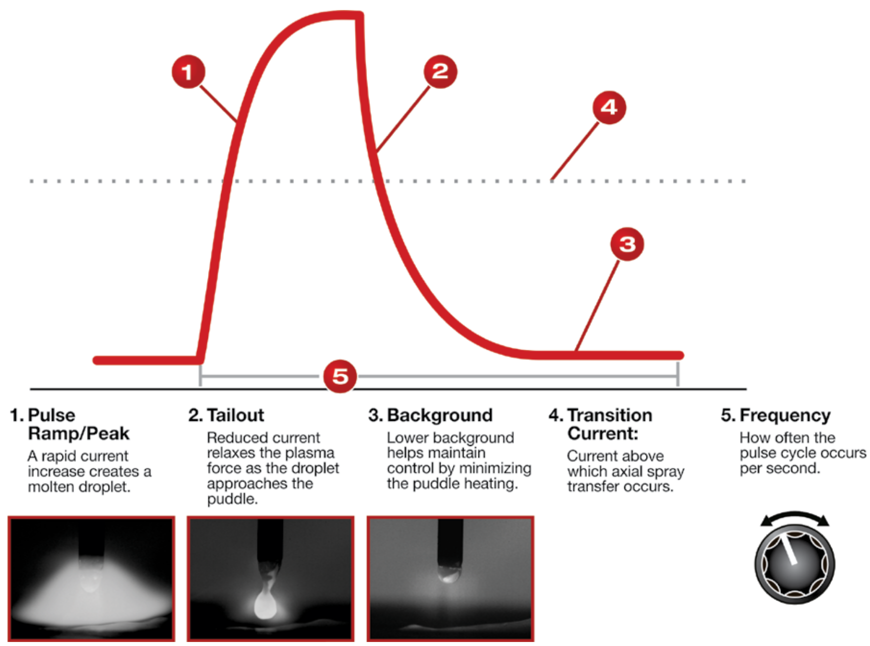


Figure 5-1: Pulsed GMAW Waveform

Constant Voltage (CV) GMAW

CV power supplies were developed many years ago specifically to be used for Gas Metal Arc Welding and have been the most commonly used power supplies, although many users have changed over to the newer technology Pulsed GMAW power supplies, especially for welding aluminum. In the CV power supply, the user presets the Arc Voltage and the Wire Feed Speed (WFS). The power supply then keeps the arc voltage constant during welding. It does this by varying the welding current to keep the arc voltage (and thus the arc length) steady. Such power supplies can be used at low currents and low voltages in short circuiting transfer or at higher currents and higher voltages for spray transfer. However, short circuiting transfer is never recommended for welding aluminum.

Typical welding parameters for CV welding are shown in Table 6-3. Note that parameters shown are only for spray transfer, so the material thicknesses are relatively large.

No parameters are shown for thinner materials, as this would require the use of welding currents below the transition current, which would make them into short circuiting transfer. Pulsed spray, AC GMAW or Pulse On Pulse processes are more suitable for thin materials

Power Mode®

Power Mode, a Lincoln Electric patented process, is a combination of constant current (CC) and constant voltage (CV) modes. In Power Mode, neither the current nor the voltage is held steady. Instead, the weld power is held constant. Figure 5-2 shows a comparison of the voltage-amperage curves for CV, CC, and Power Mode. In Power Mode, the wire feed speed and the power levels (in KW) are preset. The power is adjusted to obtain the appropriate arc length for the preset WFS.

Like CV, Power Mode can be used over the entire range of wire feed speeds to provide short circuiting transfer and axial spray transfer. However, the high thermal conductivity of aluminum still makes short circuiting transfer inadvisable, so Power Mode should usually be used on thicker materials at higher wire feed speeds. When used in this manner, Power Mode can show considerable advantage over conventional CV modes. Specifically, Power Mode gives more consistent penetration and a more stable arc than CV. Please consult Table 6-3 to find recommended CV parameters for various thicknesses.

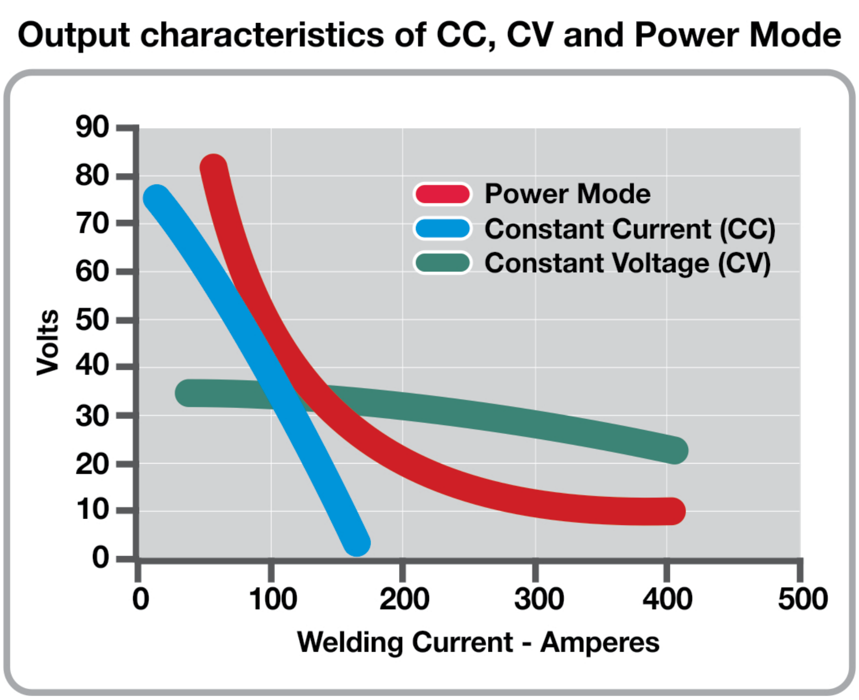


Figure 5-2: Output Characteristics of CC, CV and Power Mode

Pulse On Pulse® Mode

Pulse On Pulse mode, a patented Lincoln invention, is similar to pulsed spray welding. In conventional pulsed spray welding, one pulse wave form is repeated ad infinitum. In contrast, in Pulse On Pulse a number of high energy pulses is followed by the same number of low energy pulses (see Figure 5-3). These pulsed waves create a weld ripple when we are in the low energy part of the waveform. Pulse On Pulse is therefore a way to obtain a very uniform weld bead with the characteristic “stacked dimes” appearance of a TIG weld. The weld ripple spacing can be varied by changing the Ultimarc™ setting.

Suggested Pulse On Pulse welding parameters for various material thicknesses are shown in Table 6-3.

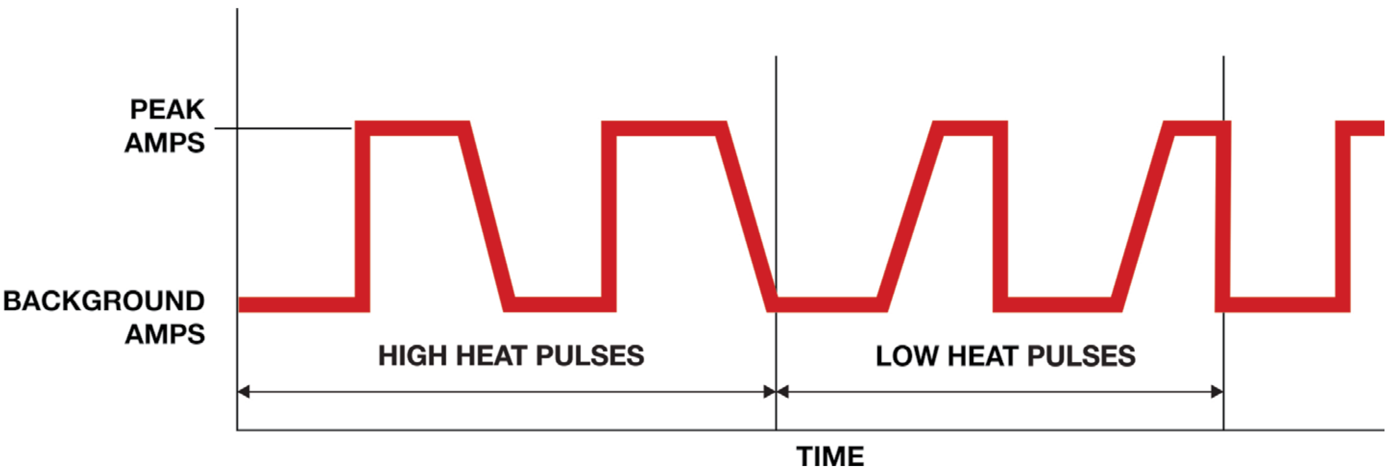


Figure 5-3: Pulse On Pulse Waveform

AC Pulse

Lincoln Electric has recently introduced a process that uses alternating current (AC) for GMAW. This is done by adding an Advanced Module, see Figure 5-4a and b, to any of the latest generation Lincoln Electric power supplies. The advantage of this process is that in GMAW, direct current electrode positive (DCEP) increases heat input and penetration while direct current electrode negative (DCEN) reduces heat input and increases weld deposition rate. Lincoln Electric has developed AC GMAW waveforms for aluminum by adding an EN pulse at the end of each EP pulse, see Figure 5-5.

Figure 5-4a: Power Source with Advanced Module

Figure 5-4b: Power Source with Advanced Module

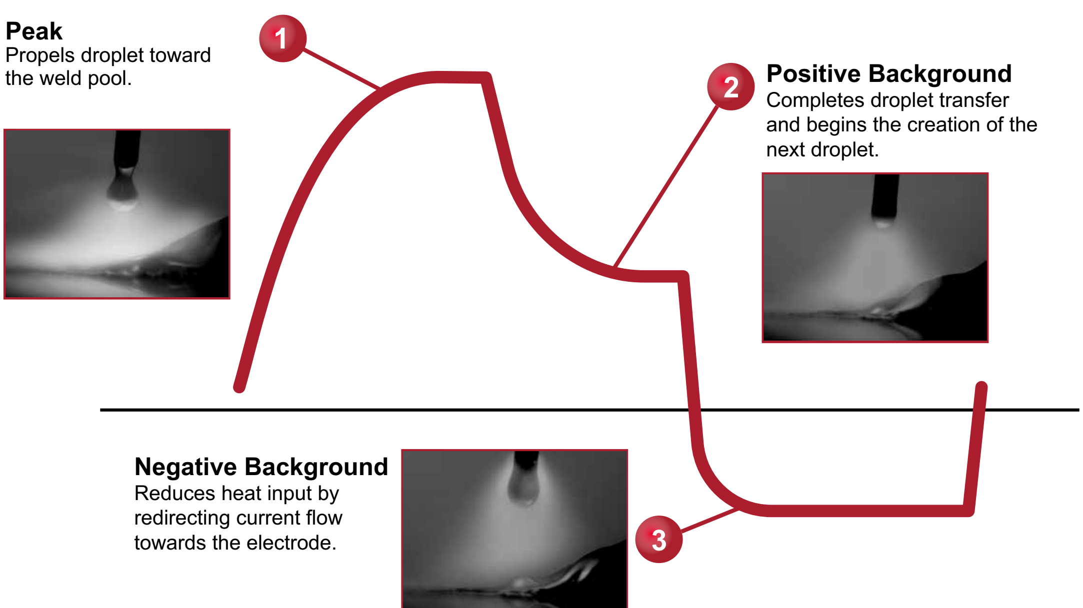


Figure 5-5: AC GMAW Waveform

AC GMAW can be used in two ways. First, to keep the wire feed speed constant, reducing heat input and allowing you to weld very thin materials. Second, to keep heat input the same, meaning the deposition rate (and therefore travel speed) can be increased to weld slightly thicker materials, 0.08 in. (2 mm) and thicker.

Welding parameters for AC GMAW are shown in Table 5-4.

