Welding Aluminum—Questions and Answers

A Practical Guide for Troubleshooting Aluminum Welding-Related Problems

2nd Edition

by

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Reviewed by the

AWS Product Development Committee

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Preface

The 2nd edition of this book was produced in order to include additional sections which contain material considered important and very appropriate for enhancing the overall content of the publication.

The additional topics that have been added are:

1. The Reduction in Strength of Aluminum Base Material after Welding—and the effect of filler alloy selection on the strength of fillet welds, with tables providing valuable data.
2. Post Weld Processing—how to regain lost strength and return aluminum alloys to their original condition after welding—considerations of both heat treatable and non-heat treatable alloys.
3. Explanations of Aluminum Heat Treatment Terms—such as solid-solution hardening, precipitation hardening, age hardening, natural aging, artificial aging, annealing, stabilizing, and stress-relieving, and their affect on aluminum alloys.
4. The use of Aluminum in Cryogenic Applications—with tables that show how mechanical properties of aluminum alloys increase as the temperature decreases.
5. Exfoliation Corrosion and Intergranular Corrosion in Aluminum—ASTM document designation: B 928/B 928M Standard Specification for High Magnesium Aluminum-Alloy Sheet and Plate for Marine Service and Similar Environments.
6. Modes of Metal Transfer Preferable to Aluminum Welding and Why—with table showing GMAW globular-to-spray transition currents for a selection of aluminum electrode diameters for welding aluminum with pure argon shielding gas.
7. Open Root Joint Welding of Aluminum Pipes—the difference between welding aluminum alloys and steel using the gas tungsten arc welding process for this specialized application.
8. Stud Welding of Aluminum—Drawn Arc Stud Welding of Aluminum and Capacitor Discharge Stud Welding of Aluminum.
9. An Overview of Plasma Arc Cutting of Aluminum—a comparison of plasma arc cutting, laser cutting, and water jet cutting.
10. Brazing and Soldering of Aluminum Alloys—an overview of the many brazing and soldering techniques.
11. Welding Specification for Friction Stir Welding—an overview of the AWS D17.3/D17.3M:2010, *Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications*.

As with the 1st edition, this book is largely comprised of individual Aluminum Questions and Answers that were originally published over a number of years in the American Welding Society (AWS) *Welding Journal*. The majority of the questions addressed herein originate from inquiries to me, primarily from individuals within the welding fabrication industry.

Also included in this collection of material are some feature articles that I have had published previously in the *Welding Journal*. The welding processes section (Chapter 7) contains information and parameters graciously provided by The Aluminum Association and reproduced from their outstanding publication “Welding Aluminum Theory and Practice—Fourth Edition.” Many of the graphics and charts within this book have been reproduced with permission from ESAB Welding and Cutting Products and were taken from material that is used by ESAB for their aluminum welding technology training programs. This book is not constructed in the format that is typically associated with text books pertaining to similar subjects. That is to say, because of the nature of the material source used for this book, the Aluminum Q&A columns, the individual chapters within this book have been compiled to best highlight and explain that material in a manner that reflects the original question and answer theme. For this reason the book deviates from the more traditional layout of a textbook, where typically you would see all the information on specific topics grouped together more specifically.

The idea for compiling this book originated through inquiries from individuals who followed the Aluminum Q&A column in the *Welding Journal* enthusiastically. They wondered if anyone had ever thought of collecting all the information within the Aluminum Q&A columns together into a practical guide for troubleshooting aluminum welding-related problems. I have tried to present this material in a logical format and have included a fairly comprehensive table of contents and index in an attempt to direct the reader to their appropriate areas of interest. If the information contained in this publication helps individuals to better understand aluminum welding and possibly assists in improving welding quality, then I will be pleased with the overall outcome.

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Chapter 1

The Advancement of Aluminum within the Welding Fabrication Industry and its Many Product Design Applications

1.1 Introduction

When we consider the advancement of aluminum within the welding fabrication industry, it becomes clear that there is a definite need for a better understanding of how to weld this material.

As aluminum welding fabrication has advanced, there have been many questions to answer associated with the welding of this material.

This introduction is intended to point out just a few of the many applications where aluminum is used in the welding fabrication industry today.

The first commercial applications of aluminum were novelty items such as mirror frames and serving trays. Cooking utensils were also a major early marketed product. In time, aluminum grew in diversity of applications to the extent that virtually every aspect of modern life was directly or indirectly affected by its use.

Today, aluminum's unique characteristics of light weight, high strength, high toughness, extreme temperature capability, versatility of extruding, excellent corrosion resistance, and recycling capabilities make it the obvious choice of material by engineers and designers for a variety of welding fabrication applications.

1.2 Automotive Industry

Perhaps the most dynamic advancement of aluminum welding fabrication today is within the automotive industry. Promoted primarily through environmental issues such as increased fuel efficiency, corrosion resistance, and recycling, we are seeing more and more components manufactured in aluminum appearing within the average automobile.

Recent developments of major structural components fabricated entirely from aluminum such as engine cradles, front and rear suspension frames, drive shafts, and wheels are complementing the more traditional nonstructural components such as heat exchangers, radiators, and air conditioning units (see Figures 1.1, 1.2, and 1.3). Many of these welded structural components are manufactured using 6xxx series base alloys, making use of this material's ability to produce complex extruded shapes and

Figure 1.1—Fabricated Wheel Often Manufactured from the 5xxx Series Aluminum Base Alloys

Figure 1.2—Drive Shaft Coupling Made from 6xxx Series Aluminum Alloys

its weldability with the GMAW (MIG) welding process. Another issue, other than fuel efficiency associated with the use of aluminum within this industry, is safety. Aluminum's basic physical characteristics lend themselves to creating automobiles that not only perform better in a collision, but can actually help to prevent crashes altogether. Aluminum's strength-to-weight ratio allows engineers to construct larger vehicle crash zones for better energy absorption. Aluminum structures can be designed to absorb the same energy as steel at only 55% of the weight (see Figure 1.4). This weight saving relates to less kinetic energy to be absorbed in a collision. Aluminum intensive vehicles provide better handling and braking capability, improving their crash-avoidance ability. A vehicle made of conventional material weighing 3300 lbs traveling at 60 mph

Figure 1.3—Fabricated Aluminum Engine Cradle

requires 213 ft to stop. Given the same drive train, an equally sized aluminum-intensive vehicle would weigh 2000 lbs and could stop in 135 ft. Similar improvements are seen in acceleration abilities, when a little extra speed could make the difference in avoiding a collision. Welding procedures used within this industry will vary, but typically, wherever possible, will make use of robotics. A typical thin wall heat exchanger fabrication is making use of the 4047 filler alloy which contains 11.0% to 13.0% silicon and provides exceptional fluidity which helps to reduce leakage rates and improve productivity. The thicker material structural applications within this industry are often able to make use of filler alloy 5356 for its improved strength and impact properties.

1.3 Shipbuilding

The fast ferries projects have advanced the use of aluminum in shipbuilding through the development of a new concept in marine transportation. With an eye on profits, shipping companies are looking at high-speed aluminum ferries as a means of fast, efficient, low-maintenance transport. The term “fast ferries” applies to hydrofoils,

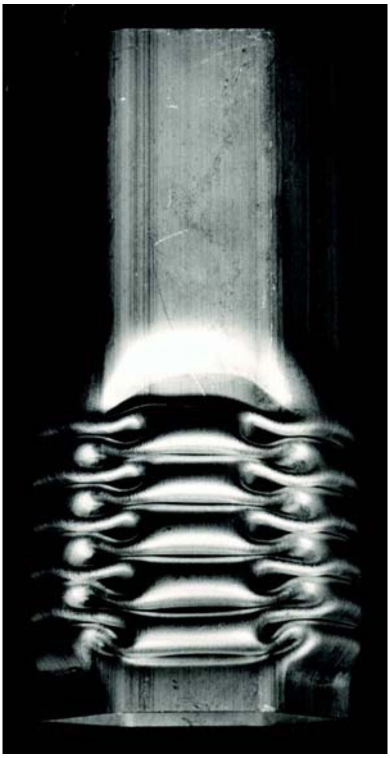


Figure 1.4—During a Car Crash, Aluminum Structures Will Fold Like an Accordion to Absorb Energy and Protect the Vehicle Passengers from Destructive Crash Forces. Pound for Pound, Aluminum Can be Up to Two-and-a-Half Times Stronger than Steel and it Can Absorb Around Twice as Much Energy. Structures Can be Designed to Fold During a Crash in a Predictable Manner.

wave-piercing catamarans and both mono-hulled and multi-hulled vessels built to carry large payloads of passengers and cargo at high speeds. Typically, these vessels are around 100 ft to 130 ft in length and travel at 30 knots to 35 knots [35 mph to 40 mph]. Aluminum-intensive mega-ferries are massive vessels measuring approximately 260 ft in length and carry up to 700 passengers and 150 cars. Quadrimarans are among the newest marine transportation innovations. Measuring 180 ft in length, newer versions are designed to carry 600 passengers. These fast ferries will regularly travel at 60 knots [69 mph] but they could achieve speeds of up to 110 knots [126.5 mph]. The shipbuilding industry has made use of the high-strength magnesium base alloys such as 5083 welded with 5183 filler alloy to obtain the minimum tensile strength requirements as specified in the codes. Often argon/helium shielding gas mixes are used to reduce porosity and obtain broader and deeper penetration for these high-quality welds. Aluminum's unique combination of light-weight, high-strength, and corrosion-resistance make these high-speed marine applications possible. The advantages of aluminum are also being used for military and other types of vessels as well (see Figures 1.5 and 1.6).

Figure 1.5—Large Military Ship Almost Exclusively Manufactured of Aluminum Alloys

Figure 1.6—Coastguard Vessel Made from 5xxx and 6xxx Series Aluminum Alloys

1.4 Recreation and Sporting Equipment

The advancement of high-tech sporting equipment and the increased use of high-strength, heat-treatable aluminum alloys such as the 7xxx series have revolutionized this industry. Many of the latest designs have incorporated these light-weight, high-performance aluminum materials. Bicycle frames, baseball bats, golf clubs, sleds, and snowmobiles are some of the many products within this industry dependent on aluminum alloys today (see Figures 1.7, 1.8, and 1.9). This industry, with its thin wall joining and its complex heat treatment, has promoted the development and use of specialized filler alloys designed to respond to thermal treatment and the development of welding techniques and equipment produced to meet their strength and cosmetic application.

Figure 1.7—High-Performance Bicycle Made from 7xxx Series Aluminum Alloy

Figure 1.8—Snowmobiles are Often Manufactured from Aluminum Alloys

Figure 1.9—Aluminum Baseball Bat

1.5 Transportation and Containers

For similar reasons as the automotive industry, transportation vehicles are adopting more aluminum. Heated rail cars with line heaters and steam lines make use of aluminum base alloy 5454, welded with filler alloy 5554 for their strength and high-temperature characteristics. Cryogenic tanks are manufactured from base alloy 5083, welded with filler alloy 5183 for their high strength at low temperature characteristics. Truck bodies and panels are manufactured from 5052, 5086, 5083, and 6061 and often welded with filler alloy 5356 for its strength characteristics (see Figures 1.10 through 1.13).