Table 5-4: AC GMAW Welding Parameters

100Ar, 1/2 in.	in (mm)	WFS (IPM)	A	V	UltimArc™
SuperGlaze® 4043 0.035 in (1.1 mm)	0.10 (2.5)	465	110	20.4-22.4	0.0
	0.08 (2.0)	390	100	19.5-21.5	0.0
	0.06 (1.5)	300	83	19.0-21.0	0.0
	0.04 (1.0)	155	56	17.5-19.5	-5.0
SuperGlaze® 4043 3/64 in (1.2 mm)	0.12 (3.0)	300	140	20.5-22.5	0.0
	0.08 (2.0)	210	105	19.2-21.2	0.0
	0.06 (1.5)	175	95	18.7-20.7	0.0
	0.04 (1.0)	110	70	17.9-19.9	-5.0
SuperGlaze® 4043 1/16 in (1.6 mm)	0.12 (3.0)	150	149	20.5-22.5	0.0
	0.08 (2.0)	115	129	20.0-22.0	-5.0
SuperGlaze® 5356 0.035 in (1.1 mm)	0.10 (2.5)	525	118	18.4-20.4	5.0
	0.08 (2.0)	460	107	18.1-20.1	2.5
	0.06 (1.5)	365	91	17.2-19.2	0.0
	0.04 (1.0)	200	58	16.3-18.3	-5.0
SuperGlaze® 5356 3/64 in (1.2 mm)	0.12 (3.0)	400	154	18.5-20.5	5.0
	0.08 (2.0)	275	118	17.9-19.9	0.0
	0.06 (1.5)	210	95	16.7-18.7	0.0
	0.04 (1.0)	120	64	15.3-17.3	-5.0
SuperGlaze® 5356 1/16 in (1.6 mm)	0.12 (3.0)	245	171	19.6-21.6	0.0
	0.08 (2.0)	125	107	16.9-18.9	0.0
	0.06 (1.5)	100	88	16.7-18.7	-10.0

5.3 POWER SUPPLIES AND WIRE DRIVES

The history of the development of power sources for aluminum GMAW welding relates to the development of CC or CV output characteristics. Prior to the development of CV power sources, CC or "drooper" type power sources were used exclusively for welding aluminum. Special techniques were required for arc striking, and special variable-speed wire drives were developed as a solution for the unstable arc length associated with constant current.

Incomplete fusion defects often accompanied the penetration problems. Because of this, many aluminum fabricators went back to CC power supplies for consistent penetration. As a result of these early difficulties, much of the available aluminum welding literature continues to advocate the use of CC supplies. Constant voltage power supplies produced since the 1990's demonstrate more consistent output. These newer CV power sources are line voltage compensated, which ensures consistent delivery of output. CV is widely used and highly recommended for aluminum GMAW.

5.4 GMAW-P POWER SUPPLIES

Today's pulsed arc power supplies are much more sophisticated than those of only a few years ago. Early pulsed power supplies had a fixed pulsing frequency based upon multiples of input frequencies, usually 60 and 120Hz. These systems were non-synergic and difficult to set up.

The 1990's introduced newer pulsed power sources that provided synergic control (one knob control) with a high speed amplifier used to control output. In the newer pulsed arc power sources, either an inverter transformer or related Chopper Technology® provide power for the arc, and software is used to direct the output of the power source.

The software developed specifically for these newer power sources provides a wide selection for a range of filler types, diameters and shielding gas compositions. In most cases, the newer power sources provide a wide selection of pulsed spray transfer, synergic CV and special Pulse on Pulse programs for use with aluminum electrodes.

In the following section, we will explain what each adjustment knob on the power supply does. Keep in mind that this is a general discussion, and your power supply may differ slightly from what is discussed below.

5.5 WELD MODE SEARCHING

The Weld Mode Search feature allows the selection of a welding mode based on certain criteria (wire size, process type, etc.).

Searching for a Weld Mode

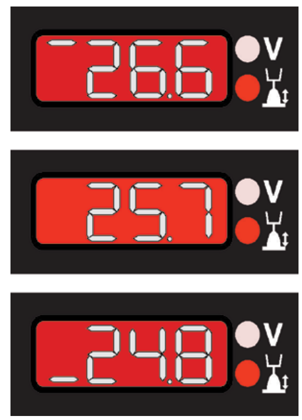
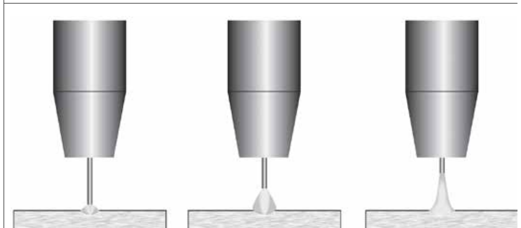
1. To search for a mode, turn the control knob until "Weld Mode Search" is displayed. This will appear in between the highest and the lowest weld mode numbers.
2. Once "Weld Mode Search" is displayed, pressing the right pushbutton labeled "Begin" will start the search process.
3. During the search process, pressing the right pushbutton typically acts as a "next" button and the left pushbutton typically acts as a "back" button.
4. Rotate the control knob, then press the right pushbutton to select relevant welding details such as welding process, wire type, wire size, etc.
5. When the final selection is made, the power source will automatically change to the weld mode found by the Weld Mode Search process. Earlier products may not have this feature. To activate this feature, a software update may be needed.

Figure 5-6: Power Wave® C300

Adjusting Voltage/Trim

The right display and knob control voltage, trim or output depending upon the process selected. Once welding is complete, the display continues to show the welding voltage for five seconds. See Table 5-5 for more details.

Table 5-5: Adjusting Voltage/Trim

Process	Display/ Function	Description	
Non-synergic GMAW (MIG)	Voltage	Adjusts the voltage. The display is blank for nonsynergic STT modes.	
Synergic GMAW (MIG)	Voltage	When the voltage knob is rotated, the display will show an upper or lower bar indicating if the voltage is above or below the ideal voltage. The display is blank for synergic STT modes. · Preset voltage above ideal voltage (Upper bar displayed) · Preset voltage at ideal voltage (No bar displayed) · Preset voltage below ideal voltage (Lower bar displayed)	
Pulse GMAW (MIG)	Trim	Pulse welding controls the arc length with 'Trim' instead of voltage. When trim (arc length) is adjusted, the Power Waveautomatically recalculates the voltage, current and time of each part of the pulse waveform for the best result. Trim adjusts the arc length and ranges from 0.50 to 1.50. Increasing the trim value increases the arc length, while decreasing the trim value decreases the arc length.	  Trim .50 Arc Length Short Trim 1.00 Arc Length Medium Trim 1.50 Arc Length Long

Wave Control

Wave Control is used to adjust the arc for exact preferences. The wave control functions vary for different processes and weld modes. See Table 5-6 for more details.

Table 5-6: Wave Control

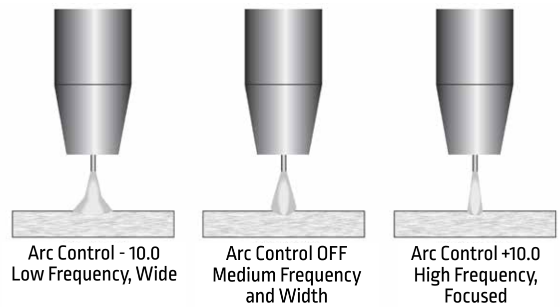
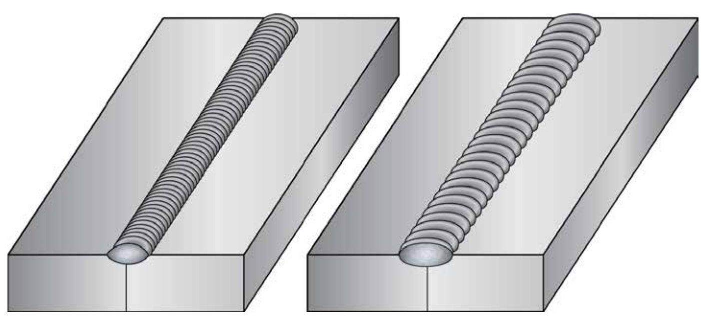
Process	Wave Control Name	Effect/Range	Description
GMAW (MIG)	Pinch	Soft (-10.0) to Crisp (10.0).	Pinch controls the arc characteristics when short-arc welding. Note: This has no effect when welding aluminum.
GMAW-P (Pulsed MIG)	UltimArc™	Soft (-10.0) to Stiff (10.0)	 For Pulse modes, Arc Control changes the pulsing frequency. When the frequency changes, the Power Wave system automatically adjusts the background current to maintain a similar heat input into the weld. Low frequencies give more control over the puddle and high frequencies minimize spatter.
GMAW-P (Pulsed MIG), Aluminum	Ultimarc	Low (-10.0) to High (10.0)	For Pulse On Pulse modes, Arc controls changes the frequency modulation. The frequency modulation controls the spacing of the ripples in the weld. Use low values for slow travel speeds and wide welds, and high values for fast travel speeds and narrower welds.  Modulation frequency =10 Wide weld and ripple spacing, slow travel speed Modulation frequency =10 Narrow weld and ripple spacing, fast travel speed

Table 5-6: Wave Control Cont'd.

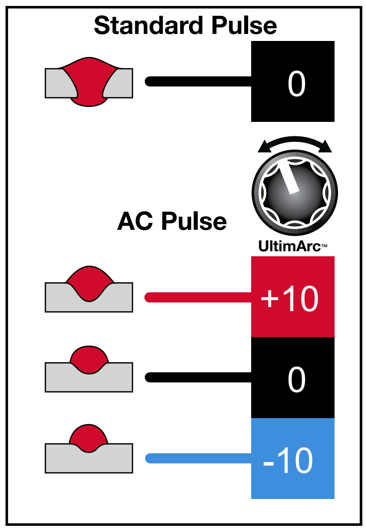
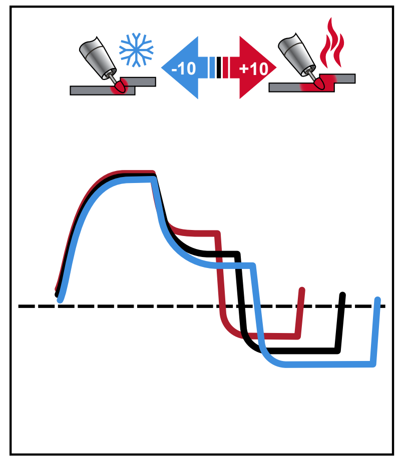
Process	Wave Control Name	Effect/Range	Description
AC GMAW	UltimArc™	Low (-10.0) to High (10.0)	Fine tunes the heat input into the plate. Increasing the setting provides more heat into the puddle, resulting in a more focused arc. Decreasing the setting reduces heat directed into the puddle, resulting in a less focused arc.  

Table 5-7: Start Options			
Process	Start Options†	Effect/Range	Description
GMAW (MIG)	Preflow* time	0 – 25.0 seconds	Starts the shielding gas for a preset amount of time before the arc is started.
	Run in WFS	Auto, OFF, 30 in/min to weld WFS	Run-In sets the wire feed speed from the time the trigger is pulled until an arc is established or 2.5 seconds. Use run-in for softer arc starts.
	Start time**, WFS, and Volts	0 – 10.0 seconds	The Start Procedure controls the WFS and Volts for a specified time at the beginning of the weld. During the start time, the machine will ramp up or down from the Start Procedure to the preset Welding Procedure.

* Preflow reduces the amount of porosity at the beginning of the weld.
** Start Time - To reduce the look of a cold start use parameters lower than that of the weld, to reduce lack of fusion use parameters higher than that of the weld.
† Newer power sources automatically set these values synergically based on wire feed speed.