Figure 1.10—Dump Trailer Usually Built from 5xxx Series and 6xxx Series Aluminum Alloys

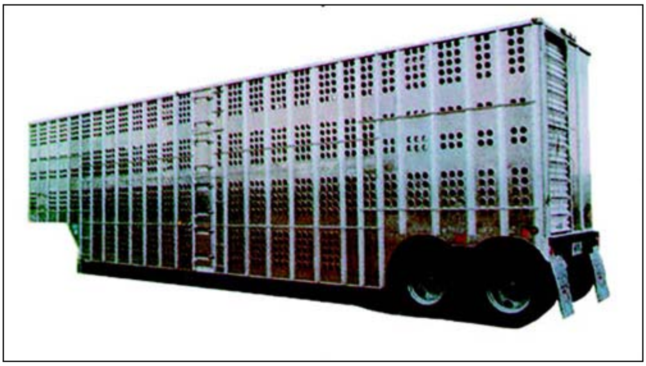


Figure 1.11—Livestock Trailers Make Use of Aluminum's Light Weight and Excellent Corrosion Resistance

Figure 1.12—LNG Tankers Make Use of the Low-Temperature Strength of Aluminum Used for the Manufacturing of These Large Spherical Vessels

Figure 1.13—Aluminum's Light Weight and Corrosion Resistance is Very Suitable for the Fabrication of Many Types of Tanker Trucks

1.6 Defense and Aerospace

These industries use high-strength 5xxx series (Al-Mg) nonheat-treatable base alloys for some applications, but also make use of some of the more specialized heat-treatable aluminum alloys with superior mechanical properties. Aluminum armor plating is used for its impact strength and strength-to-weight ratio (see Figures 1.14 and 1.15). Alloy 5083 and 7039 base materials are welded with 5356 filler, and 2519 base material is welded with 2319 filler. Missiles are constructed of 2019 alloy, welded with 4145 filler and 2219 alloy welded with 2319 filler. Perhaps the most exotic aluminum alloys, with exceptional strength over a wide range of operating temperatures, are used in the aerospace industry (see Figures 1.16 and 1.17). Some of these alloys are 2219, 2014, 2090, 2024, and 7075. These base materials are typically used in specialized high-performance applications and have their own welding characteristics and associated problems, which require special considerations when joining.

Figure 1.14—The Light Weight Allows Aluminum Armored Vehicles Like This to Travel at High Speed

Figure 1.15—The Corrosion Resistance and Light Weight of Aluminum Allows this Military Amphibious Vehicle to Travel at High Speeds on Land and Over Water

Figure 1.16—High-Performance, High-Strength, Heat-Treatable Aluminum Alloys are Used on the Space Shuttle Projects

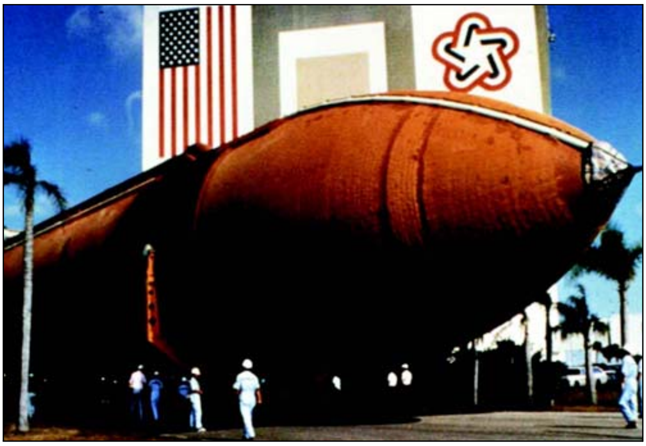


Figure 1.17—The Space Shuttle Fuel Tank is Fabricated from High-Strength Aluminum Alloys

1.7 Conclusion

The use of aluminum continues to grow within the welding fabrication industry in both size and complexity, and with it the need for resources which can provide industry with the technical support required to understand how best to weld this material.

Chapter 2

What is the History of Aluminum and Aluminum Welding?

2.1 Introduction

To appreciate the history of aluminum welding, it helps if we are familiar with the history of aluminum itself. Today people come into close contact with aluminum on an everyday basis and seldom give the material a second thought. In America alone, nearly 100 billion aluminum beverage cans are used each year. More than 60% of these cans are recycled and made into new aluminum items. Within just one industry sector, the automotive industry, we have seen major advancements in aluminum as a material of preference. The average modern automobile contains more aluminum than ever before. Radiators, engine blocks, transmission housings, wheels, body panels, bumpers, space frames, engine cradles, drive shafts and suspension frames are now commonly made of aluminum and found on many of today's automotive models. As well as our automobiles, homes and office buildings have become more aluminum intensive, incorporating such items as window frames, gutters, electrical wiring, siding, and roofing materials. The homes and offices are also often equipped with furniture made from aluminum alloys.

To appreciate aluminum in today's world, we should remember that it was an aluminum engine that powered the Wright Brothers first flight at Kitty Hawk, North Carolina on December 17, 1903. And, what is probably more relevant, if aluminum had not been available for the development of the aircraft industry, aircraft, as we know them today, would not exist. The extremely high-strength-to-weight ratio of aluminum is the very reason why today's large aircraft can fly with such relatively small engines. The United States is the world's largest producer of aluminum, although it is made in abundance in many other areas of the world. Containers and packaging are aluminum's largest market; transportation (cars, trucks, planes, trains) is second, followed by building and construction. Today, aluminum surrounds us, from cooking utensils that we use in our kitchens to highway signs that guide us down our roads. Aluminum components can be found almost everywhere. As commonplace and important as aluminum is in our everyday lives today, you would suspect that it has been around for a very long time. In actuality, the process of converting aluminum ore into the metal that we know and use everyday as aluminum was discovered relatively recently. Industrial production of aluminum only began in the late 19th century, making this material very much a latecomer among the common metals.

2.2 The Story Behind the Metal

Aluminum is one of 92 metallic elements that have existed since Earth was formed. It makes up about 8% of the earth's crust, exceeded only by oxygen (47%) and silicon (27%). Despite aluminum's abundance, it was not until 2000 years into the Iron Age that it was freed from its mineral state. Over countless millennia, (through physical and chemical action), the ancient aluminum-silicon rocks were ground down to exceedingly fine particles. These particles formed aluminous clays from which primitive pottery was made. In a wide belt around the Earth, hard rain and high temperatures baked and pounded clays and other compounds to form large deposits of aluminum ore. This ore was discovered first at Les Baux, France, where it became known as "bauxite." When the ore was refined, it formed aluminum oxide, also known as "alumina."

For thousands of years, people tried without success to develop something similar to what we now know as metallic aluminum. The primary reason for such a late development of this metal was the difficulty of extracting it from its ore. It combines strongly with oxygen in a compound that, unlike iron, cannot be reduced in a reaction with carbon.

Sometime between 1808 and 1812, Englishman Sir Humphrey Davy was the first to concentrate what he suspected to be a new metal mixed with iron from its naturally occurring ores. Davy named the new element "aluminum," derived from alum, its bisulfate salt, which was known already to the ancient Egyptians for its use in dyeing. Hans Christian Orsted first succeeded in making aluminum on a laboratory scale in Denmark in 1825; Friedrich Wohler did the same in Germany a little later. Finally, in 1854, Frenchman Henri-Etienne Sainte-Clair Deville (who named the ore "bauxite") found a way to produce aluminum through a chemical process. Even though several plants were established to make this new metal, it was so expensive that samples were displayed to the public next to the crown jewels of France at the Paris Exposition of 1855. It took more than 30 additional years before a more economical process of making aluminum was developed.

In 1886 by an amazing coincidence, two men (one in France, and the other in the United States of America) simultaneously discovered the electrolytic process for producing aluminum that is still used today. Charles Martin Hall was an Oberlin (Ohio) College student when he became interested in producing aluminum inexpensively. He continued to use the college laboratory after he graduated in 1885 and discovered his method eight months later. He had ultimately developed a workable electrolytic process that formed molten aluminum when purified alumina was dissolved in a molten salt called cryolite and electrolyzed with direct current. When Hall went to patent his process, he discovered a French patent for essentially the same process, discovered by Paul L. T. Heroult. This process is now known as the Hall-Heroult process. After several unsuccessful attempts by Charles Martin Hall to interest financial backers in promoting the discovery, he obtained the support of Alfred E. Hunt and a few of his friends. Together they formed the Pittsburgh Reduction Company (later to become the Aluminum Company of America, *ALCOA*). Understanding aluminum's potential, Hall founded an industry in the U.S. that contributed to the development of many others, particularly the manufacture of aircraft and automobiles. The industrial production of aluminum began in earnest around 1888 at about the same time in America and in Europe—in the U.S., in Pittsburgh, PA, using Hall's process, and in Switzerland at

Neuhausen using Heroult's process. By 1914, the Hall-Heroult process had brought the cost of aluminum down incredibly. Aluminum, once a precious metal used for fine jewelry, is now becoming an accessible material that can be used to advantage for many applications. Consequently, the production of aluminum multiplied amazingly. In 1918, it had already reached the 180 000 ton level, and it has maintained steady long-term growth ever since. The production and consumption of aluminum grew, on average, through the mid-1970s to more than 8% per year. The total consumption of aluminum in the western world reached 2 million tons in 1952 and 20 million tons in 1989. Aluminum had been recognized as a material of the future.

2.3 Developments in Welding Aluminum

After the initial discovery of a suitable method to produce aluminum as a cost effective material, the next step was to modify and improve upon the basic material.

Pure aluminum has some unique and very important characteristics, its corrosion resistance and electrical conductivity being two of the most important. However, pure aluminum, because of its relatively low strength, was not the most suitable material for structural applications.

It was soon found that by adding relatively small amounts of alloying elements to pure aluminum, major changes could be made to the material's properties. One of the first aluminum alloys to be produced was the aluminum-copper alloy. Around 1910 the phenomenon of precipitation hardening in this family of alloys was discovered. Many of these precipitation-hardening alloys would produce immediate interest within the developing aircraft industry. Following the aluminum-copper alloys, many other alloys were developed; one of these was the 3xxx series alloys which were predominantly used for cookware. Pots and pans were made from these aluminum manganese alloys. The 3xxx series alloys were found to have excellent properties at elevated temperatures and for that reason are still used today for radiators and other heat exchangers. Figure 2.1 shows a Tea Pot Souvenir from the National Aluminium Week held in the U.K. in October 1932.

It was found that by adding such elements as copper (Cu), manganese (Mn), magnesium (Mg), silicon (Si), and zinc (Zn) and combinations of these elements, various physical and mechanical characteristics of pure aluminum could be dramatically changed. Many of these new alloys could match the strength of good quality carbon steel at one third of the weight. The development of many new aluminum alloys, which were suitable for structural application, immediately posed the question of suitable joining methods. It is one thing to have a desirable base material, but without a practical and reliable method of joining such a material, it becomes impractical to use it as a fabrication material.

The development of welding procedures for aluminum alloys was somewhat different than that of carbon steel. Because of the many variations of aluminum base alloys and the different affects each alloying element would have on the weldability of the base materials, it was necessary to develop many different filler alloys to accommodate these variables. For instance, some of the aluminum base alloys were of a particular chemistry, having been designed that way for specific desirable mechanical and physical characteristics that ultimately were proven to not be the most suited to good weldabil-

Figure 2.1—Tea Pot Souvenir from the National Aluminium Week Held in the U.K. in October 1932

ity. These base alloy chemistries were not conducive to the most desirable solidification characteristics, and often rendered the base alloys particularly prone to solidification cracking. The various degrees of solidification crack sensitivity for each of the different alloys needed to be established to provide guidance for the development of suitable welding procedures that would produce consistently crack-free welds. This welding development work was a major project in itself. Much development work was performed by the aluminum base material manufacturers, as it was most certainly to their advantage to show that aluminum could be reliably welded, and also by some of the first aluminum fabricators, who recognized the potential of this new material and were eager to use it within their manufacturing operations. Two of the pioneers in welding development in the U.S. were ALCOA (The Aluminum Corporation of America) and Kaiser Aluminum and Chemical Corporation. Their publication *Welding ALCOA Aluminum* was first published in 1954, and *Welding Kaiser Aluminum* was first published in 1967.