Table 5-8: End Options			
Process	Start Options†	Effect/Range	Description
GMAW (MIG)	Spot timer	5.0 seconds	Sets the length for welding when the trigger is pulled. If the trigger is released before the Spot Timer is complete, welding stops. This option has no effect in 4-step trigger mode.
	Crater* time, WFS and Volts	0.0 – 10.0 seconds, Auto	Crater procedure controls the WFS and volts for a specified time at the end of the weld after the trigger is released. During the crater time, the machine will ramp up or down from the weld procedure to the crater procedure. Crater is not commonly used with the STT process.
	Burnback Time	0.0 – 0.25 seconds	The burnback time is the amount of time that the weld output continues after the wire stops feeding. It prevents the wire from sticking in the puddle and prepares the end of the wire for the next arc start.
	Postflow Time	0.0 – 0.25 seconds	Adjusts the time that shielding gas flows after the welding output turns off.

* Crater: Use to reduce/eliminate the likelihood of crater cracking. Depending on the weld size the parameters will differ.
† Newer power sources automatically set these values synergically based on wire feed speed.

5.6 WIRE DRIVES AND CONTROLS

Reliable feeding of the softer aluminum solid wire electrodes through a welding torch presents more of a challenge than feeding carbon steel electrodes. Aluminum wire is much less rigid than steel wire, so it is harder to push through a GMAW torch. Special wire drives and GMAW guns are available to enhance the feedability of aluminum electrode. They fall into four main categories:

1. Push Type Feeders

Standard wire feeders, employed for carbon steel solid wire electrodes, can also be referred to as "push type feeders." In this type of equipment, a spool of wire is mounted on a spindle located to the rear of the drive. A shielding gas pre-flow and post-flow timer/control should be available. There is a set of drive rolls (two-roll or four-roll) on the feeder that pushes the wire through from the spool mounting device through the gun cable and then through the contact tip.

For aluminum electrode, the use of highly polished "U" groove drive rolls is recommended. In all of the ensuing scenarios, the use of hard shell nylon or Teflon® type liners is strongly recommended. This type of system, with some modifications described below, can also be used to feed softer aluminum wire under the following circumstances:

- The gun cable must be kept short; 10-12 ft. (3.0-3.6 m) is the practical maximum length. The shorter the GMAW gun cable, the better the overall performance. Use Teflon® or hard shelled nylon electrode liners.
- If 1/16 in. (1.6 mm) diameter wire is used, either 4043 or 5356 filler alloys can be pushed. The thicker electrodes have higher column strength. Again, use Teflon® or hard shell nylon electrode liners.
- 3/64 in. (1.2 mm) 5356 filler metal can generally be pushed, but 3/64 in. (1.2 mm) 4043 filler metal will usually result in wire feeding problems if pushed.
- Plastic- or aluminum-specific inlet and outlet guides and special aluminum contact tips are also recommended.
- U-grooved type drive rolls should be used.

2. Push–Pull Type Feeders

A solution to the problem of feeding either small diameter or softer aluminum wire is to use a "push–pull" feeder. In most push-pull feeders, the pull motor in the welding gun is the "master" motor and the push motor in the cabinet is the "slave" motor.

Wire feed speed is controlled by the motor on the gun handle, and the cabinet contains a motor system designed to provide a slack wire reducing effect on the electrode. This push-pull type of aluminum wire drive system provides the most consistent daily performance when compared to the other types of systems. Figure 5-9 shows a complete push-pull system.

Figure 5-9: Complete Push-Pull Drive System

The push-pull systems handle aluminum diameters from 0.030 to 1/16 in. (0.8 - 1.6 mm). They reliably feed aluminum wire up to 50 ft. (15.2 m) from the control cabinet.

3. Push–Pull GMAW Guns

Figure 5-10 shows a push-pull gun. The bulged area of the gun handle houses the pull drive motor. This permits the use of a more integrated approach for feeding aluminum. There are several control methodologies to coordinate the push motor with the pull motor. Lincoln Electric synchronizes the speed of the two motors so that the speed of the pull motor is slightly higher than that of the push motor. This keeps the wire under tension in the gun cable.

Figure 5-10: Magnum Push-Pull Gun

4. Spool Guns

Another solution for light duty aluminum welding is the spool gun shown in Figure 5-11. In this system, a 1 lb. (0.5 kg) spool of filler wire is mounted directly on the rear of the GMAW gun, so that it is only pushed a few inches past the drive rolls, show in inset. These spool guns are usually air-cooled and rated for 200 A maximum at 60% duty cycle, so they are not recommended for high current or high duty cycle welding.

Figure 5-11: Spool Gun

5.7 ALUMINUM FEEDING ENHANCEMENTS

- Drive rolls should always be the polished "U" groove type for aluminum. The "U" groove is designed to cradle the softer electrode without altering its shape and the high polish prevents the accumulation of aluminum oxide in the drive roll groove. Steel electrodes use either knurled rolls or a "V" groove configuration. Drive rolls designed for carbon steel electrodes should not be used for feeding aluminum.
- Inlet and outlet wire guides for feeding aluminum should be made from Teflon®, nylon or other suitable plastic material. A typical wire guide for aluminum is shown in Figure 5-12. Wire guides for steel wire are usually made from steel and should not be used to feed aluminum.
- Gun liners for aluminum welding should be either Teflon®, nylon or other plastic liner material. Some of these types of aluminum liners will have a short coiled brass liner section located at the front of the plastic liner. Liners for guns made to feed steel are usually made from spirally wound small diameter steel wire. These types of liners should not be used for feeding aluminum. They will shave the aluminum wire and then quickly clog the path.

Figure 5-12: Drive Rolls and Wire Guide for Aluminum

- Most manufacturers make contact tips specifically for aluminum wire. Aluminum readily expands as it absorbs the heat of the arc. Aluminum contact tips for a given size aluminum wire are designed to accommodate the thermal expansion of the wire — the inside diameter of the contact tip is slightly larger than those for the same size steel wire. Contact tips for welding steel are not suitable for welding aluminum.
- Some drive roll kits for aluminum include springs specifically designed to deliver the appropriate tension on the drive rolls. When these are included with a kit, they must be used as they are a different tension than the springs.

Some welders, after encountering aluminum feeding problems, opt to use oversize contact tips, i.e., 1/16 in. (1.6 mm) tips on 3/64 in. (1.2 mm) wire. This is usually unacceptable. The contact tip must transfer current to the wire. An oversized tip will not allow consistent current transfer. Arcing in the tip will occur, which will produce sharp burrs on the bore of the tip.

Another unacceptable practice is to use a wire straightener and tighten it down hard so that all of the cast is removed from the wire. Because the wire needs cast to make proper contact in the tip, removing all of the cast usually results in burnback.

- The contact tip should be flush with the end of the gas nozzle or recessed approximately 1/8 in. (3.2 mm). The tip should not extend past the gas nozzle.

5.8 SHIELDING GAS

The only shielding gases for welding aluminum are argon and mixtures of argon and helium. Shielding gas components such as oxygen, hydrogen or CO_2 should never be used for aluminum GMAW. Even in trace amounts, these gases will adversely affect the weld. However, it has been determined that additional amounts of nitric oxide of less than 1% minimize the formation of ozone. Gas mixtures of argon or argon/helium with a nitric oxide addition are often sold for welding aluminum and work well.

The recommended shielding gas for welding aluminum up to approximately 1/2 in. (12.7 mm) in thickness is 100% argon. Above this thickness, where additional energy is needed to melt the material, it is common to use gas mixtures of 75% argon/25% helium or 75% helium/25% argon. The use of helium in the arc increases the arc voltage and weld penetration and provides additional energy to enable heavier section thickness welding. It also expands the cross sectional shape of the finished weld, giving it a more rounded appearance. Shielding gas flow rates range from 30 to 100 cubic feet/hour (cfh) (14 to 47 L/min). Higher flow rates are employed for wider diameter gas nozzles and when using higher helium two-part blends.

5.9 WELDING TECHNIQUES

Black soot on the surface or the adjacent areas of a weld is referred to as smut. Smut is made up of finely divided oxides of aluminum and magnesium. The weld itself should be bright and shiny, with no smut on it. Smut at the edges of the weld is expected and normal, especially when using a 5XXX filler metal. This occurs because 5XXX fillers contain appreciable magnesium, which is very effective at forming smut. Otherwise, the presence of smut usually indicates that adjustments in technique are necessary.

The most common mistake beginners make when learning aluminum GMAW, is holding too long a contact tip to work distance (CTWD). Shorter CTWD's, 1/2 in. to 5/8 in. (12.7 - 15.8 mm), are required when welding aluminum. If the CTWD is too long, the gas shielding will be insufficient and the weld will most likely be covered in black smut.

It is not uncommon to get a cold-looking weld bead for the first 1/2 in. (approximately 12.7 mm) of the weld. This is due to the high thermal conductivity of aluminum. You can minimize this condition by using a power supply with a hot start. A common alternative used in the absence of a hot start control is to strike the arc about 1 in. (25.4 mm) ahead of the nominal weld starting point and quickly maneuver the arc back to the desired starting point. This action has the effect of providing preheat to the aluminum base material, and it provides improved fusion at the beginning of the weld. Another alternative is to strike the arc on a run-on tab that is removed later.

While welding, hold the torch with a push angle of 5° to 10° (also known as a leading torch angle). If you hold the torch using a drag angle (also known as a lagging torch angle), then the gas shielding will be absent from the molten puddle and the finished weld will appear gray or black.

Be careful when you extinguish the arc. Terminating the arc abruptly will result in a deep weld crater that may contain a shrinkage crack.

There are a number of ways to minimize the size and depth of the crater:

» Use weld tabs; start and terminate the weld on them.
» A power supply with an arc decay control allows the electrode and current to tail off for a predetermined wire feed speed per unit of time. This permits a controlled fill of the aluminum weld crater.
» Near the end of the weld, progressively increase the travel speed. The effect here is to reduce the size of the weld bead and diminish the overall size of the crater. This is known as a "feathering" or "back step" technique.
» At the end of the weld, reverse the direction of the torch to place the crater within the body of the weld bead.

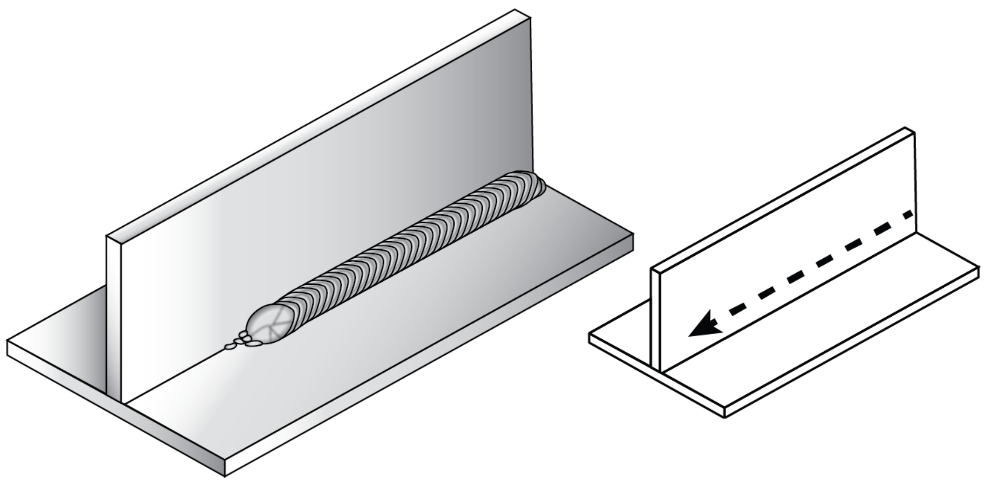


Figure 5-13: Straight Progression Weld

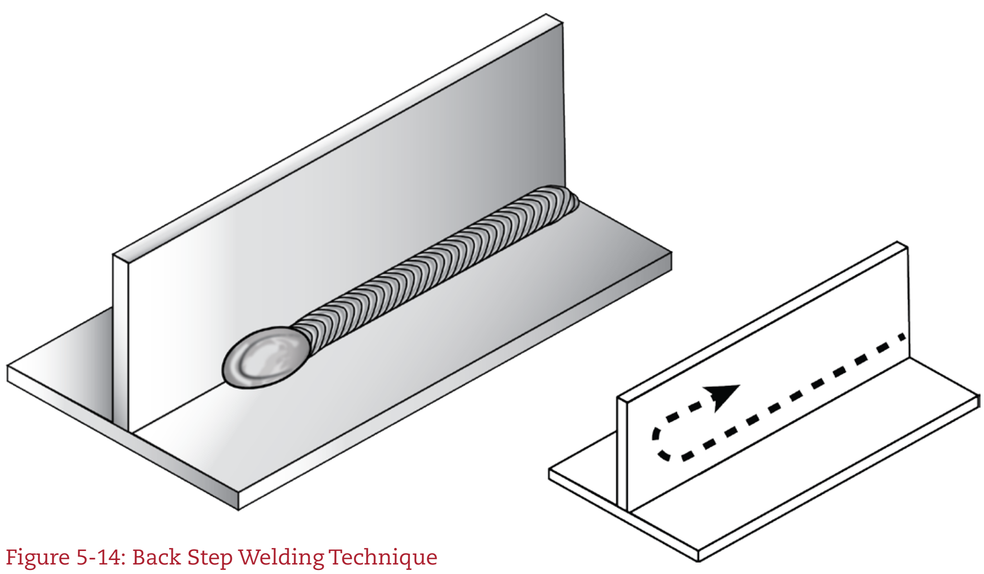


Figure 5-14: Back Step Welding Technique

Some welders learn GMAW by keeping a very steady, constant motion in the travel direction to make a very smooth weld with a minimum of weld ripples. This is known as a straight progression type weld bead (see Figure 5-12). Other welders learn to weld by using the back step technique (see Figure 5-13). Each of these techniques produces a weld with distinct, evenly spaced ripples. Each technique produces acceptable finished welds.

The finished weld should be bright and free from oxides and smut. A "frost line" or cleaning stripe approximately 1/16 in. to 1/8 in. (1.6 to 3.2 mm) wide should be visible along each edge of the weld. These stripes show the area where the reverse polarity arc has removed the oxide from the aluminum surface. If the weld metal is black or gray, or if the cleaning stripes are not present, something is wrong. The most likely causes are either the arc length is too long or the torch angle is wrong. You may expect to find some weld smut at the edges of the weld. There will also be some weld smut present at weld starts, stops and at internal and external corners. More smut will be present when using 5XXX filler than when using 4XXX filler.

Some weld defects or discontinuities may be small enough that they don't seriously impair the mechanical properties of the weld joint. On the other hand, some discontinuities may cause immediate joint failure. The effects of other discontinuities may be more insidious.

In this section, we will not attempt to assess the acceptability or rejectability of specific discontinuities. Instead, we will discuss the appearance of the various types of weld defects and suggest methods to minimize or eliminate these defects.

Cracking

Cracking occurs when a combination of a susceptible microstructure or chemistry and a sufficiently high solidification stress are present. If you reduce the stress or change the microstructure or chemistry, the cracking can be eliminated.
All weld cracking in aluminum is caused by hot cracking. That is, it takes place during weld solidification.

Crater Cracking

If the arc is extinguished rapidly, there isn't enough filler metal present to avoid forming a deep "crater." The geometry of the crater intensifies the solidification stresses in the area near the crater. If they are high enough, a crack forms in and around the crater. Figure 6-1 shows a crater crack.

Figure 6-1: Radiograph Showing a Crater Crack

In order to eliminate crater cracking, the geometric discontinuity of the crater must be minimized, i.e., the crater must be filled in as much as possible. There are several methods to prevent crater cracking:

- Use a power supply with a crater fill option.
- Rapidly restrike and extinguish the arc a few times while keeping the wire tip in the crater. This will build up the crater.
- Run the weld bead to the end of the workpiece, then reverse direction and increase travel speed in the new travel direction.

Longitudinal Cracking

Longitudinal cracking occurs relatively frequently. Figure 6-2 shows a longitudinal crack. Weld cracking can usually be eliminated by taking the following precautions:

- Heat-treatable alloys are crack sensitive and will crack if welded autogenously. Make sure you add filler metal.
- Make sure you add enough filler metal in welding any alloy. Do not deposit thin, concave groove welds or small or concave fillets. They may crack. Weld passes in both groove welds and fillet welds should be convex.
- If you encounter cracking in making a square butt weld, try a V-groove preparation. It will allow the addition of more filler metal. Similarly, if you're using a bevel prep, try a V-prep instead.
- Reduce the clamping pressure to allow the material to move slightly during solidification. High stress is occasionally caused by the joint geometry, which may need to be changed.

Figure 6-2: Radiograph Showing Longitudinal Weld Cracking

Liquation Cracking

Liquation cracking is common in lap and fillet welds in thin heat-treatable alloys. It is not usually seen in the nonheat-treatable alloys or in butt joints. It manifests itself as a short, longitudinal crack in the parent material on the back side of a weld. It is caused by the melting of low-melting-point compounds, which segregate at the grain boundaries in heat-treatable alloys near the fusion boundaries in the partial fusion zone. In order to minimize it, weld penetration into the parent metal needs to be controlled in lap and fillet welds. Welds having 30 or 40% penetration into the parent metal will almost never cause a crack, while welds penetrating 70 - 80% into the parent metal will often cause a small crack on the back side of a weld.

Incomplete Penetration

Figure 6-3 shows a weld with incomplete penetration. Incomplete penetration is often caused by insufficient weld current at a travel speed that is too high. However, the use of an arc voltage that is too high can also result in the arc bridging the weld root and not penetrating completely. You should also take care when backgouging a two–sided weld. Insufficient backgouging can sometimes result in incomplete penetration. It is sometimes surprising how deep the backgouge must go to get to sound metal.

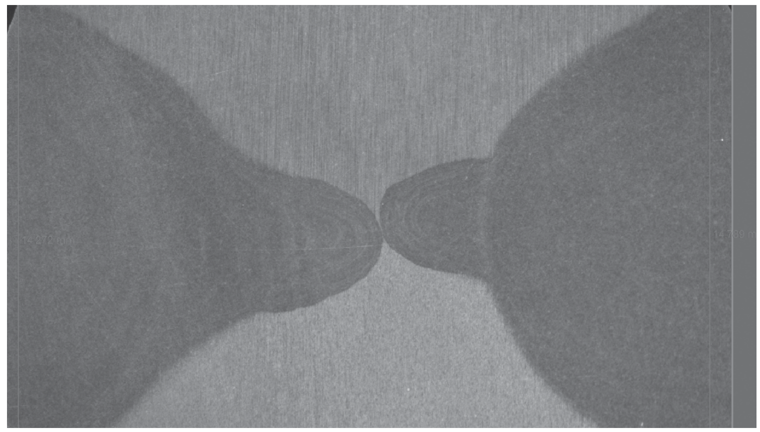


Figure 6-3: Cross section of weld showing incomplete fusion

Incomplete Fusion

Incomplete fusion, shown in Figure 6-4, is usually caused by welding over heavy oxides, insufficient interpass cleaning or poor bead placement. Remove heavy oxides before welding. The weld smut and oxides must be removed before making another weld pass. Aluminum is prone to develop fine – line Lack Of Fusion (LOF) defects if proper welding techniques are not used and/or proper pre–weld and / or interpass cleaning is not performed. Also to prevent LOF, GMAW should not be performed in the short circuiting transfer mode. Such defects are often very subtle and difficult to detect, even when radiography is used. Figure 6-4 shows such a LOF on the weld sidewall. In order to make it more visible, a red arrow has been added to point out the LOF.

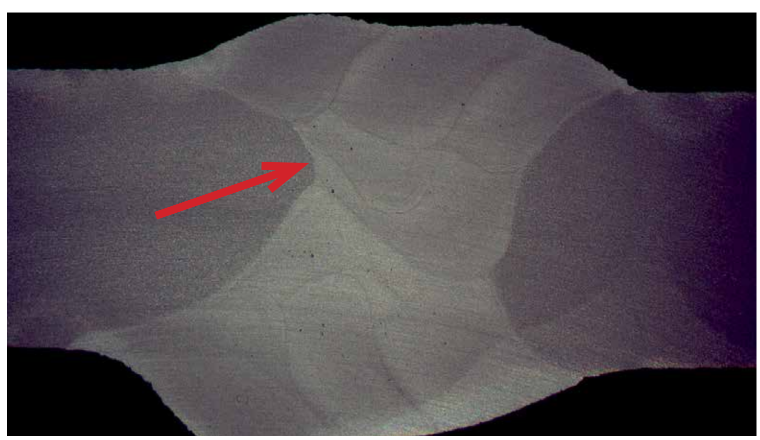


Figure 6-4: Cross section of weld showing lack of side wall fusion

Porosity

Figure 6-5 shows excessive porosity in a fracture surface of a weld. Porosity in aluminum welds is caused by hydrogen trapped in the welds as it solidifies and cools. We have already explained that the source of this hydrogen is oils, greases or water vapor dissociated by the welding arc. Eliminate the sources of these contaminants to control weld porosity. It is also helpful to use an upward progression when welding in the vertical position rather than the typical downward progression, as this helps minimize weld porosity.

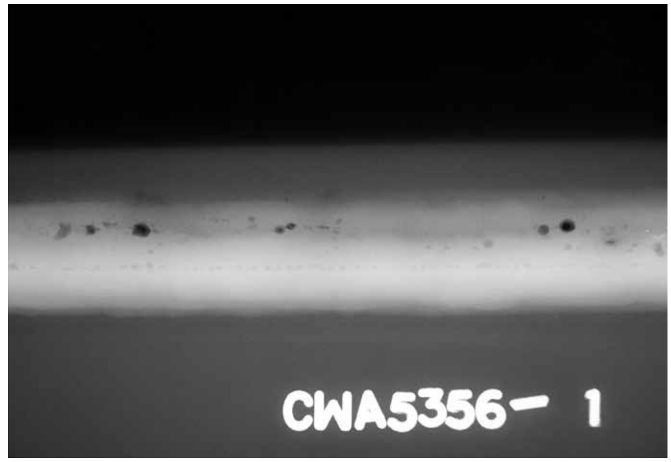


Figure 6-5: Radiograph showing excessive porosity

Copper Contamination

Copper contamination will appear white on a radiograph, as shown in Figure 6-6. Copper contamination is usually larger and “fuzzier” than tungsten, which appears as individual small particles.

Copper contamination is often encountered in GMAW and is caused when the wire burns back and fuses to the copper contact tip. The copper and aluminum quickly alloy and deposit copper in the aluminum weld. If this occurs, the copper contamination must be ground out and repaired because the aluminum/copper alloy deposited is very brittle.

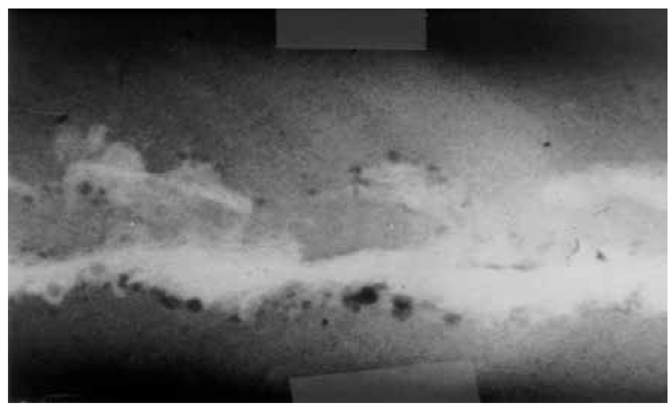


Figure 6-6: Radiograph Showing Copper Contamination (Copper contamination shows up as a lighter and irregularly shaped areas)

Copper contamination can also be caused by copper backing bars or copper tooling. While the use of copper backing bars is acceptable, the joint preparation must be such that the arc is not allowed to directly strike the copper bar. If it does, the copper bar will melt and alloy with the aluminum. Using copper backing bars is acceptable, but be sure to avoid wide root openings.