To be competitive in the modern industrial world, a structural metal must be readily weldable. The earliest welding techniques suitable for aluminum included oxyfuel gas welding (see Figure 2.2) and resistance welding. Arc welding of aluminum was mainly restricted to the Shielded Metal Arc Process (SMAW) sometimes referred to as the Manual Metal Arc Process (MMA). This welding process uses a flux-coated welding electrode. It was soon found that this process was not the most suited for welding aluminum. One of the main problems was corrosion caused by flux entrapment, particularly in fillet welds where the flux could be trapped behind the weld and promote corrosion from the back of the weld.

The breakthrough for aluminum as a structural material occurred with the introduction in the 1940s of the inert gas welding processes. Such processes as Gas Metal Arc Welding (GMAW), also referred to as Metal Inert Gas Welding (MIG), and Gas Tung-

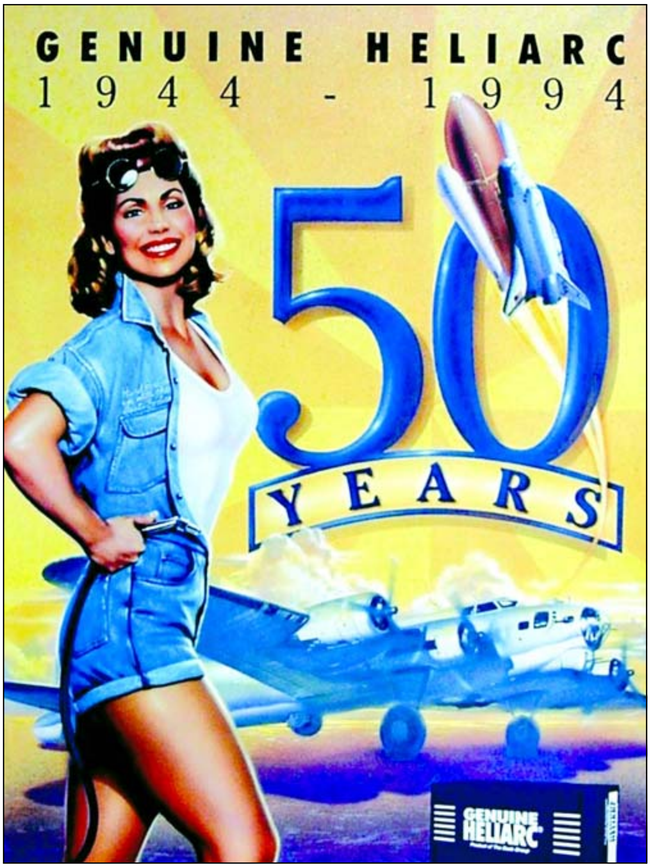
Figure 2.2—U.S. Military Water Bottle Stamped 1918 and Welded with the Oxyfuel Gas Welding Process

sten Arc Welding (GTAW), also referred to as Tungsten Inert Gas Welding (TIG) (see Figure 2.3). With the introduction of a welding process that used an inert gas to protect the molten aluminum during welding, it became possible to make high-quality, high-strength welds at high speeds and in all positions, without corrosive fluxes.

Today, aluminum and its alloys are readily weldable using a variety of techniques and welding processes including newer processes such as Laser Beam Welding (LBW) and Friction Stir Welding (FSW); however, the GTAW/TIG and GMAW/MIG welding processes remain the most popular.

? What is the history behind the welding of aluminum? Is Heliarc welding still a viable option for welding aluminum? Why do we not see as much gas welding or stick electrode welding of aluminum in industry?

***A:** During my attempt to address these questions, I will also try to clarify some of the terms and definitions used.*



Note: Heliarc is a trade name that is used for the GTAW/TIG welding process.

Figure 2.3—1944–1994 Advertisement Celebrating 50 Years of Heliarc

2.4 The History of Heliarc Welding (Gas Tungsten Arc Welding)

Heliarc is an old traditional name, sometimes still used today, for the gas tungsten arc welding (GTAW) process. This same welding process is often referred to as the tungsten inert gas (TIG) welding process (particularly in Europe). The term "Heliarc" refers to the helium that was used as a shielding gas when the process was first used in production because it was the inert gas available at the time.

The GTAW process is quite often a viable option for welding aluminum. It was developed in 1944 and is still extensively used to successfully weld aluminum alloys today. Some of the highest quality welds used in critical applications, such as complete joint penetration pipe welds on cryogenic pressure vessels, are almost exclusively made with this welding process. Alternating current (AC) is used for most applications, but direct current (DC) power is employed for some specialized applications. The GTAW process was developed earlier than the gas metal arc welding (GMAW) process and for a time was used to weld aluminum of all metal thicknesses and joint types. The GTAW process has since been replaced by the GMAW process for many aluminum welding applications, primarily because of the increased speed of the GMAW process to weld thicker sections. However, GTAW still has an important place in the aluminum welding industry. Gas tungsten arc welding with alternating current and pure argon shielding gas is now most often used to weld thinner gages of aluminum (up to 1/4 in [6.4 mm]) and also for applications where aesthetics are most important.

Alternating current is the most popular method of gas tungsten arc welding aluminum. A balanced wave AC arc provides cleaning action for most applications and divides the arc heat about evenly between electrode and base material. Gas tungsten arc welding power sources for AC welding, which allows for adjustment of the balance between polarities, enables the user to choose either enhanced arc cleaning or greater penetration capabilities. For some more specialized applications, we can find GTAW used in the direct-current electrode-negative (DCEN) mode. This method provides arc concentration of roughly 80% of the heat at the base material and about 20% at the electrode. This results in relatively deep and narrow weld penetration, and very little, if any, significant arc cleaning during the welding operation. Typically used with pure helium shielding gas, this method of welding is capable of welding much greater thicknesses of material (up to 1 in [25 mm]) and is most often used in automatic joint welding applications.

The third mode of GTAW is direct-current electrode-positive (DCEP). With this method, about 20% of the heat is generated at the base plate and 80% at the electrode. It creates excellent cleaning action but very shallow penetration. This is probably the least used method of GTAW.

2.5 Gas Welding (Oxyacetylene Welding)

“Gas welding” is a nonstandard term for the oxyfuel gas welding (OFW) process. This was one of the earliest welding processes used for welding aluminum. Figure 2.2 shows a U.S. Army water canteen welded by the OFW process and dated 1918. This canteen was probably used in the “Great War” (World War I) and was welded around 25 years prior to the development of the inert gas welding processes (GTAW and GMAW). Oxyfuel gas welding is a gas welding process. It achieves coalescence by using the heat from an oxygen-fuel gas flame, and for aluminum, an active flux to remove the oxide and shield the weld pool. Very thick joints have been welded with this process, but the most common applications have been for sheet metal. One of the problems with this welding process is that the flux used is hygroscopic, meaning it absorbs moisture from the surrounding atmosphere. When moist, the flux becomes corrosive to aluminum. Therefore, after welding, the flux must be removed to minimize the chance for corrosion. Because it can be difficult to be certain that all traces of flux have been removed, it was often necessary to finish the operation with an acid dip to neutralize any flux residue. Other disadvantages of using this process for welding aluminum are that mechanical strengths tend to be lower and heat-affected zones (HAZs) wider than with arc welding. Also, it is only practical in the flat and vertical positions, and distortion can tend to be extreme. Most of the problems are attributed to corrosive flux and excessive heat input associated with this process. The oxyfuel gas welding process was widely used for welding aluminum prior to the development of the inert gas welding process; but has limited use today.

2.6 Stick Electrode Welding (Shielded Metal Arc Welding)

This is a nonstandard term for shielded metal arc welding (SMAW).

Prior to the development of the inert gas welding processes (GTAW and GMAW), arc welding of aluminum was mainly restricted to the shielded metal arc welding (SMAW) process, sometimes referred to as the manual metal arc (MMA) process. This welding process uses a flux-coated welding electrode. The electrodes are straight lengths of aluminum rod, coated with flux. The flux acts to dissolve the aluminum oxide on both the base metal and the rod during welding, which is necessary if coalescence is to occur. Some of the flux components vaporize in the arc to form shielding gases that help to stabilize the arc and shield both it and the weld pool from the surrounding atmosphere.

One of the main problems with this welding process is corrosion caused by flux entrapment, particularly in fillet welds where the flux can be trapped behind the weld and promote corrosion from the back of the weld. Other problems are that welds from this process are prone to gross porosity; there are no electrodes available for the high-magnesium-content base metals; and electrodes, once exposed to the air, begin to absorb moisture into the flux, which eventually corrodes the aluminum core and produces excessive porosity problems. It was soon found that this process was not the best suited for welding aluminum. Today's welding codes and standards for aluminum structures do not recognize this welding process.

2.7 Conclusion

Without a doubt, the breakthrough for aluminum as a welded structural material occurred with the introduction in the 1940s of the inert gas welding processes. With the introduction of a welding process that used an inert gas to protect the molten aluminum during welding, it became possible to make high-quality, high-strength welds at high speeds and in all positions without corrosive fluxes.

Chapter 3

Aluminum Alloys and Metallurgy

3.1 The Aluminum Alloy Designation System

In North America, The Aluminum Association Inc. is responsible for the allocation and registration of aluminum alloys. Currently there are close to 500 wrought aluminum alloys and over 250 aluminum alloys in the form of castings and ingots registered with The Aluminum Association. The alloy chemical composition limits for all of these registered alloys are contained in The Aluminum Association's *Teal Book* titled *International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys* and in their *Pink Book* titled *Designations and Chemical Composition Limits for Aluminum Alloys in the Form of Castings and Ingot*. These publications can be extremely useful to the welding engineer when developing welding procedures, and when the consideration of chemistry and its association with crack sensitivity is of importance. Aluminum alloys can be categorized into a number of groups based on the particular material's characteristics such as its ability to respond to thermal and mechanical treatment and the primary alloying element added to the aluminum alloy. When we consider the numbering/identification system used for aluminum alloys, the above characteristics are identified. The wrought and cast aluminums have different systems of identification; the wrought having a 4-digit system, and the castings having a 3-digit and 1-decimal place system.

3.1.1 Introduction

With the growth of aluminum within the welding fabrication industry, and its acceptance as an excellent alternative to steel for many applications, there are increasing requirements for those involved with developing aluminum projects to become more familiar with this group of materials. To fully understand aluminum, it is advisable to start by becoming acquainted with the aluminum identification/designation system, the many aluminum alloys available and their characteristics.

3.1.2 Wrought Alloy Designation System

We shall first consider the 4-digit wrought aluminum alloy identification system.

The first digit (Xxxx) indicates the principal alloying element, which has been added to the aluminum alloy and is often used to describe the aluminum alloy series, i.e., 1000 series, 2000 series, 3000 series, up to 8000 series (see Table 3.1).

Table 3.1—Wrought Aluminum Alloy Designation System

Alloy Series	Principal Alloying Element
1xxx	99.000% Minimum Aluminum
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc
8xxx	Other Elements

The second single digit (xXxx), if different from 0, indicates a modification of the specific alloy, and the third and fourth digits (xxXX) are arbitrary numbers given to identify a specific alloy in the series. Example: In alloy 5183, the number 5 indicates that it is of the magnesium alloy series, the 1 indicates that it is the 1st modification to the original alloy 5083, and the 83 identifies it in the 5xxx series.