Solving Problems in Qualifying Weld Procedures

Many fabricators encounter difficulties in qualifying welding procedures or welders for aluminum. Most codes require the use of reduced section tensile tests and guided bend tests for procedure qualification. Therefore, we will discuss these two requirements.

Difficulties in Meeting Tensile Test Requirements

All codes have minimum tensile test values. Samples removed from procedure qualification test plates must meet these values. However, the weld often does not have to meet the same minimum requirements as the parent material. For example, all codes require that 6061-T6 material have a minimum tensile strength of 40 ksi (276 MPa). Welds in 6061-T6 only have to meet 24 ksi (165 MPa) minimum. It is important to understand what is required for the specific alloy being used. In general, the minimum tensile properties required for nonheat-treatable alloys are those of the annealed "O" temper base material. No such rule exists for the heat-treatable alloys. Consult the applicable fabrication code to determine the minimum tensile properties required for the alloy being used.

There are several reasons why samples fail tensile testing. For heat-treatable alloys, it is usually because excessive heat input has been used. Common reasons for excessive heat input include the following:

- Use of excessive preheat. Preheat should be no more than 200°F (93°C) and isn't needed unless the ambient temperature is below 32°F (0°C).
- Interpass temperature that is too high. Maximum interpass temperature should be 250°F (121°C).
- Technique issues such as the use of very wide weave passes, which can cause excessive heat input. Stringer passes should generally be used, although weaving is acceptable as long as the weave width is no wider than four times the wire diameter.

Weld defects can also cause premature tensile failures. Observe the fracture face of the failed tensile sample. The presence of weld defects should be fairly obvious. Lack of fusion or lack of penetration defects are especially prone to cause tensile failure.

Where the code requires the tensile sample to meet 40 ksi (276 MPa) minimum tensile strength, the use of 5356 is not recommended. Higher strength filler alloys, such as 5183 or 5556, are recommended for these applications.

Difficulties in Meeting Bend Test Requirements

Most bend test failures are caused by the welder's lack of familiarity with the bend test requirements for aluminum welds. Some points to remember are as follows:

1. The ductility of aluminum welds is lower than that of steel welds. Ensure the test radius is correct for the alloy under test. Figure 6-7 shows the bend test requirements of AWS D1.2, which are the same as those in most fabrication codes.

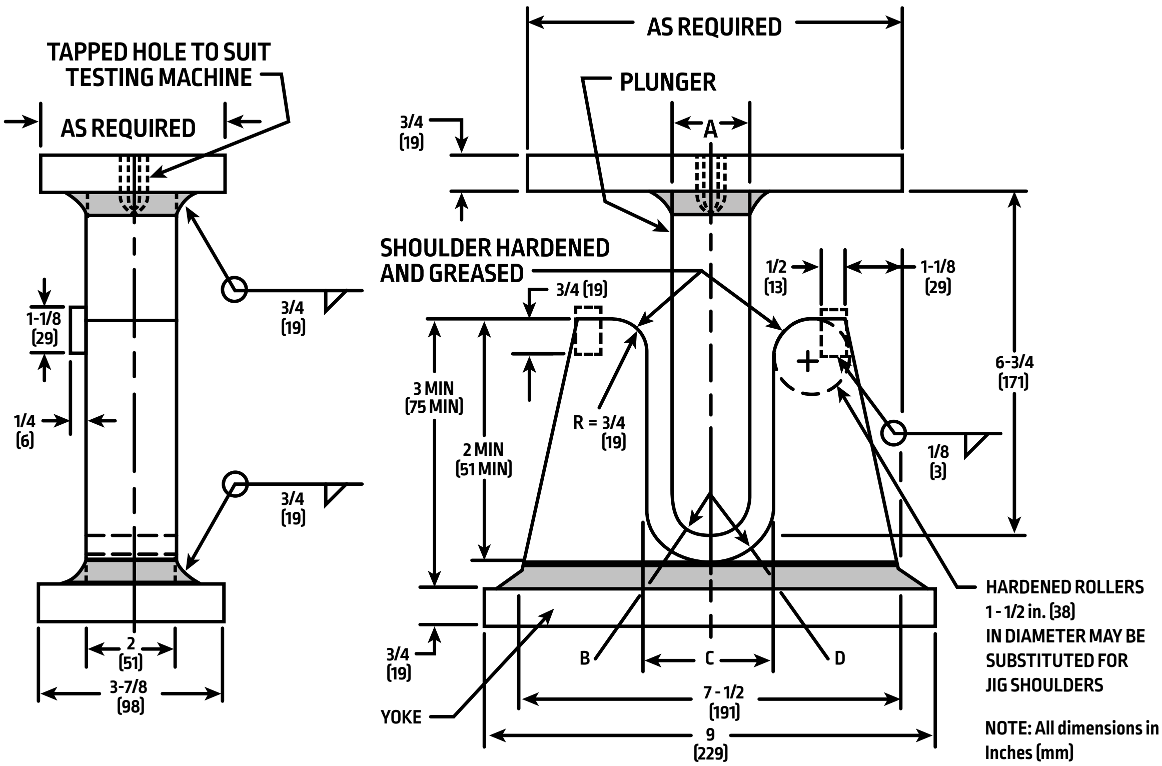


Figure 6-7: AWS D1.2 Requirements

Table 6-1: AWS D1.2 Requirements

Thickness of Specimen in. (mm)	A in. (mm)	B in. (mm)	C in. (mm)	D in. (mm)	Materials
3/8 (10)	1-1/2 (38)	3/4 (19)	2-3/8 (60)	1-3/16 (30)	M21 and M22
t	4t	2t	6t + 1/8 (3)	3t + 1/16 (1.6)	
1/8 (3)	2-1/16 (52)	1-1/32 (26)	2-3/8 (60)	1-3/16 (30)	M23 and F23 Welds
t <1/8 (<3)	16-1/2t	8-1/4t	18-1/2t + 1/16 (1.6)	9-1/4t + 1/32 (1)	
3/8 (10)	2-1/2 (64)	1-1/4 (32)	3-3/8 (86)	1-11/16 (43)	M25 and Annealed M23
t	6-2/3t	3-1/3t	8-2/3t + 1/8 (3)	4-1/3t + 1/16 (1.6)	
3/8 (10)	3 (75)	1-1/2 (38)	3-7/8 (98)	1-15/16 (49)	M27 and Annealed M24
t	8t	4t	10t + 1/8 (3)	5t + 1/16 (1.6)	

2. If the bend sample fails with little or no distortion before breaking, the most likely cause is a defect in the weld. Any lack of fusion or insufficient penetration in the weld will quickly open up on bending and cause the sample to break in half. A visual examination of the fracture surface will reveal these defects.

3. Ensure the bend test sample preparation is correct.
   a. Make sure grinding or machining marks go along the length of the sample, not across it. Marks going across the sample can act as crack initiation sites.
   b. Don't leave square corners on the sample. All codes allow a radius at the corners of 1/2 the sample thickness or 1/4 in. (6.4 mm), whichever is less. Adhering to this radius reduces the probability of initiating a crack in the corners.

4. Special precautions are necessary when testing welds in 6061 or other M23 (per AWS) or P23 (per ASME Section IX) materials because of their limited ductility. In recognition of this, both AWS D1.2 and ASME Section IX require bend test samples in 6061 and other M23 materials to be machined to 1/8 in. (3.2 mm) thickness, instead of the normal 3/8 in. (9.5 mm) thickness. If 6061 samples are machined to 3/8 in. (9.5 mm) thickness and tested around a standard radius mandrel, they often fail. AWS D1.2 alternatively allows samples in M23 materials to be machined to 3/8 in. (9.5 mm) thick and annealed before testing, but ASME Section IX has no such provision.

5. The use of the standard plunger-type bend tester is responsible for many bend test failures. This test fixture works well for steel because the mechanical properties of the weld, HAZ and parent material are all similar. However, in aluminum, the HAZ is usually much weaker than the remainder of the sample. If the sample is tested in a plunger–type tester, the bend strain is concentrated in the HAZ. Instead of bending smoothly around the mandrel, the sample often forms a sharp kink at the HAZ and then fails at the kink.

A much better test for welded aluminum bend samples is the wraparound guided bend test, shown in Figure 6-8. In this test, the sample is pulled around the mandrel and forced to stay in contact with it. These test jigs are often made from rotary tubing benders. Both AWS D1.2 and ASME Section IX encourage the use of these testers for aluminum. The same is true of most of the rules of many maritime societies such as the American Bureau of Shipping (ABS), Lloyd's Register (LR), Bureau Veritas (BV), Det Norske Veritas Germanischer Lloyd (DNV GL) and the like.

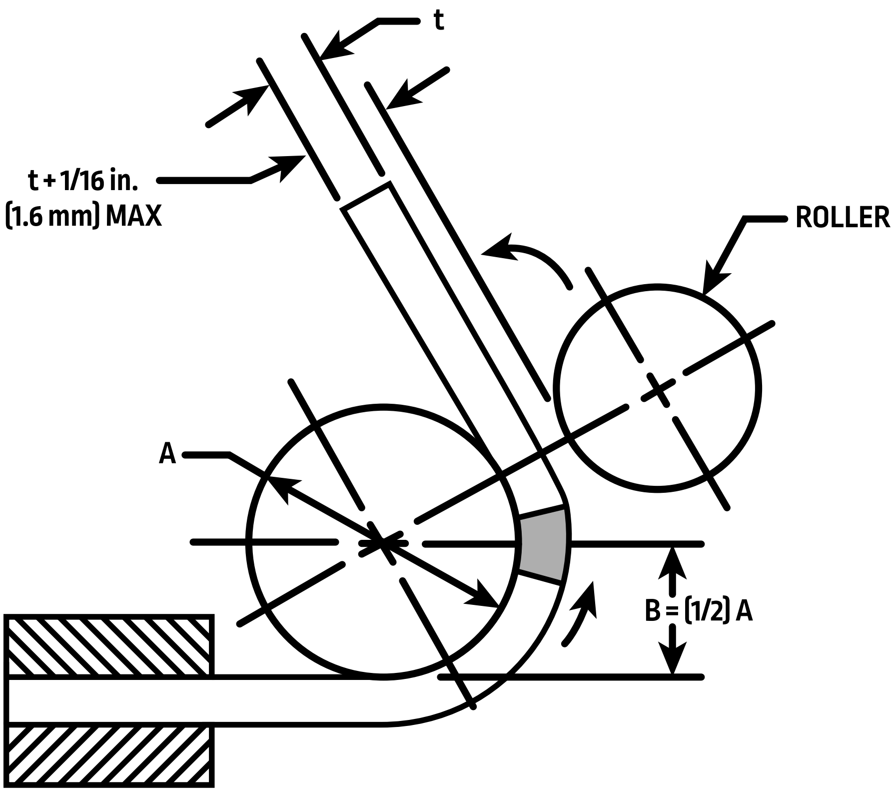


Figure 6-8: Wraparound Guided Bend Test

Table 6-2: Wraparound Guided Bend Test			
Thickness of Specimen in. (mm)	A in. (mm)	B in. (mm)	Materials
3/8 (9.0)	1-1/2 (38.0)	3/4 (19.0)	M21 and M22
t	4t	2t	
1/8 (3.0)	2-1/16 (52.4)	1-1/32 (26.2)	M23 and F23 Welds
t[<1/8] (3.0)	16-1/2t	8-1/4T	
3/8 (9.0)	2-1/2 (63.5)	1-1/4 (31.8)	M25 and Annealed M23
t	6-2/3t	3-1/3t	
3/8 (9.0)	3 (76.2)	1-1/2 (38.0)	M27 and Annealed M24
t	8t	4t	

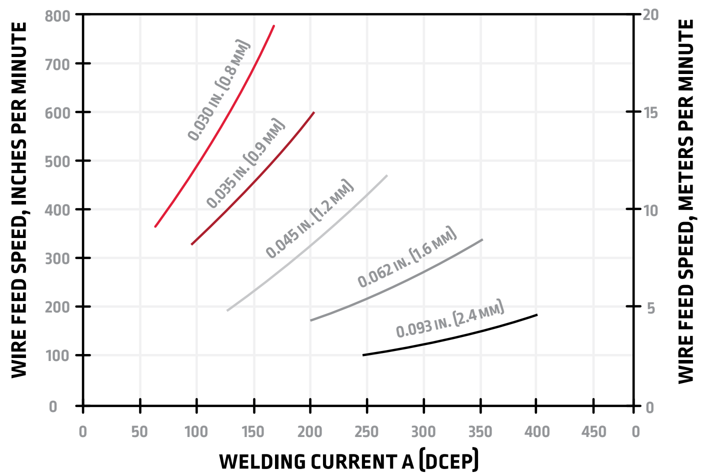


Figure 6-9: Welding Current vs. WFS for ER4043 Aluminum Electrodes at a Fixed Stickout

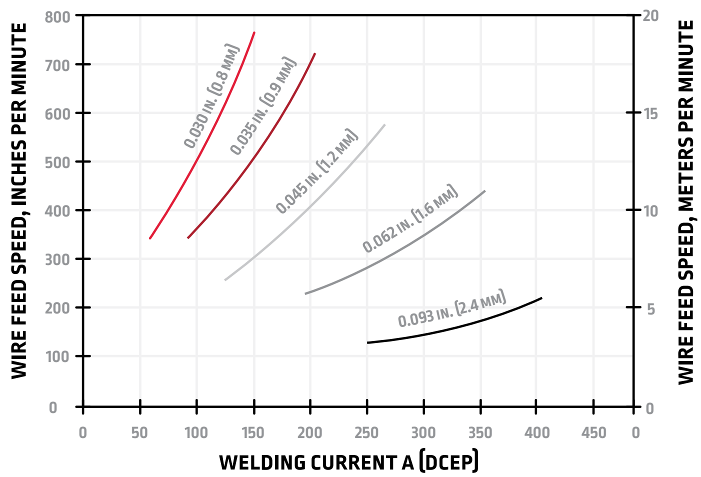


Figure 6-10: Welding Current vs. WFS for ER5356 Aluminum Electrodes at a Fixed Stickout

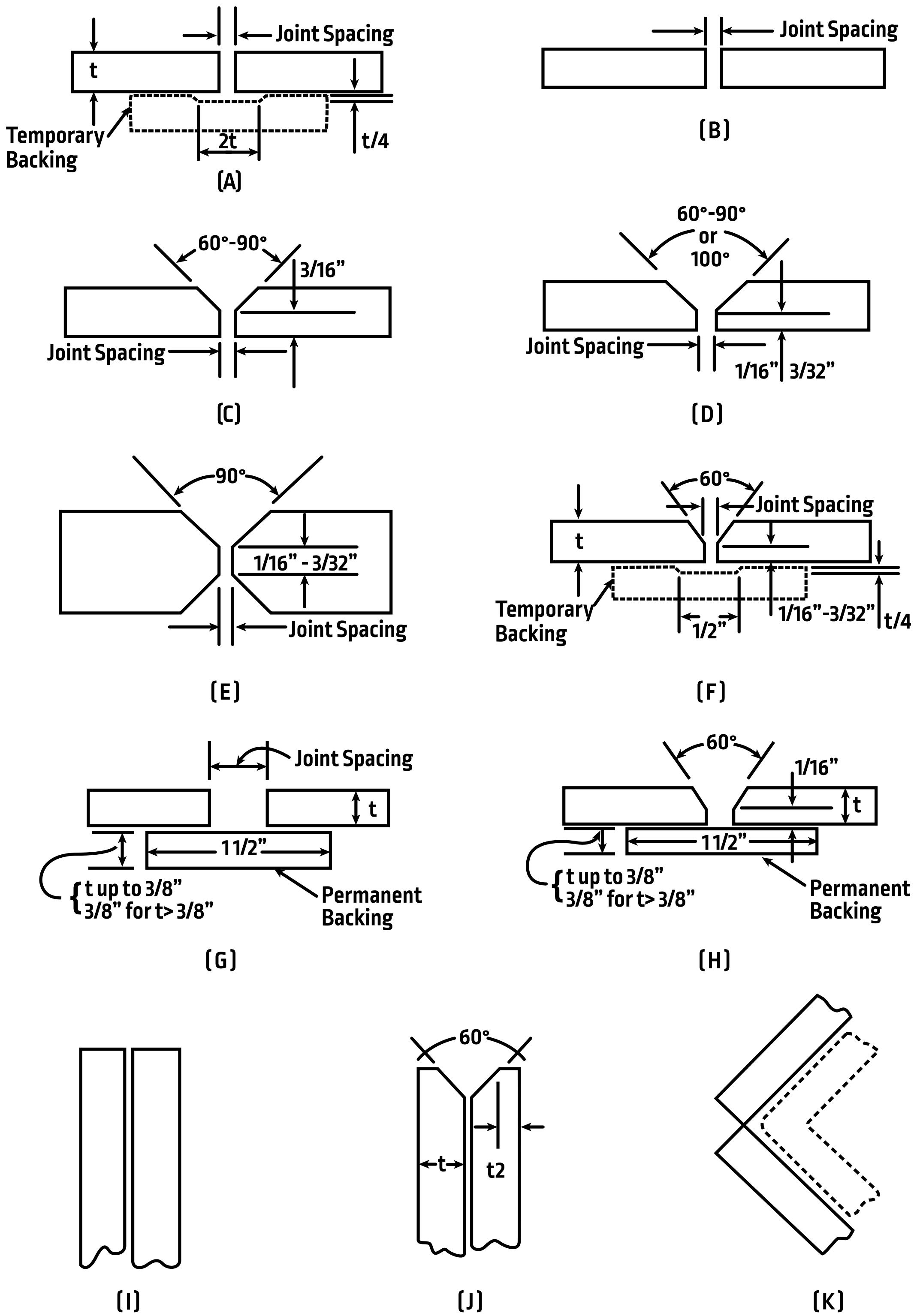


Figure 6-11: Welding Joint Designs for Aluminum GMAW Groove Welding — Flat, Horizontal, Vertical and Overhead

Table 6-3 specifies fillet joints; however, the parameters for aluminum GMAW of groove joints will generally be the same as for fillet joints.

Table 6-3: Welding Guidelines for Aluminum GMAW

Alloy	Diameter in. [mm]	Proc	Material Thickness in. [mm]	Position	Joint	WFS (IPM)	Current	Trim or Power	Voltage	Weld Size in. [mm]	# of Passes	Travel Speed (IPM)
4043	0.035 [0.9]	CV	3/16 [4.8]	Horz.	Fillet	585	172.4	-	23.3	3/16 [4.8]	1	31.4
4043	0.035 [0.9]	CV	3/16 [4.8]	Vert. Up	Fillet	555	160.3	-	22.8	3/16 [4.8]	1	29.8
4043	0.035 [0.9]	CV	3/16 [4.8]	Overhead	Fillet	575	167.1	-	23	3/16 [4.8]	1	30.8
4043	0.035 [0.9]	CV	1/4 [6.4]	Horz.	Fillet	665	188.9	-	23.2	1/4 [6.4]	1	20.1
4043	0.035 [0.9]	CV	1/4 [6.4]	Vert. Up	Fillet	650	179.3	-	24.4	1/4 [6.4]	1	19.6
4043	0.035 [0.9]	CV	1/4 [6.4]	Overhead	Fillet	660	181.5	-	24.5	1/4 [6.4]	1	19.9
4043	0.035 [0.9]	Power Mode	3/16 [4.8]	Horz.	Fillet	585	190.9	5	26.1	3/16 [4.8]	1	31.4
4043	0.035 [0.9]	Power Mode	3/16 [4.8]	Vert. Up	Fillet	550	172.1	4.05	23	3/16 [4.8]	1	29.5
4043	0.035 [0.9]	Power Mode	3/16 [4.8]	Overhead	Fillet	535	168.1	4	23	3/16 [4.8]	1	28.7
4043	0.035 [0.9]	Power Mode	1/4 [6.4]	Horz.	Fillet	670	201.7	5.35	26.5	1/4 [6.4]	1	20.2
4043	0.035 [0.9]	Power Mode	1/4 [6.4]	Vert. Up	Fillet	640	197.7	5.11	25.8	1/4 [6.4]	1	19.3
4043	0.035 [0.9]	Power Mode	1/4 [6.4]	Overhead	Fillet	650	197	5.25	26.6	1/4 [6.4]	1	19.6
4043	0.035 [0.9]	Pulse	3/16 [4.8]	Horz.	Fillet	585	184	1	23.5	3/16 [4.8]	1	31.4
4043	0.035 [0.9]	Pulse	3/16 [4.8]	Vert. Up	Fillet	560	165.1	0.98	23	3/16 [4.8]	1	30
4043	0.035 [0.9]	Pulse	3/16 [4.8]	Overhead	Fillet	570	182.8	1.03	23.7	3/16 [4.8]	1	30.6
4043	0.035 [0.9]	Pulse	1/4 [6.4]	Horz.	Fillet	665	228.8	1	25.1	1/4 [6.4]	1	20.1
4043	0.035 [0.9]	Pulse	1/4 [6.4]	Vert. Up	Fillet	640	186.3	0.96	24.1	1/4 [6.4]	1	19.3
4043	0.035 [0.9]	Pulse	1/4 [6.4]	Overhead	Fillet	645	196.5	1.02	25.1	1/4 [6.4]	1	19.5
4043	3/64 [1.2]	CV	3/16 [4.8]	Horz.	Fillet	310	194.3	-	25	3/16 [4.8]	1	29.8
4043	3/64 [1.2]	CV	3/16 [4.8]	Vert. Up	Fillet	300	163.3	-	24.2	3/16 [4.8]	1	28.9
4043	3/64 [1.2]	CV	3/16 [4.8]	Overhead	Fillet	310	191.9	-	24.6	3/16 [4.8]	1	29.8
4043	3/64 [1.2]	CV	1/4 [6.4]	Horz.	Fillet	350	194.8	-	25.2	1/4 [6.4]	1	18.9
4043	3/64 [1.2]	CV	1/4 [6.4]	Vert. Up	Fillet	315	190	-	25	1/4 [6.4]	1	17
4043	3/64 [1.2]	CV	1/4 [6.4]	Overhead	Fillet	335	202.3	-	25.7	1/4 [6.4]	1	18.1
4043	3/64 [1.2]	CV	3/8 [9.5]	Horz.	Fillet	385	208.6	-	26.8	3/8 [9.5]	1	9.3