The only exception to this alloy numbering system is with the 1xxx series aluminum alloys (pure aluminums) in which case, the last 2 digits provide the minimum aluminum percentage above 99%, i.e., Alloy 1350 (99.50% minimum aluminum).

3.1.3 Cast Alloy Designation

The cast alloy designation system is based on a 3 digit-plus decimal designation xxx.x (i.e., 356.0). The first digit (Xxx.x) indicates the principal alloying element, which has been added to the aluminum alloy (see Table 3.2).

The second and third digits (xXX.x) are arbitrary numbers given to identify a specific alloy in the series. The number following the decimal point indicates whether the alloy is a casting (.0) or an ingot (.1 or .2). A capital letter prefix indicates a modification to a specific alloy.

Example: Alloy—A356.0 the capital A (Axxx.x) indicates a modification of alloy 356.0. The number 3 (A3xx.x) indicates that it is of the silicon plus copper and/or magnesium series. The 56 (Ax56.0) identifies the alloy within the 3xx.x series, and the .0 (Axxx.0) indicates that it is a final shape casting and not an ingot.

3.1.4 The Aluminum Temper Designation System

If we consider the different series of aluminum alloys, we will see that there are considerable differences in their characteristics and consequent application. The first point to recognize, after understanding the identification system, is that there are two dis-

Table 3.2—Cast Aluminum Alloy Designation System

Alloy Series	Principal Alloying Element
1xx.x	99.000% minimum Aluminum
2xx.x	Copper
3xx.x	Silicon Plus Copper and/or Magnesium
4xx.x	Silicon
5xx.x	Magnesium
6xx.x	Unused Series
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other Elements

tinctly different types of aluminum within the series mentioned above. These are the *Heat-Treatable Aluminum alloys* (those which can gain strength through the addition of heat) and the *Nonheat-Treatable Aluminum alloys*. This distinction is particularly important when considering the affects of arc welding on these two types of materials.

The 1xxx, 3xxx, and 5xxx series wrought aluminum alloys are nonheat-treatable and are strain hardenable only. The 2xxx, 6xxx, and 7xxx series wrought aluminum alloys are heat-treatable and the 4xxx series consist of both heat-treatable and nonheat-treatable alloys. The 2xx.x, 3xx.x, 4xx.x, and 7xx.x series cast alloys are heat-treatable. Strain hardening is not generally applied to castings.

The heat-treatable alloys acquire their optimum mechanical properties through a process of thermal treatment, the most common thermal treatments being Solution Heat Treatment and Aging. Solution Heat Treatment is the process of heating the alloy to an elevated temperature (around 990°F [532°C]) to put the alloying elements or compounds into solution. This is followed by quenching, usually in water, to produce a supersaturated solution at room temperature. Solution heat treatment is usually followed by aging. Aging is the precipitation of a portion of the elements or compounds from a supersaturated solution to yield desirable properties. The aging process is divided into two types: aging at room temperature, which is termed natural aging, and aging at elevated temperatures termed artificial aging. Artificial aging temperatures are typically about 320°F [160°C]. Many heat-treatable aluminum alloys are used for welding fabrication in their solution heat-treated and artificially aged condition.

The nonheat-treatable alloys acquire their optimum mechanical properties through Strain Hardening. Strain hardening is the method of increasing strength through the application of cold working. The Temper Designation System addresses the material conditions called tempers. The Temper Designation System is an extension of the alloy numbering system and consists of a series of letters and numbers which follow the alloy designation number and are connected by a hyphen. Examples: 6061-T6, 6063-T4, 5052-H32, 5083-H112.

The temper designations are listed in detail in Tables 3.3, 3.4, and 3.5.

Further to the basic temper designation, there are two subdivision categories: one addressing the "H" Temper—Strain Hardening, and the other addressing the "T" Temper—Thermally Treated designation.

Table 3.3—The Basic Temper Designations

Letter	Meaning
F	**As Fabricated**—Applies to products of a forming process in which no special control over thermal or strain hardening conditions is employed.
O	**Annealed**—Applies to product which has been heated to produce the lowest strength condition to improve ductility and dimensional stability.
H	**Strain Hardened**—Applies to products which are strengthened through cold-working. The strain hardening may be followed by supplementary thermal treatment, which produces some reduction in strength. The "H" is always followed by two or more digits (see Table 3.4).
W	**Solution Heat-Treated**—An unstable temper applicable only to alloys which age spontaneously at room temperature after solution heat-treatment.
T	**Thermally Treated**—To produce stable tempers other than F, O, or H. Applies to product which has been heat-treated, sometimes with supplementary strain-hardening, to produce a stable temper. The "T" is always followed by one or more digits (see Table 3.5).

Table 3.4—Subdivisions of H Temper—Strain Hardened

The first digit after the H indicates a basic operation:

H1	Strain Hardened Only
H2	Strain Hardened and Partially Annealed
H3	Strain Hardened and Stabilized
H4	Strain Hardened and Lacquered or Painted

The second digit after the H indicates the degree of strain hardening:

HX2	Quarter Hard
HX4	Half Hard
HX6	Three-Quarters Hard
HX8	Full Hard
HX9	Extra Hard

Table 3.5—Subdivisions of T Temper—Thermally Treated

T1	Naturally aged after cooling from an elevated temperature shaping process, such as extruding
T2	Cold worked after cooling from an elevated temperature shaping process and then naturally aged
T3	Solution heat-treated, cold worked, and naturally aged
T4	Solution heat-treated and naturally aged
T5	Artificially aged after cooling from an elevated temperature shaping process
T6	Solution heat-treated and artificially aged
T7	Solution heat-treated and stabilized (overaged)
T8	Solution heat-treated, cold worked, and artificially aged
T9	Solution heat-treated, artificially aged, and cold worked
T10	Cold worked after cooling from an elevated temperature shaping process and then artificially aged
Additional digits indicate stress relief. For example:	
TX51 or TXX51	Stress relieved by stretching
TX52 or TXX52	Stress relieved by compressing

3.1.5 Aluminum Alloys and Their Characteristics

If we consider the seven series of wrought aluminum alloys, we will appreciate their differences and understand their applications and characteristics.

3.1.6 1xxx Series Alloys (Nonheat-treatable—with ultimate tensile strength of 10 ksi to 27 ksi [69 MPa to 186 MPa])

This series is often referred to as the pure aluminum series because these alloys are required to contain a minimum of 99.0% aluminum. They are weldable. However, because of their narrow melting range, they require certain considerations to produce acceptable welding procedures. When considered for fabrication, these alloys are selected primarily for their superior corrosion resistance such as in specialized chemical tanks and piping or for their excellent electrical conductivity as in bus bar applications. These alloys have relatively poor mechanical properties and would seldom be considered for general structural applications. These base alloys are often welded with matching filler material or with 4xxx filler alloys dependent on application and performance requirements.

3.1.7 2xxx Series Alloys (Heat-treatable—with ultimate tensile strength of 27 ksi to 62 ksi [186 MPa to 427 MPa])

These are aluminum/copper alloys (copper additions ranging from 0.7% to 6.8%), and are high-strength, high-performance alloys that are often used for aerospace and aircraft applications. They have excellent strength over a wide range of temperature. Some of these alloys are considered nonweldable by the arc welding processes because of their susceptibility to hot cracking and stress corrosion cracking; however, others are arc welded very successfully with the correct welding procedures. These base materials are often welded with high-strength 2xxx series filler alloys designed to match their performance, but can sometimes be welded with the 4xxx series fillers containing silicon or silicon and copper, dependent on the application and service requirements.

3.1.8 3xxx Series Alloys (Nonheat-treatable—with ultimate tensile strength of 16 ksi to 41 ksi [110 MPa to 283 MPa])

These are the aluminum/manganese alloys (manganese additions ranging from 0.05% to 1.8%) and are of moderate strength, have good corrosion resistance, good formability and are suited for use at elevated temperatures. One of their first uses was pots and pans, and they are the major component today for heat exchangers in vehicles and power plants. Their moderate strength, however, often precludes their consideration for structural applications. These base alloys are welded with 1xxx, 4xxx, and 5xxx series filler alloys, dependent on their specific chemistry and particular application and service requirements.

3.1.9 4xxx Series Alloys (Heat-treatable and nonheat-treatable—with ultimate tensile strength of 25 ksi to 55 ksi [172 MPa to 379 MPa])

These are the aluminum/silicon alloys (silicon additions ranging from 0.6% to 21.5%) and contain both heat-treatable and nonheat-treatable alloys. Silicon, when added to aluminum, reduces its melting point and improves its fluidity when molten. These characteristics are desirable for filler materials used for both fusion welding and brazing. Consequently, this series of alloys is predominantly found as filler material. Silicon, independently in aluminum, is nonheat-treatable; however, a number of these silicon alloys have been designed to have additions of magnesium or copper, which provides them with the ability to respond favorably to solution heat treatment. Typically, these heat-treatable filler alloys are used only when a welded component is to be subjected to postweld thermal treatments.

3.1.10 5xxx Series Alloys (Nonheat-treatable—with ultimate tensile strength of 18 ksi to 51 ksi [124 MPa to 352 MPa])

These are the aluminum/magnesium alloys (magnesium additions ranging from 0.2% to 6.2%) and have the highest strength of the nonheat-treatable alloys. In addition, this alloy series is readily weldable, and is used for a wide variety of applications such as shipbuilding, transportation, pressure vessels, bridges, and buildings. The magnesium base alloys are often welded with filler alloys, which are selected after consideration of the magnesium content of the base material, and the application and service conditions of the welded component. Alloys in this series with more than 3.0% magnesium are not recommended for elevated temperature service above 150°F [66°C] because of their potential for sensitization and subsequent susceptibility to stress corrosion cracking. Series 5xxx alloys with less than approximately 2.5% magnesium can be welded successfully with the 5xxx or 4xxx series filler alloys. Because of problems associated with eutectic melting and associated poor as-welded mechanical properties, it is not recommended to weld material in this alloy series that contain higher amounts of magnesium with the 4xxx series fillers. The base alloy 5052 is generally recognized as the 5xxx series alloy that has the maximum magnesium content that can be successfully welded with a 4xxx series filler alloy. It is recommended that the higher magnesium content base materials only be welded with 5xxx filler alloys, which generally match the base alloy composition.

3.1.11 6xxx Series Alloys (Heat-treatable—with ultimate tensile strength of 18 ksi to 58 ksi [124 MPa to 400 MPa])

These are the aluminum/magnesium–silicon alloys (magnesium and silicon additions of around 1.0%) and are found widely throughout the welding fabrication industry, used predominantly in the form of extrusions, and incorporated in many structural components. The addition of magnesium and silicon to aluminum produces a compound of magnesium-silicide, which provides this material its ability to become solution heat-treated for improved strength. These alloys are naturally solidification crack sensitive, and for this reason, they should not be arc welded autogenously (without filler material). The addition of adequate amounts of filler material during the arc welding process is essential to provide dilution of the base material, thereby preventing the hot cracking problem. They are welded with both 4xxx and 5xxx filler materials, dependent on the application and service requirements.