Table 6-3: Welding Guidelines for Aluminum GMAW

Alloy	Diameter in. [mm]	Proc	Material Thickness in. [mm]	Position	Joint	WFS (IPM)	Current	Trim or Power	Voltage	Weld Size in. [mm]	# of Passes	Travel Speed (IPM)
4043	3/64 [1.2]	CV	3/8 [9.5]	Vert. Up	Fillet (root)	350	195.8	-	25.6	1/4 [6.4]	1	18.9
4043	3/64 [1.2]	CV	3/8 [9.5]	Vert. Up	Fillet (fill)	330	194.7	-	25.8	3/8 [9.5]	2	28.6
4043	3/64 [1.2]	CV	3/8 [9.5]	Overhead	Fillet (root)	420	221.3	-	25.6	1/4 [6.4]	1	22.7
4043	3/64 [1.2]	CV	3/8 [9.5]	Overhead	Fillet (fill)	375	199.6	-	26.6	3/8 [9.5]	2	32.5
4043	3/64 [1.2]	Power Mode	3/16 [4.8]	Horz.	Fillet	300	180.6	4.6	24.6	3/16 [4.8]	1	28.9
4043	3/64 [1.2]	Power Mode	3/16 [4.8]	Vert. Up	Fillet	270	161.5	4	27.7	3/16 [4.8]	1	26
4043	3/64 [1.2]	Power Mode	3/16 [4.8]	Overhead	Fillet	290	179	4.25	23.4	3/16 [4.8]	1	27.9
4043	3/64 [1.2]	Power Mode	1/4 [6.4]	Horz.	Fillet	360	203.6	5.4	26	1/4 [6.4]	1	19.5
4043	3/64 [1.2]	Power Mode	1/4 [6.4]	Vert. Up	Fillet	315	193.8	4.95	25.5	1/4 [6.4]	1	17
4043	3/64 [1.2]	Power Mode	1/4 [6.4]	Overhead	Fillet	350	204.3	5.03	24.3	1/4 [6.4]	1	18.9
4043	3/64 [1.2]	Power Mode	3/8 [9.5]	Horz.	Fillet	420	242.2	6.35	26.1	3/8 [9.5]	1	10.1
4043	3/64 [1.2]	Power Mode	3/8 [9.5]	Vert. Up	Fillet (root)	365	209.3	5.65	26.1	1/4 [6.4]	1	19.8
4043	3/64 [1.2]	Power Mode	3/8 [9.5]	Vert. Up	Fillet (fill)	335	190	5.1	25.9	3/8 [9.5]	2	29
4043	3/64 [1.2]	Power Mode	3/8 [9.5]	Overhead	Fillet (root)	420	229	5.95	25.6	1/4 [6.4]	1	22.7
4043	3/64 [1.2]	Power Mode	3/8 [9.5]	Overhead	Fillet (fill)	340	200	5.3	26	3/8 [9.5]	2	29.4
4043	3/64 [1.2]	Pulse	3/16 [4.8]	Horz.	Fillet	325	159	0.98	23.2	3/16 [4.8]	1	31.3
4043	3/64 [1.2]	Pulse	3/16 [4.8]	Vert. Up	Fillet	305	150.9	1	22.8	3/16 [4.8]	1	29.3
4043	3/64 [1.2]	Pulse	3/16 [4.8]	Overhead	Fillet	320	181.2	1.09	24	3/16 [4.8]	1	30.8
4043	3/64 [1.2]	Pulse	1/4 [6.4]	Horz.	Fillet	360	200.5	1.05	24.3	1/4 [6.4]	1	19.5
4043	3/64 [1.2]	Pulse	1/4 [6.4]	Vert. Up	Fillet	320	163.4	1.06	23.6	1/4 [6.4]	1	17.3
4043	3/64 [1.2]	Pulse	1/4 [6.4]	Overhead	Fillet	360	204.2	1.1	24.7	1/4 [6.4]	1	19.5
4043	3/64 [1.2]	Pulse	3/8 [9.5]	Horz.	Fillet	500	269.6	1.05	27.4	3/8 [9.5]	1	12
4043	3/64 [1.2]	Pulse	3/8 [9.5]	Vert. Up	Fillet (root)	425	217.2	0.98	24.5	1/4 [6.4]	1	23
4043	3/64 [1.2]	Pulse	3/8 [9.5]	Vert. Up	Fillet (fill)	350	170	1.06	24.3	3/8 [9.5]	2	30.3

Table 6-3: Welding Guidelines for Aluminum GMAW

Alloy	Diameter in. (mm)	Proc	Material Thickness in. (mm)	Position	Joint	WFS (IPM)	Current	Trim or Power	Voltage	Weld Size in. (mm)	# of Passes	Travel Speed (IPM)
4043	3/64 (1.2)	Pulse	3/8 (9.5)	Overhead	Fillet (root)	420	226.3	0.96	24.3	1/4 (6.4)	1	22.7
4043	3/64 (1.2)	Pulse	3/8 (9.5)	Overhead	Fillet (fill)	385	195.5	1.08	25	3/8 (9.5)	2	33.3
4043	1/16 (1.6)	CV	1/4 (6.4)	Horz.	Fillet	225	233.6	-	24.5	1/4 (6.4)	1	21.6
4043	1/16 (1.6)	CV	1/4 (6.4)	Vert. Up	Fillet	190	197.3	-	23.8	1/4 (6.4)	1	18.3
4043	1/16 (1.6)	CV	1/4 (6.4)	Overhead	Fillet	205	212.4	-	24.8	1/4 (6.4)	1	19.7
4043	1/16 (1.6)	CV	3/8 (9.5)	Horz.	Fillet	250	240	-	24	3/8 (9.5)	1	10.7
4043	1/16 (1.6)	CV	3/8 (9.5)	Vert. Up	Fillet (root)	200	192	...	22	3/8 (9.5)	1	25.7
4043	1/16 (1.6)	CV	3/8 (9.5)	Vert. Up	Fillet (fill)	200	185	...	23.6	3/8 (9.5)	2	25.7
4043	1/16 (1.6)	CV	3/8 (9.5)	Overhead	Fillet	225	240	-	26	3/8 (9.5)	1	9.6
4043	1/16 (1.6)	Power Mode	1/4 (6.4)	Horz.	Fillet	225	240	6.3	25.7	1/4 (6.4)	1	21.6
4043	1/16 (1.6)	Power Mode	1/4 (6.4)	Vert. Up	Fillet	180	195	5.05	25.7	1/4 (6.4)	1	17.3
4043	1/16 (1.6)	Power Mode	1/4 (6.4)	Overhead	Fillet	200	225	5.8	25.3	1/4 (6.4)	1	19.2
4043	1/16 (1.6)	Power Mode	3/8 (9.5)	Horz.	Fillet	250	250	6.8	26.8	3/8 (9.5)	1	10.7
4043	1/16 (1.6)	Power Mode	3/8 (9.5)	Vert. Up	Fillet	200	225	6	26.3	3/8 (9.5)	1	8.6
4043	1/16 (1.6)	Power Mode	3/8 (9.5)	Overhead	Fillet	225	240	6.35	26	3/8 (9.5)	1	9.6
4043	1/16 (1.6)	Pulse	1/4 (6.4)	Horz.	Fillet	225	226	1.05	23.6	1/4 (6.4)	1	21.6
4043	1/16 (1.6)	Pulse	1/4 (6.4)	Vert. Up	Fillet	180	160	1.1	23.6	1/4 (6.4)	1	17.3
4043	1/16 (1.6)	Pulse	1/4 (6.4)	Overhead	Fillet	200	195	1.1	23.2	1/4 (6.4)	1	19.2
4043	1/16 (1.6)	Pulse	3/8 (9.5)	Horz.	Fillet	250	225	1.1	25	3/8 (9.5)	1	10.7
4043	1/16 (1.6)	Pulse	3/8 (9.5)	Vert. Up	Fillet	200	200	1.1	23	3/8 (9.5)	1	8.6
4043	1/16 (1.6)	Pulse	3/8 (9.5)	Overhead	Fillet	225	220	1.1	24	3/8 (9.5)	1	9.6
5356	0.035 (0.9)	CV	3/16 (4.8)	Horz.	Fillet	770	185.3	-	21.6	3/16 (4.8)	1	41.3
5356	0.035 (0.9)	CV	3/16 (4.8)	Vert. Up	Fillet	750	183	-	22	3/16 (4.8)	1	40.2
5356	0.035 (0.9)	CV	3/16 (4.8)	Overhead	Fillet	775	184.7	-	22.2	3/16 (4.8)	1	41.6

Table 6-3: Welding Guidelines for Aluminum GMAW												
Alloy	Diameter in. (mm)	Proc	Material Thickness in. (mm)	Position	Joint	WFS (IPM)	Current	Trim or Power	Voltage	Weld Size in. (mm)	# of Passes	Travel Speed (IPM)
5356	0.035 (0.9)	CV	1/4 (6.4)	Horz.	Fillet	800	201.7	-	23.6	1/4 (6.4)	1	24.1
5356	0.035 (0.9)	CV	1/4 (6.4)	Vert. Up	Fillet	750	183	-	22.4	1/4 (6.4)	1	22.6
5356	0.035 (0.9)	CV	1/4 (6.4)	Overhead	Fillet	800	199.5	-	23.4	1/4 (6.4)	1	24.1
5356	0.035 (0.9)	Power Mode	3/16 (4.8)	Horz.	Fillet	770	186.7	4.25	22.6	3/16 (4.8)	1	41.3
5356	0.035 (0.9)	Power Mode	3/16 (4.8)	Vert. Up	Fillet	750	180	4	22	3/16 (4.8)	1	40.2
5356	0.035 (0.9)	Power Mode	3/16 (4.8)	Overhead	Fillet	775	191	4.2	21.8	3/16 (4.8)	1	41.6
5356	0.035 (0.9)	Power Mode	1/4 (6.4)	Horz.	Fillet	800	203	4.96	24.1	1/4 (6.4)	1	24.1
5356	0.035 (0.9)	Power Mode	1/4 (6.4)	Vert. Up	Fillet	750	189	4.3	22.7	1/4 (6.4)	1	22.6
5356	0.035 (0.9)	Power Mode	1/4 (6.4)	Overhead	Fillet	800	197.6	4.75	23.3	1/4 (6.4)	1	24.1
5356	0.035 (0.9)	Pulse	3/16 (4.8)	Horz.	Fillet	770	172.7	0.82	21	3/16 (4.8)	1	41.3
5356	0.035 (0.9)	Pulse	3/16 (4.8)	Vert. Up	Fillet	750	176	0.87	21.8	3/16 (4.8)	1	40.2
5356	0.035 (0.9)	Pulse	3/16 (4.8)	Overhead	Fillet	775	188	0.94	23.6	3/16 (4.8)	1	41.6
5356	0.035 (0.9)	Pulse	1/4 (6.4)	Horz.	Fillet	510	216	0.98	23.3	1/4 (6.4)	1	15.4
5356	0.035 (0.9)	Pulse	1/4 (6.4)	Vert. Up	Fillet	500	212.2	0.84	21.8	1/4 (6.4)	1	15.1
5356	0.035 (0.9)	Pulse	1/4 (6.4)	Overhead	Fillet	510	219.9	1	23.4	1/4 (6.4)	1	15.4
5356	3/64 (1.2)	CV	3/16 (4.8)	Horz.	Fillet	470	209	-	21.6	3/16 (4.8)	1	45.2
5356	3/64 (1.2)	CV	3/16 (4.8)	Vert. Up	Fillet	430	190	-	20.9	3/16 (4.8)	1	41.4
5356	3/64 (1.2)	CV	3/16 (4.8)	Overhead	Fillet	475	206	-	21.6	3/16 (4.8)	1	45.7
5356	3/64 (1.2)	CV	1/4 (6.4)	Horz.	Fillet	500	208	-	23	1/4 (6.4)	1	27.1
5356	3/64 (1.2)	CV	1/4 (6.4)	Vert. Up	Fillet	460	192.1	-	20.4	1/4 (6.4)	1	24.9
5356	3/64 (1.2)	CV	1/4 (6.4)	Overhead	Fillet	480	196.8	-	21.5	1/4 (6.4)	1	26
5356	3/64 (1.2)	CV	3/8 (9.5)	Horz.	Fillet	610	275.2	-	25.5	3/8 (9.5)	1	14.7
5356	3/64 (1.2)	CV	3/8 (9.5)	Vert. Up	Fillet (root)	440	192.4	-	22.9	1/4 (6.4)	1	23.8
5356	3/64 (1.2)	CV	3/8 (9.5)	Vert. Up	Fillet (fill)	410	186.2	-	23.7	3/8 (9.5)	2	35.5

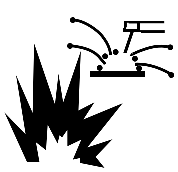
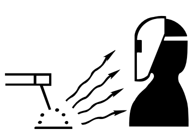
Table 6-3: Welding Guidelines for Aluminum GMAW