3.1.12 7xxx Series Alloys (Heat-treatable—with ultimate tensile strength of 32 ksi to 88 ksi [221 MPa to 607 MPa])

These are the aluminum/zinc alloys (zinc additions ranging from 0.8% to 12.0%) and comprise some of the highest strength aluminum alloys. These alloys are often used in high-performance applications such as aircraft, aerospace, and competitive sporting equipment. Like the 2xxx series of alloys, this series incorporates alloys which are considered unsuitable candidates for arc welding, and others, which are often arc welded successfully. The commonly welded alloys in this series, such as 7005, are predominantly welded with the 5xxx series filler alloys.

3.1.13 Conclusion

Today's aluminum alloys, together with their various tempers, comprise a wide and versatile range of manufacturing materials. For optimum product design and successful welding procedure development, it is important to understand the differences between the many alloys available and their various performance and weldability characteristics. When developing arc welding procedures for these different alloys, consideration must be given to the specific alloy being welded to make sure that the correct steps have been taken to ensure the highest quality results. It is often said that arc welding of aluminum is not difficult, "it's just different." I believe that an important part of understanding these differences is to become familiar with the various alloys, their characteristics, and their identification system.

3.2 What is the Affect of Arc Welding on the Heat-Affected Zone (HAZ) of Aluminum Alloys?

3.2.1 Introduction

To appreciate the affect of arc welding on the heat-affected zone of various aluminum alloys, it is necessary to evaluate the various types of aluminum alloys, how these alloys obtain their strength and the potential for changes in strength after welding.

3.2.2 The Various Types of Aluminum Alloys

Considering the seven aluminum alloy series used for wrought alloys, the main alloying elements used for producing each of the alloy series are immediately identifiable. Further examination of each of these elements' effects on aluminum is possible.

Series	***Primary Alloying Element***
1xxx	Aluminum—99.00% or Greater
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc

3.2.3 The Principal Effects of Alloying Elements in Aluminum

The principal effects of alloying elements in aluminum are discussed below.

3.2.4 Pure Aluminum 1xxx

Although the 1xxx series are almost pure aluminum, they will respond to strain hardening, especially if they contain appreciable amounts of impurities such as iron and silicon. However, even in the strain-hardened condition, the 1xxx series alloys have very low strength when compared to the other series of aluminum alloys. The most common applications for the 1xxx series alloys are aluminum foil, electrical buss bars, metallizing wire and some chemical tanks and piping systems. These alloys are non-heat-treatable.

3.2.5 Copper (Cu) 2xxx

The aluminum-copper alloys typically contain between 2% to 6% of copper, with small additions of other elements. The copper provides substantial increases in strength and facilitates precipitation hardening. These alloys include some of the highest strength heat-treatable aluminum alloys. The most common applications for the 2xxx series alloys are aerospace, military vehicles, and rocket fins.

3.2.6 Manganese (Mn) 3xxx

The addition of manganese to aluminum increases strength to an extent through solution strengthening. It improves strain hardening and does not significantly reduce ductility or corrosion resistance. These are moderate strength nonheat-treatable materials that retain strength at elevated temperatures. However, for major structural applications, they are rarely used. The most common applications for the 3xxx series alloys are cooking utensils, radiators, air conditioning condensers, evaporators, heat exchangers beverage containers, residential siding, and handling and storage equipment.

3.2.7 Silicon (Si) 4xxx

The addition of silicon to aluminum reduces melting temperature and improves fluidity. Silicon alone in aluminum produces a nonheat-treatable alloy; however, in combination with magnesium, it produces a precipitation hardening heat-treatable alloy. Consequently, there are both heat-treatable and nonheat-treatable alloys within the 4xxx series. The most common application for silicon additions to aluminum is the manufacturing of aluminum castings. The most common applications for the 4xxx series alloys are filler wires for fusion welding and brazing of aluminum.

3.2.8 Magnesium (Mg) 5xxx

The addition of magnesium to aluminum increases mechanical properties through solid solution strengthening. Additionally, it improves their strain hardening ability. These alloys are the highest strength nonheat-treatable aluminum alloys. They are considered optimal for and extensively used for structural applications. The 5xxx series alloys are produced mainly as sheet and plate and only occasionally as extrusions. These alloys strain harden quickly, therefore, they are difficult and expensive to extrude. Some common applications for the 5xxx series alloys are truck and train bodies, buildings, armored vehicles, ship and boat building, chemical tankers, pressure vessels, and cryogenic tanks.

3.2.9 Magnesium and Silicon (Mg_2Si) 6xxx

The addition of magnesium and silicon to aluminum produces the compound magnesium-silicide (Mg_2Si). The formation of this compound provides the 6xxx series their heat-treatability. The 6xxx series alloys extrude both easily and economically. For this reason, they are most often found in an extensive selection of extruded shapes. These alloys form an important complementary system with the 5xxx series alloy. The 5xxx series alloy used in the form of plate and the 6xxx series used in an extruded form are often joined to the plate. Some of the common applications for the 6xxx series alloys are handrails, drive shafts, automotive frame sections, bicycle frames, tubular lawn furniture, scaffolding, stiffeners and braces used on trucks, boats, and many other structural fabrications.

3.2.10 Zinc (Zn) 7xxx

The addition of zinc to aluminum (in conjunction with some other elements, primarily magnesium and/or copper) produces heat-treatable aluminum alloys of the highest strength. The zinc substantially increases strength and permits precipitation hardening. Some of these alloys can be susceptible to stress corrosion cracking and for this reason are not usually fusion welded. Other alloys within this series are often fusion welded with excellent results. Some of the common applications of the 7xxx series alloys are aerospace, armored vehicles, baseball bats, and bicycle frames.

3.2.11 How Aluminum Alloys Obtain Their Strength

As seen above, aluminum alloys consist of both heat-treatable and nonheat-treatable types. The addition of alloying elements to aluminum is the principal method used to produce a selection of different materials used in a wide assortment of applications. The principle reason for adding the major alloying elements is to facilitate an improvement in the alloys physical and/or mechanical characteristics. Typically, addition of primary alloying elements to aluminum is to provide improvement in strain hardening and/or precipitation hardening characteristics.

3.2.12 Strain Hardening

Strain hardening, used extensively to produce the strain-hardened tempers in the nonheat-treatable aluminum alloys, is an important process that increases the strength of materials that heat treatment cannot strengthen. This process involves a change of shape brought about by the input of mechanical energy. As deformation proceeds, the material becomes stronger but harder and less ductile. For example, the strain hardened temper of H18, full-hard material is obtainable with a cold work equal to about a 75% reduction in area. The H16, H14, and H12 tempers obtained with lesser amounts of cold working represent three-quarter-hard, half-hard, and quarter-hard conditions, respectively.

3.2.13 Heat Treatment

Precipitation hardening of aluminum alloys is accomplished by a solution heat treatment that is followed by aging of the material. Solution heat-treating is achieved by heating a material to a suitable temperature, holding at that temperature for a long enough time to allow constituents to enter into solid solution, then cooling rapidly to hold the constituents in solution. Usually this is followed by precipitation hardening, or what is also termed artificial aging. This is achieved by reheating the alloy to a lower temperature and holding it at this temperature for a prescribed period. The result is to produce a metallurgical structure within the material that provides superior mechanical properties. If, during heat treatment, the material is held at temperature for too long or the temperature used is too high, the material will become over-aged, resulting in a decrease in tensile strength. It is important to recognize that the precipitation hardening process is both time and temperature controlled.

3.2.14 The Affect of Arc Welding on the Heat-Affected Zone

To make a welded joint in an aluminum structure using the arc welding process melting of the base material must occur. During the melting operation, heat transfers through conduction into the base material adjacent to the weld. Typically, the completed weldment is divided into three distinct areas: the weld metal, the heat-affected zone adjacent to the weld, and the base material beyond the HAZ that has been unaffected by the welding operation. Because the HAZ will experience cycles of heating and cooling during the welding operation, arc welding on materials which have been strengthened by strain hardening or precipitation hardening, will change its properties and may be extremely different than that of the original base alloy and the unaffected area of the base material (see Figures 3.1 and 3.2).

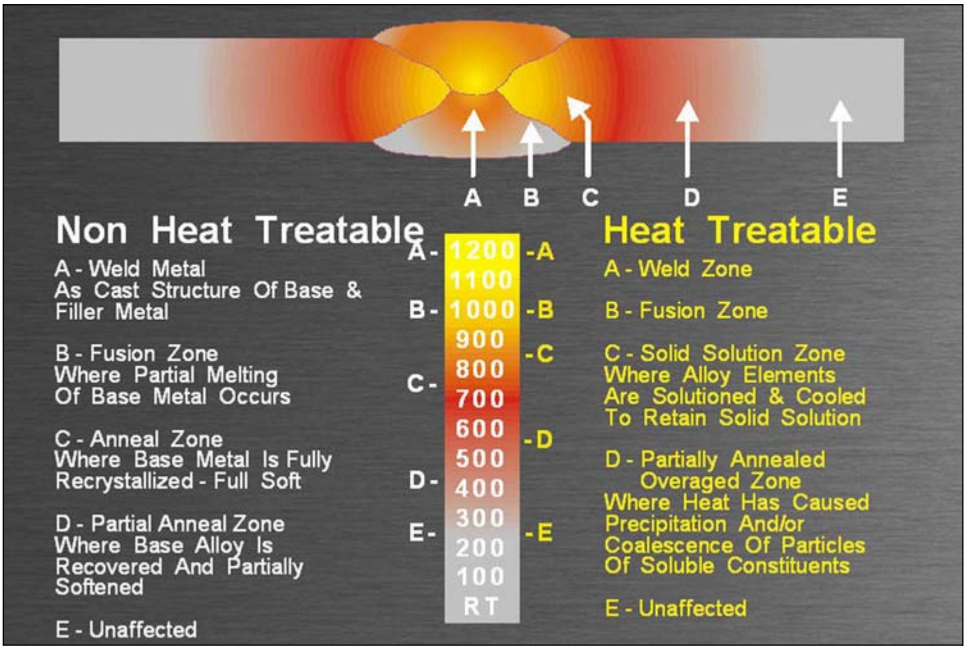


Figure 3.1—Shows the HAZ on Both the Heat-Treatable and Nonheat-Treatable Alloys

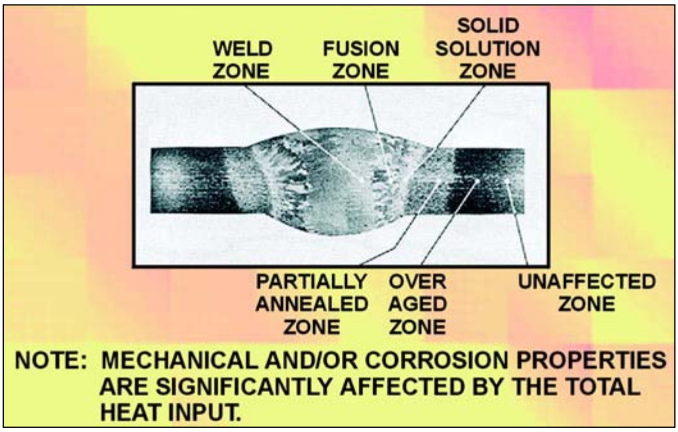


Figure 3.2—The Welding Heat Affect on a Heat-Treatable Alloy

3.2.15 Nonheat-Treatable Alloys

What is important from a HAZ perspective is that aluminum alloys strengthened by strain hardening can be restored to a full soft, ductile condition by annealing. Annealing eliminates the strain hardening, as well as the microstructure that is developed because of cold working. The heating of the HAZ, which takes place during the arc welding operation, is sufficient to anneal the base material within the HAZ area. For this reason the minimum tensile strength requirements for as-welded nonheat-treatable alloys is based on the annealed strength of the base alloy. Typical tensile strengths of nonheat-treatable alloys in their tempered condition and as-welded are shown in Table 3.6.

Table 3.6—Typical Tensile Strength Properties of Groove Welds—Nonheat-Treatable Alloys

Base Alloy and Temper	Base Alloy Tensile Strength		As-Welded Tensile Strength	
	ksi	MPa	ksi	MPa
1060-H18	19	131	10	69
5052-H32	33	228	27	186
5052-H39	42	290	27	186
5086-H34	47	324	38	262
5086-H38	53	365	38	262
5083-H116	46	317	43	296
3003-H34	35	241	16	110
3004-H38	41	283	24	165

3.2.16 Heat-Treatable Alloys

In the case of the heat-treatable alloys, the HAZ will not be fully annealed. Typically, the HAZ is not maintained at an adequate temperature for a sufficient period to anneal fully the HAZ. This does not suggest that experiences in a reduction in strength in the HAZ will not occur. The affect on the HAZ of a heat-treatable alloy that is welded in the solution heat-treated and artificially aged condition is typically one of partially annealed and over-aged. This condition is affected by the heat input during the welding operation. The general rule is, the higher the heat input, the lower the as-welded strength. Typical tensile strengths of some of the heat-treatable alloys in their temper condition and as-welded are shown in Table 3.7.

3.2.17 Conclusion

Dependant on the particular aluminum alloy type and its temper, there are often significant difference between the tensile strength of the HAZ and the tensile strength of the unaffected area of the welded component. The reduction in tensile strength of the

Table 3.7—Typical Tensile Strength Properties of Groove Welds—Heat-Treatable Alloys

	Base Alloy Tensile Strength		As-Welded Tensile Strength	
Base Alloy and Temper	**ksi**	**MPa**	**ksi**	**MPa**
6063-T6	31	214	19	131
6061-T6	45	310	27	186
6061-T4	35	241	27	186
2219-T81	66	455	35	241
2014-T6	70	483	34	234
7005-T53	57	393	43	296

HAZ under controlled conditions, particularly with the nonheat-treatable alloys, can be somewhat predictable. The reduction in tensile strength of the HAZ in the heat-treatable alloys is more susceptible to welding conditions and strength can be reduced below the required minimum requirement if excessive heating occurs during the welding operation.

3.3 Is There a Filler Alloy that Can be Used to Weld All Aluminum Base Alloys, and How Do I Weld Aluminum Alloys 7075 and 2024?

? I work in a small welding repair shop and am often asked to perform repair welding on aluminum structures. Sometimes I know the base metal type and sometimes I don't. I have two questions relating to repairing aluminum. First, is there a filler metal that can be used to successfully weld all types of aluminum alloys? Second, I come into contact, from time to time, with two aluminum alloys that are difficult to obtain arc welding information about. These alloys are 2024 and 7075. Can you provide some information on how to weld these alloys with either the gas metal arc or gas tungsten arc welding processes?

3.3.1 A Filler Alloy for All Aluminum Base Alloys

With regard to your first question, the short answer is there is no filler metal that is suitable for welding all types of aluminum alloys. There are currently close to 500 wrought aluminum alloys and more than 250 aluminum alloys in the form of castings and ingots registered with The Aluminum Association. The alloy chemical composition limits for all these registered alloys are contained in The Aluminum Association's teal-colored book titled *International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloy*" and in its pink-colored book titled *Designations and Chemical Composition Limits for Aluminum Alloys in the Form of Castings and Ingot*.

Aluminum alloys can be categorized into a number of groups based on the particular material's characteristics, such as its ability to respond to thermal and mechanical treatment and the primary alloying element added. Probably the most important consideration encountered during repair operations is identification of the base metal type. If the base material type is not available through a reliable source, it can be difficult to select a suitable welding procedure.

There are some guides as to the most probable type of aluminum used in different applications. For example, most extruded aluminum is 6xxx series (Al-Mg-Si). In the automotive industry, air-conditioning systems and heat exchangers are typically made from 3003 sheet and 6061 tubing. Car wheels are often made from 5454, which, because of its controlled magnesium (less than 3% Mg), is suitable for temperature applications. Ship hulls are often manufactured from 5083 (5% Mg), which is recognized as a marine material.

Unfortunately, there is no guarantee. If the base material type is not known, or unavailable, the only reliable way to establish the exact type of aluminum alloy is through chemical analysis. A small sample of the base material must be sent to a reliable aluminum testing laboratory and a chemical analysis performed. Generally, the chemistry can then be evaluated and a determination made regarding the most suitable filler metal and welding procedure. Be aware that incorrect assumptions about the chemistry of an aluminum alloy can seriously affect the welding results.

3.3.2 Welding 2024 and 7075

In response to the second question, the reason you are having difficulty finding information on welding 2024 and 7075 is because both materials belong to a small group of aluminum alloys generally considered to be unweldable by arc welding. These materials are often found in aircraft, sporting equipment, and other types of high-performance, safety-critical equipment and are not usually arc welded on the original component. Probably the two most commonly found aluminum alloys within this category are 2024, which is an aluminum-copper-magnesium alloy, and 7075, which is an aluminum-zinc-copper-magnesium alloy. Both materials can become susceptible to stress corrosion cracking after welding. This phenomenon is particularly dangerous because it is not detectable immediately after welding, but usually develops at a later date when the component is in service. The completed weld joint can appear to be of excellent quality immediately after welding. However, changes that occur within the base material adjacent to the weld during the welding process can produce a metallurgical condition that results in intergranular microcracking, which may be susceptible to propagation and cause failure of the welded component. Failure probability can be high, and the time to failure is generally unpredictable and dependent on variables such as tensile stress applied to the joint, environmental conditions, and the period of time the component is subjected to these variables.

I strongly recommend great care be taken in considering the repair of components made from these materials. It must be stressed that arc welding repairs should not be performed on these alloys and they should not be returned to service if there is any possibility of a weld failure becoming the cause of damage or injury to person or property.

3.3.3 Conclusion

In answer to your first question, and as discussed above, there is no filler metal suitable for welding all aluminum base alloys. The answer to your second question, the reason you can not find any information on how to weld 7075 and 2024 base alloys is that both of these materials are not suitable for arc welding.

3.4 What are the Differences Between the Heat-Treatable and Nonheat-Treatable Aluminum Alloys?

? I have often heard the terms Heat-Treatable and Nonheat-Treatable Aluminum Alloys. What are the differences between these alloys, and how does the type of base alloy affect the final strength of the weld?

3.4.1 Understanding the Basic Differences Between Heat-Treatable and Nonheat-Treatable Aluminum Alloys

Heat-Treatable and Nonheat-Treatable are the two basic types of aluminum alloys. They are both widely used in welding fabrication and have somewhat different characteristics associated with their chemical and metallurgical structure, and their reactions during the arc welding process.

To best answer the question, we first need to understand the basic differences between these two groups of alloys.

3.4.2 Nonheat-Treatable Aluminum Alloys

The strength of these alloys is initially produced by alloying the aluminum with additions of other elements. These alloys consist of the pure aluminum alloys (1xxx series), manganese alloys (3xxx series), silicon alloys (4xxx series) and magnesium alloys (5xxx series). A further increase in strength of these alloys is obtained through various degrees of cold working or strain hardening. Cold working or strain hardening is accomplished by rolling, drawing through dies, stretching or similar operations where area reduction is obtained. Regulating the amount of total reduction in area of the material controls its final properties. Material which has been subjected to a strain-hardening temper, may also be given a final, elevated temperature treatment called “stabilizing,” to ensure that the final mechanical properties do not change over time.

The letter “H” followed by numbers denotes the specific condition obtained from strain hardening.

The first number following the “H” indicates the basic operations used during or after strain hardening:

H1—Strain hardened only

H2—Strain hardened and partially annealed

H3—Strain hardened and stabilized

The second number following the "H" indicates the degree of strain hardening:

HX2—Quarter Hard

HX4—Half Hard

HX6—Three-Quarter Hard

HX8—Full Hard

HX9—Extra Hard

3.4.3 Heat-Treatable Aluminum Alloys

The initial strength of these alloys is also produced by the addition of alloying elements to pure aluminum. These elements include copper (2xxx series), magnesium and silicon, which is able to form the compound magnesium silicide (6xxx series), and zinc (7xxx series). When present in a given alloy, singly or in various combinations, these elements exhibit increasing solid solubility in aluminum as the temperature increases. Because of this reaction, it is possible to produce significant additional strengthening to the heat-treatable alloys by subjecting them to an elevated thermal treatment, quenching, and, when applicable, precipitation heat-treatment known also as artificial aging.

NOTE: Because of additions of magnesium and or copper, there are also a number of silicon (4xxx series) alloys that are heat-treatable.

In solution heat-treatment, the material is typically heated to temperatures of 900°F to 1050°F [482°C to 566°C], depending upon the alloy. This causes the alloying elements within the material to go into solid solution; rapid quenching, usually in water, which freezes or traps the alloying elements in solution, follows this process.

Precipitation heat-treatment or artificial aging is used after solution heat-treatment. This involves heating the material for a controlled time at a lower temperature (around 250°F to 400°F [121°C to 204°C]). This process, used after solution heat-treatment, both increases strength and stabilizes the material.

3.4.4 How Does the Type of Material, Heat-Treated or Nonheat-Treated, Affect the Completed Strength of the Weld?

In short, the difference in transverse tensile strength of the completed groove weld is governed by the reaction of the base material to the heating and cooling cycles during the welding operation.

Generally speaking, the nonheat-treatable alloys are annealed in the heat-affected zone adjacent to the weld. This is unavoidable when arc welding, as we will reach the annealing temperature, and extended time at these temperatures is not required to anneal the base material.

The heat-treatable alloys are usually not fully annealed during the welding operation but are subjected to a partial anneal and overaging process. These alloys are very susceptible to time at temperature; the higher the temperature and the longer at that temperature, the more significant the loss of strength in the base material adjacent to the weld. For this reason, it is important to control the overall heat input, preheating, and interpass temperatures when welding the heat-treatable alloys.

Typically, the common heat-treatable base alloys, such as 6061-T6, lose a substantial proportion of their mechanical strength after welding. For example, 6061-T6 typically has 45 000 psi tensile strength prior to welding and around 27 000 psi in the as-welded condition. One option with the heat-treatable alloys is postweld heat-treatment to return the mechanical strength to the manufactured component. If postweld heat-treating is considered, the filler alloy's ability to respond to the heat-treatment should be evaluated.

Most of the commonly used filler alloys will not respond to postweld heat treatment without substantial dilution with the heat-treatable base alloy. This is not always easy to achieve and can be difficult to control consistently. For this reason, filler alloys have been developed to independently respond to heat-treatment.

As an example, filler alloy 4643 was developed for welding 6xxx series base alloys and developing high mechanical properties in the postweld heat-treated condition. This alloy was developed by taking the well-known alloy 4043, reducing the silicon, and adding 0.10% to 0.30% magnesium, thus ensuring its ability to unquestionably respond to postweld heat-treatment.

3.4.5 Conclusion

The primary difference between the nonheat-treatable and the heat-treatable aluminum alloys is associated with the methods used to change the mechanical properties of these materials. Both materials can be affected by the heat generated during the arc welding process. The affect of heating during welding is usually more predictable on the nonheat-treatable alloys than it is on the heat-treatable alloys.