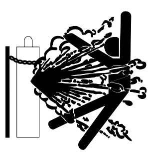
Alloy	Diameter in. (mm)	Proc	Material Thickness in. (mm)	Position	Joint	WFS (IPM)	Current	Trim or Power	Voltage	Weld Size in. (mm)	# of Passes	Travel Speed (IPM)
5356	3/64 (1.2)	CV	3/8 (9.5)	Overhead	Fillet (root)	450	200	-	23.7	1/4 (6.4)	1	24.4
5356	3/64 (1.2)	CV	3/8 (9.5)	Overhead	Fillet (fill)	435	188.8	-	23.5	3/8 (9.5)	2	37.7
5356	3/64 (1.2)	Power Mode	3/16 (4.8)	Horz.	Fillet	450	205	4.5	21	3/16 (4.8)	1	43.3
5356	3/64 (1.2)	Power Mode	3/16 (4.8)	Vert. Up	Fillet	430	200	4.15	21	3/16 (4.8)	1	41.4
5356	3/64 (1.2)	Power Mode	3/16 (4.8)	Overhead	Fillet	475	207	4.55	21.8	3/16 (4.8)	1	45.7
5356	3/64 (1.2)	Power Mode	1/4 (6.4)	Horz.	Fillet	475	240	5.8	25	1/4 (6.4)	1	25.7
5356	3/64 (1.2)	Power Mode	1/4 (6.4)	Vert. Up	Fillet	460	210	4.65	22	1/4 (6.4)	1	24.9
5356	3/64 (1.2)	Power Mode	1/4 (6.4)	Overhead	Fillet	490	240	5.9	24.5	1/4 (6.4)	1	26.5
5356	3/64 (1.2)	Power Mode	3/8 (9.5)	Horz.	Fillet	600	260	7	27	3/8 (9.5)	1	14.4
5356	3/64 (1.2)	Power Mode	3/8 (9.5)	Vert. Up	Fillet (root)	520	214.5	4.65	21.4	3/8 (9.5)	1	12.5
5356	3/64 (1.2)	Power Mode	3/8 (9.5)	Vert. Up	Fillet (fill)	500	204.5	4.7	22.5	3/8 (9.5)	1	12
5356	3/64 (1.2)	Power Mode	3/8 (9.5)	Overhead	Fillet (root)	545	236	5.65	23.3	3/8 (9.5)	1	13.1
5356	3/64 (1.2)	Power Mode	3/8 (9.5)	Overhead	Fillet (fill)	525	226	5.5	24.2	3/8 (9.5)	1	12.6
5356	3/64 (1.2)	Pulse	3/16 (4.8)	Horz.	Fillet	470	200.6	0.94	21.8	3/16 (4.8)	1	45.2
5356	3/64 (1.2)	Pulse	3/16 (4.8)	Vert. Up	Fillet	430	185.5	0.94	20.5	3/16 (4.8)	1	41.4
5356	3/64 (1.2)	Pulse	3/16 (4.8)	Overhead	Fillet	475	200	0.94	21.7	3/16 (4.8)	1	45.7
5356	3/64 (1.2)	Pulse	1/4 (6.4)	Horz.	Fillet	510	216	0.98	23.3	1/4 (6.4)	1	27.6
5356	3/64 (1.2)	Pulse	1/4 (6.4)	Vert. Up	Fillet	500	212.2	0.84	21.8	1/4 (6.4)	1	27.1
5356	3/64 (1.2)	Pulse	1/4 (6.4)	Overhead	Fillet	500	219.9	1	23.4	1/4 (6.4)	1	27.1
5356	3/64 (1.2)	Pulse	3/8 (9.5)	Horz.	Fillet	610	271.9	1	24.9	3/8 (9.5)	1	14.7
5356	3/64 (1.2)	Pulse	3/8 (9.5)	Vert. Up	Fillet (root)	475	192.9	0.9	21.7	1/4 (6.4)	1	25.7
5356	3/64 (1.2)	Pulse	3/8 (9.5)	Vert. Up	Fillet (fill)	425	180.8	1.05	22.8	3/8 (9.5)	2	36.8
5356	3/64 (1.2)	Pulse	3/8 (9.5)	Overhead	Fillet (root)	520	208.4	0.9	22.6	1/4 (6.4)	1	28.1
5356	3/64 (1.2)	Pulse	3/8 (9.5)	Overhead	Fillet (fill)	465	195	1.05	23.7	3/8 (9.5)	2	40.3

Table 6-3: Welding Guidelines for Aluminum GMAW

Alloy	Diameter in. [mm]	Proc	Material Thickness in. [mm]	Position	Joint	WFS (IPM)	Current	Trim or Power	Voltage	Weld Size in. [mm]	# of Passes	Travel Speed (IPM)
5356	1/16 [1.6]	CV	1/4 [6.4]	Horz.	Fillet	330	265	-	22.6	1/4 [6.4]	1	31.7
5356	1/16 [1.6]	CV	1/4 [6.4]	Vert. Up	Fillet	285	222	-	21.5	1/4 [6.4]	1	27.4
5356	1/16 [1.6]	CV	1/4 [6.4]	Overhead	Fillet	310	235	-	24.4	1/4 [6.4]	1	29.8
5356	1/16 [1.6]	CV	3/8 [9.5]	Horz.	Fillet	360	278.5	-	24.8	3/8 [9.5]	1	15.4
5356	1/16 [1.6]	CV	3/8 [9.5]	Vert. Up	Fillet (root)	300	240	-	22.4	1/4 [6.4]	1	28.9
5356	1/16 [1.6]	CV	3/8 [9.5]	Vert. Up	Fillet (fill)	290	230	-	22.4	3/8 [9.5]	2	44.6
5356	1/16 [1.6]	CV	3/8 [9.5]	Overhead	Fillet (root)	330	257.5	-	23.3	1/4 [6.4]	1	31.7
5356	1/16 [1.6]	CV	3/8 [9.5]	Overhead	Fillet (fill)	300	250	-	24	3/8 [9.5]	2	46.2
5356	1/16 [1.6]	Power Mode	1/4 [6.4]	Horz.	Fillet	340	264	6.2	23.3	1/4 [6.4]	1	32.7
5356	1/16 [1.6]	Power Mode	1/4 [6.4]	Vert. Up	Fillet	300	230	5	22	1/4 [6.4]	1	28.9
5356	1/16 [1.6]	Power Mode	1/4 [6.4]	Overhead	Fillet	310	243	5.45	22.3	1/4 [6.4]	1	29.8
5356	1/16 [1.6]	Power Mode	3/8 [9.5]	Horz.	Fillet	360	287	7.7	26.5	3/8 [9.5]	1	15.4
5356	1/16 [1.6]	Power Mode	3/8 [9.5]	Vert. Up	Fillet (root)	310	240	5.3	21.4	1/4 [6.4]	1	29.8
5356	1/16 [1.6]	Power Mode	3/8 [9.5]	Vert. Up	Fillet (fill)	295	237	5.35	22.3	3/8 [9.5]	2	45.4
5356	1/16 [1.6]	Power Mode	3/8 [9.5]	Overhead	Fillet (root)	330	256	5.65	21.9	1/4 [6.4]	1	31.7
5356	1/16 [1.6]	Power Mode	3/8 [9.5]	Overhead	Fillet (fill)	310	245	5.5	22.1	3/8 [9.5]	2	47.7
5356	1/16 [1.6]	Pulse	1/4 [6.4]	Horz.	Fillet	335	251	0.98	23.5	1/4 [6.4]	1	32.2
5356	1/16 [1.6]	Pulse	1/4 [6.4]	Vert. Up	Fillet	270	207	1.02	20.3	1/4 [6.4]	1	26
5356	1/16 [1.6]	Pulse	1/4 [6.4]	Overhead	Fillet	305	232	1.05	22	1/4 [6.4]	1	29.3
5356	1/16 [1.6]	Pulse	3/8 [9.5]	Horz.	Fillet	360	280	1.08	24.7	3/8 [9.5]	1	15.4
5356	1/16 [1.6]	Pulse	3/8 [9.5]	Vert. Up	Fillet (root)	300	220	0.96	21	1/4 [6.4]	1	28.9
5356	1/16 [1.6]	Pulse	3/8 [9.5]	Vert. Up	Fillet (fill)	295	225	1.05	21.3	3/8 [9.5]	2	45.4
5356	1/16 [1.6]	Pulse	3/8 [9.5]	Overhead	Fillet (root)	330	250	1	21.6	1/4 [6.4]	1	31.7
5356	1/16 [1.6]	Pulse	3/8 [9.5]	Overhead	Fillet (fill)	305	237	1.1	22	3/8 [9.5]	2	47

Welding Safety Checklist

HAZARD	FACTORS TO CONSIDER	PRECAUTION SUMMARY
Electric shock can kill 	» Wetness » Welder in or on workpiece » Confined space » Electrode holder and cable insulation	» Insulate welder from workpiece and ground using dry insulation. Rubber mat or dry wood. » Wear dry, hole-free gloves. (Change as necessary to keep dry.) » Do not touch electrically "hot" parts or electrode with bare skin or wet clothing. » If wet area and welder cannot be insulated from workpiece with dry insulation, use a semiautomatic, constant voltage welder or stick welder with voltage reducing device. » Keep electrode holder and cable insulation in good condition. Do not use if insulation is damaged or missing.
Fumes and gases can be dangerous 	» Confined area » Positioning of welder's head » Lack of general ventilation » Electrode types, i.e., manganese, chromium, etc. See MSDS » Base metal coatings, galvanize, paint	» Use ventilation or exhaust to keep air breathing zone clear, comfortable. » Use helmet and positioning of head to minimize fume in » breathing zone. » Read warnings on electrode container and material safety data sheet (MSDS) for electrode. » Provide additional ventilation/exhaust where special ventilation requirements exist. » Use special care when welding in a confined area. » Do not weld unless ventilation is adequate.
Welding sparks can cause fire or explosion 	» Containers which have held combustibles » Flammable materials	» Do not weld on containers which have held combustible materials (unless strict AWS F4.1 procedures are followed). Check before welding. » Remove flammable materials from welding area or shield from sparks, heat. » Keep a fire watch in area during and after welding. » Keep a fire extinguisher in the welding area. » Wear fire retardant clothing and hat. Use earplugs when welding ovehead.
Arc rays can burn eyes and skin 	» Process: gas-shielded arc most severe	» Select a filter lens which is comfortable for you while welding. » Always use helmet when welding. » Provide non-flammable shielding to protect others. » Wear clothing which protects skin while welding.
Confined space  	» Metal enclosure » Wetness » Restricted entry » Heavier than air gas » Welder inside or on workpiece	» Carefully evaluate adequacy of ventilation especially where electrode requires special ventilation or where gas may displace breathing air. » If basic electric shock precautions cannot be followed to insulate welder from work and electrode, use semiautomatic, constant voltage equipment with cold electrode or stick welder with voltage reducing device. » Provide welder helper and method of welder retrieval from outside enclosure.

Welding Safety Checklist		
HAZARD	FACTORS TO CONSIDER	PRECAUTION SUMMARY
General work area hazards	» Cluttered area	» Keep cables, materials, tools neatly organized.
	» Indirect work (welding ground) connection	» Connect work cable as close as possible to area where welding is being performed. Do not allow alternate circuits through scaffold cables, hoist chains, ground leads.
	» Electrical equipment	» Use only double insulated or properly grounded equipment. » Always disconnect power to equipment before servicing.
	» Engine-driven equipment	» Use in only open, well ventilated areas. » Keep enclosure complete and guards in place. » See Lincoln Electric service shop if guards are missing. » Refuel with engine off. » Is using auxiliary power, osha may require gfi protection or assured grounding program (or isolated windings if less than 5kw).
	» Gas cylinders	» Never touch cylinder with the electrode. » Never lift a machine with cylinder attached. » Keep cylinder upright and chained to support.

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