3.5 What are the Alloying Elements in Aluminum Alloys?

? I have been informed that pure aluminum is not usually used for structural applications and that to produce aluminum that is of adequate strength for the manufacture of structural components, it is necessary to add other elements to the aluminum. What elements are added to these aluminum alloys? What affect do they have on the material's performance? And in what applications are these alloys used?

3.5.1 The Addition of Alloying Elements to Aluminum

Your acquired information is essentially correct. It would be very unusual to find pure aluminum (1xxx series of alloys) chosen for structural fabrication because of their strength characteristics. Although the 1xxx series are almost pure aluminum, they will respond to strain hardening and especially so if they contain appreciable amounts of impurities such as iron and silicon. However, even in the strain-hardened condition, the 1xxx series alloys have very low strength when compared to the other series of aluminum alloys. When the 1xxx series alloys are chosen for a structural application, they are most often chosen for their superior corrosion resistance and/or their high electrical conductivity. The most common applications for the 1xxx series alloys are aluminum foil, electrical buss bars, metallizing wire and chemical tanks and piping systems.

The addition of alloying elements to aluminum is the principal method used to produce a selection of different materials that can be used in a wide assortment of structural applications.

If we consider the seven designated aluminum alloy series used for wrought alloys, we can immediately identify the main alloying elements used for producing each of the alloy series. We can then go further and examine each of these elements' effects on aluminum. I have also added some other commonly used elements and their effects on aluminum.

Series	***Primary Alloying Element***
1xxx	Aluminum—99.00% or Greater
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc

3.5.2 The Principal Effects of Alloying Elements in Aluminum

The principal effects of alloying elements in aluminum are as follows:

3.5.2.1 Copper (Cu) 2xxx

The aluminum-copper alloys typically contain between 2% to 10% copper, with smaller additions of other elements. The copper provides substantial increases in strength and facilitates precipitation hardening. The introduction of copper to aluminum can also reduce ductility and corrosion resistance. The susceptibility to solidification cracking of aluminum-copper alloys is increased; consequently, some of these alloys can be the most challenging aluminum alloys to weld. These alloys include some of the highest strength heat-treatable aluminum alloys. The most common applications for the 2xxx series alloys are aerospace, military vehicles, and rocket fins.

3.5.2.2 Manganese (Mn) 3xxx

The addition of manganese to aluminum increases strength somewhat through solution strengthening and improves strain hardening while not appreciably reducing ductility or corrosion resistance. These are moderate strength nonheat-treatable materials that retain strength at elevated temperatures and are seldom used for major structural applications. The most common applications for the 3xxx series alloys are cooking utensils, radiators, air conditioning condensers, evaporators, heat exchangers, and associated piping systems.

3.5.2.3 Silicon (Si) 4xxx

The addition of silicon to aluminum reduces melting temperature and improves fluidity. Silicon alone in aluminum produces a nonheat-treatable alloy; however, in combination with magnesium it produces a precipitation hardening heat-treatable alloy. Consequently, there are both heat-treatable and nonheat-treatable alloys within the 4xxx series. Silicon additions to aluminum are commonly used for the manufacturing of castings. The most common applications for the 4xxx series alloys are filler wires for fusion welding and brazing of aluminum.

3.5.2.4 Magnesium (Mg) 5xxx

The addition of magnesium to aluminum increases strength through solid solution strengthening and improves their strain hardening ability. These alloys are the highest strength nonheat-treatable aluminum alloys and are, therefore, used extensively for structural applications. The 5xxx series alloys are produced mainly as sheet and plate and only occasionally as extrusions. The reason for this is that these alloys strain harden quickly and, are, therefore difficult and expensive to extrude. Some common applications for the 5xxx series alloys are truck and train bodies, buildings, armored vehicles, ship and boat building, chemical tankers, pressure vessels, and cryogenic tanks.

3.5.2.5 Magnesium and Silicon (Mg_2Si) 6xxx

The addition of magnesium and silicon to aluminum produces the compound magnesium-silicide (Mg_2Si). The formation of this compound provides the 6xxx series their heat-treatability. The 6xxx series alloys are easily and economically extruded and for this reason are most often found in an extensive selection of extruded shapes. These alloys form an important complementary system with the 5xxx series alloy. The 5xxx series alloy used in the form of plate and the 6xxx are often joined to the plate in some extruded form. Some of the common applications for the 6xxx series alloys are handrails, drive shafts, automotive frame sections, bicycle frames, tubular lawn furniture, scaffolding, boats, stiffeners and braces used on trucks, plus many other structural fabrications.

3.5.2.6 Zinc (Zn) 7xxx

The addition of zinc to aluminum (in conjunction with some other elements, primarily magnesium and/or copper) produces heat-treatable aluminum alloys of the highest strength. The zinc substantially increases strength and permits precipitation hardening. Some of these alloys can be susceptible to stress corrosion cracking and for this reason are not usually fusion welded. Other alloys within this series are often fusion welded with excellent results. Some of the common applications of the 7xxx series alloys are aerospace, armored vehicles, baseball bats, and bicycle frames.

3.5.2.7 Iron (Fe)

Iron is the most common impurity found in aluminum and is intentionally added to some pure (1xxx series) alloys to provide a slight increase in strength.

3.5.2.8 Chromium (Cr)

Chromium is added to aluminum to control grain structure, to prevent grain growth in aluminum-magnesium alloys, and to prevent recrystallization in aluminum-magnesium-silicon or aluminum-magnesium-zinc alloys during heat treatment. Chromium will also reduce stress corrosion susceptibility and improves toughness.

3.5.2.9 Nickel (Ni)

Nickel is added to aluminum-copper and to aluminum-silicon alloys to improve hardness and strength at elevated temperatures and to reduce the coefficient of expansion.

3.5.2.10 Titanium (Ti)

Titanium is added to aluminum primarily as a grain refiner. The grain refining effect of titanium is enhanced if boron is present in the melt or if it is added as a master alloy containing boron largely combined as TiB_2. Titanium is a common addition to aluminum weld filler wire as it refines the weld structure and helps to prevent weld cracking.

3.5.2.11 Zirconium (Zr)

Zirconium is added to aluminum to form a fine precipitate of intermetallic particles that inhibit recrystallization.

3.5.2.12 Lithium (Li)

The addition of lithium to aluminum can substantially increase strength and, Young's modulus, promote precipitation hardening and decrease density.

3.5.2.13 Lead (Pb) and Bismuth (Bi)

Lead and bismuth are added to aluminum to assist in chip formation and improve machinability. These free machining alloys are often not weldable because the lead and bismuth produce low melting constituents and can produce poor mechanical properties and/or high crack sensitivity on solidification.

3.5.3 Conclusion

There are many aluminum alloys used in industry today—close to 500 wrought alloys and over 250 casting alloys are currently registered with The Aluminum Association. Certainly one of the most important considerations encountered during the welding of aluminum is the identification of the aluminum base alloy type to be welded. If the base material type of the component to be welded is not available through a reliable source, it can be difficult to select a suitable welding procedure. There are some general guidelines as to the most probable type of aluminum used in different applications, such as those mentioned above. However, it is very important to be aware that incorrect assumptions as to the chemistry of an aluminum alloy can result in very serious effects on the weld performance. It is strongly recommended that positive identification of the type of aluminum is made and that welding procedures be developed and tested to verify weld performance (see Figure 3.3).

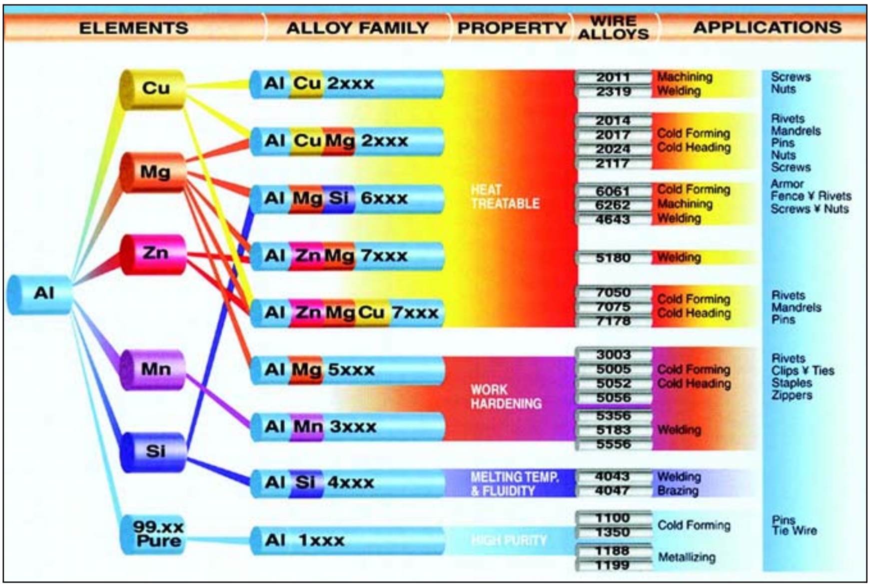


Figure 3.3—Aluminum Alloys Used in Common Applications

3.6 What are Weldable and Unweldable Aluminum Alloys?

? I have heard, on occasion, reference made to some aluminum alloys as unweldable. What does this mean? Are there such aluminum alloys, and if so, what makes them unweldable?

3.6.1 The Definition of the Term “Unweldable”

I shall start by saying that the majority of aluminum-based alloys can be successfully arc welded when using the correct welding procedures. However, yes, there are some aluminum-based alloys that are occasionally referred to as unweldable. These groups of alloys are well known as being unsuitable for arc welding and, for this reason, are joined mechanically by riveting or bolting.

Before we start examining the various reasons for the poor weldability of these alloys, we should start by considering the term “unweldable.” This is a nonstandard term that is sometimes used to describe aluminum alloys that can be difficult to arc weld without encountering problems during and/or after welding. These problems are usually associated with cracking, most often hot cracking, and on occasion, stress-corrosion cracking (SCC).

3.6.2 Difficult-to-Weld Alloys

When we consider the aluminum alloys that fall into this difficult-to-weld category, we can divide them into different groups.

We will first consider the small selection of aluminum alloys that were designed for machinability, not weldability, such as 2011 and 6262 that contain 0.20–0.6 Bi, 0.20–0.6 Pb and 0.40–0.7 Bi, 0.40–0.07 Pb, respectively. The addition of these elements (bismuth and lead) to these materials greatly assists in chip formation in these free-machining alloys. However, because of the low solidification temperatures of these elements, they can seriously reduce the ability to successfully produce sound welds in these materials.

There are a number of aluminum alloys that are quite susceptible to hot cracking if arc welded. These alloys are usually heat-treatable alloys and are most commonly found in the 2xxx-series, aluminum-copper (Al-Cu), and 7xxx-series, aluminum-zinc (Al-Zn) groups of materials.

To understand why some of these alloys are unsuitable for arc welding (unweldable), we need to consider the reasons why some aluminum alloys can be more susceptible to hot cracking.

Hot cracking, or solidification cracking, occurs in aluminum welds when high levels of thermal stress and solidification shrinkage are present while the weld is undergoing various degrees of solidification. The hot-cracking sensitivity of any aluminum alloy is influenced by a combination of mechanical, thermal, and metallurgical factors.

A number of high-performance, heat-treatable aluminum alloys have been developed by combining various alloying elements to improve the materials' mechanical properties. In some cases, the combination of the required alloying elements has produced materials with high hot-cracking sensitivity.

3.6.3 Coherence Range

Perhaps the most important factor affecting the hot-crack sensitivity of aluminum welds is the temperature range of dendrite coherence and the type and amount of liquid available during the freezing process. Coherence is when the dendrites begin to interlock with one another to the point that the melted material begins to form a mushy stage. The coherence range is the temperature between the formation of coherent-interlocking dendrites and the solidus temperature; this could be referred to as the mushy range during solidification. The wider the coherence range, the more likely hot cracking will occur because of the accumulating strain of solidification between the interlocking dendrites.

3.6.4 The 2xxx-Series Alloys (Al-Cu)

Hot-cracking sensitivity in the Al-Cu alloys increases as we add Cu up to approximately 3%, and then decreases to a relatively low level at 4.5% and above. Alloy 2219 with 6.3% Cu shows good resistance to hot cracking because of its relatively narrow coherence range. Alloy 2024 contains approximately 4.5% Cu, which may initially encourage us to suppose that it would have relatively low crack sensitivity. However, Alloy 2024 also contains a small amount of magnesium (Mg). The small amount of Mg in this alloy depresses the solidus temperature, but it does not affect the coherence temperature; therefore, the coherence range is extended and the hot-cracking tendency is increased.

The problem to be considered when welding 2024 is that the heat of the welding operation will allow segregation of the alloying constituents at the grain boundaries, and the presence of Mg, as stated above, will depress the solidus temperature. Because these alloying constituents have lower melting phases, the stress of solidification may cause cracking at the grain boundaries and/or establish the condition within the material conducive to stress-corrosion cracking later. High heat input during welding, repeated weld passes, and larger weld sizes can all increase the grain-boundary segregation problem (segregation is a time-temperature relationship) and subsequent cracking tendency.

3.6.5 The 7xxx-Series Alloys (Al-Zn)

The 7xxx-series of alloys can also be separated into two groups as far as weldability is concerned. These are the Al-Zn-Mg and the Al-Zn-Mg-Cu types.

The Al-Zn-Mg alloys, such as 7005, resist hot cracking better and exhibit better joint performance than the Al-Zn-Mg-Cu alloys, such as 7075. The Mg content in this group (Al-Zn-Mg) of alloys would generally increase the cracking sensitivity. However, zirconium is added to refine grain size, and this effectively reduces the cracking tendency. This alloy group is easily welded with the high-magnesium filler metals, such as 5356, which ensures the weld contains sufficient magnesium to prevent cracking. Silicon-based filler metals, such as 4043, are not generally recommended for these alloys because the excess Si introduced by the filler metal can result in the formation of excessive amounts of brittle Mg_2Si particles in the weld.

The Al-Zn-Mg-Cu alloys, such as 7075, have small amounts of Cu added. The small amounts of Cu, along with the Mg, extend the coherence range and, therefore, increase the crack sensitivity. A similar situation can occur with these materials as with the 2024-type alloys. The stress of solidification may cause cracking at the grain boundaries and/or establish the condition within the material conducive to stress-corrosion cracking later.

3.6.6 Conclusion

It should be stressed that the problem of higher susceptibility to hot cracking from increasing the coherence range is not only confined to the welding of these more susceptible base alloys, such as 2024 and 7075. Crack sensitivity can be substantially increased when welding incompatible dissimilar base metals (which are normally easily welded to themselves) and/or through the selection of an incompatible filler metal. For example, by joining a weldable 2xxx series base metal to a weldable 5xxx series base metal. If we mix high Cu and high Mg, we can extend the coherence range and, therefore, increase the crack sensitivity. An example would be using a 5xxx series filler metal to weld a 2xxx series base metal or a 2xxx series filler metal on a 5xxx series base metal.

3.7 How do I Establish the Strengths of Aluminum Alloys, Base Material, Welds, and Filler Alloys?

I have recently been involved in the development of aluminum arc welded structures. Having worked with steel structures for many years, aluminum is new to me. How can I identify the aluminum base metal strengths, filler metal strengths, and the as-welded joint strengths of aluminum welds? I am also confused by the AWS filler metal classifications for aluminum. They do not give the filler metal strength, unlike the classifications for steel, which include the minimum tensile strengths of the filler metals.

To address your question appropriately, it is necessary to divide it into three separate sections, aluminum base alloy strength, aluminum filler metal strength and as-welded aluminum joint strength, and the AWS filler metal classification system for aluminum.

3.7.1 Aluminum Base Alloy Strength

One of the most extensively used references for information regarding the mechanical properties of aluminum base alloys is *Aluminum Standards and Data*, published by The Aluminum Association. This manual contains useful information and data pertaining to chemical composition limits, mechanical and physical properties, tolerances, and other characteristics of various aluminum and aluminum alloy wrought products. The content of the manual is subject to periodic revision to include advances in production methods, to add data on new alloys and products, and to delete those alloys that become inactive. The latest edition is comprised as follows:

The first three sections of the manual contain general information that is useful for comparing materials. The typical properties and characteristics listed in these first three sections are not guaranteed and should not be used for design purposes. The fourth section contains information relating to testing, inspection, and identification. The fifth section lists the definitions of many terms used in the wrought aluminum industry.

The remaining 12 sections of the manual consist of composition limits, mechanical property limits, dimensional tolerances, and other data classified by product form. Such products as sheet and plate, fin stock, foil, wire, rod and bar rolled or cold finished and extruded, tube and pipe, structural profiles channels and I-beams, forging stock, forgings, and electrical conductor bus bars. The mechanical property and product dimensional tolerance limits in these sections are statistically based guaranteed limits and may be used as the basis of design.

3.7.2 Aluminum Filler Metal Strength and As-Welded Aluminum Joint Strength

The strength of aluminum filler metals and as-welded strength of arc welded joints is an extremely broad subject; therefore, for this discussion, the focus will be transverse groove weld tensile strength and longitudinal and transverse shear strength of fillet welds. The transverse groove weld tensile strength is a property often used for evaluating the performance of groove welds when conducting welding procedure qualification tests. By utilizing the relevant welding codes and standards, you will find the minimum allowable tensile strength values. For example, AWS D1.2:2008, *Structural Welding Code—Aluminum*, has these values listed in Table 3.2 of the standard. The transverse tensile strength of an arc welded aluminum groove weld in the as-welded condition is contingent on the tensile strength of the heat-affected zone (HAZ) of the weld. The HAZ is the area of base metal immediately adjacent to the weld where mechanical properties or microstructure is transformed by the heat of the welding. In the nonheat-treatable aluminum alloys, the HAZ is near the annealed condition of the base alloy. In the heat-treatable alloys, the HAZ will typically become partially annealed and over-aged, depending on the original temper of the base alloy prior to welding and the heat input during welding. The tensile strength values provided in the welding codes, such as AWS D1.2, are for test evaluation purposes and assists with the development and qualification of welding procedures. These values are not intended to be used for design calculations.

Aluminum filler metal manufacturers often publish the typical fillet weld shear strength values of the filler metals that they supply. These values are a comparison between the various filler metals and are values that may be expected to be achieved if fillet weld shear strength testing is performed. These values are not intended to be used for design calculations.

For design purposes, there are values for both groove weld tensile strength and fillet weld shear strength, which are published in The Aluminum Association's *Aluminum Design Manual*, Part IA, and Section 7. These values are strengths; they must be reduced by using an appropriate safety factor. The Aluminum Design Manual specifies a safety factor on welds of 1.95 for building-type structures. In terms of the AWS D1.2, *Structural Welding Code—Aluminum*, Section 2.1, Structural Design, "Welds shall be sized for strength requirements using the effective areas defined in Section 2 of this code in conformance with the Aluminum Design Manual Specification for Aluminum Structures unless otherwise required by the contract documents."

3.7.3 The AWS Filler Metal Classification System for Aluminum

The American Welding Society (AWS) provides specifications for aluminum filler metals, and these specifications are discussed in Section 8 of this document. The AWS filler metal classification system for aluminum does not provide information relating to the strength of filler metals. To understand the reason why the aluminum filler metal classification system is different from steel, it is necessary to consider the overall differences in filler metal selection between these two metals.

When welding steel it is fairly typical to use a filler metal with very similar chemistry and strength to that of the base alloy being welded. When welding aluminum, there are often other variables that may need further consideration. Often, there are a number of filler metals that may be used to join any given aluminum base alloy. The selection of the most suitable filler metal is usually dependent on the service conditions of the manufactured component. In some cases, a trade-off situation emerges, where it is required to choose between different characteristics of the completed weld in order of importance. Some considerations for the selection of a filler metal for aluminum that vary from those of steel are as follows:

1. **Ease of Welding.** This is the relative freedom from weld cracking, and it is often based on the chemistry developed between the base alloy and filler metal when combined in the weld. Unlike steel, aluminum base alloys are often welded with filler metals with a very different chemistry than that of the base alloy to avoid high crack sensitivity.

2. **Ductility.** It is not uncommon to have the choice between two filler metals that have substantially different ductility.

3. **Corrosion Resistance.** Because there is the possibility of using a filler metal with different chemistry than that of the base alloy, there is a possibility of a difference in solution potential between base alloy and filler metal.

4. **Sustained Temperature Service.** The reaction of some filler metal chemistries at sustained elevated temperature may promote premature component failure from stress corrosion cracking.

5. **Color Match.** Base alloy and filler metal color match after anodizing can be a major cosmetic concern in some applications.

6. **Postweld Heat Treatment.** The ability of the filler metal to respond to postweld heat treatment associated with filler metal chemistry and joint design. Some filler metals will not respond to heat treatment; others will respond favorably to heat treatment only if they acquire sufficient amounts of alloying elements from the base material during welding; and others will respond regardless of dilution.

It is apparent that the system used for the selection of filler metals for aluminum welding is quite different from that of steel. The filler metal selection system for aluminum is based largely on chemistry issues. The classification system for aluminum filler metals is based on chemistry and not mechanical properties. It is common practice to use a filler metal selection chart that addresses the variables to consider when choosing the most suitable filler metal for a particular aluminum welding application (see Section 4.8 for Filler Alloy Selection Chart).

3.7.4 Conclusion

There are published resources available for establishing the typical and design-allowable strengths of the aluminum base alloys and their welded joints. Several of these publications are listed in this section. See also the sources of additional information listed in Annex A.

- *Aluminum Standards and Data*, available from The Aluminum Association at: www.aluminum.org.

- AWS D1.2, *Structural Welding Code—Aluminum*, available from the American Welding Society at www.aws.org.

- *Aluminum Design Manual Specification for Aluminum Structures*, available from The Aluminum Association at: www.aluminum.org.

3.8 What is the Affect of Natural Aging on 6061 Aluminum Base Alloy?

I have a technical question that I hope you can help with. The issue being debated is whether welded 6061 would naturally respond by aging (without heat treatment) to a tensile strength just below 40 ksi [276 MPa] in a matter of days. The question is would 6061 precipitation hardening aluminum alloy, when welded with a heat-treatable filler such as 4643, regain significant tensile strength over time by "naturally aging" similar to what is shown in graphs by the ASM Committee on Heat Treating of Aluminum Alloys? Also, would these strength gains also be evident in the HAZ?

3.8.1 The Heat-Treated Condition of the Base Alloy

The 6061 aluminum base alloy is usually provided in either the -T4 or -T6 condition. The first and most common -T6 condition is obtained by submitting the material to a solution heat treatment of approximately 990°F [532°C], followed by a water quench and then an artificial age of approximately 350°F [177°C] for 8 hours (h). The artificial age is also known as precipitation hardening. The second, and less commonly known 6061-T4 condition is achieved by solution heat-treating the material, as in the -T6 condition, followed by "natural" aging. Natural aging is the process which allows the material to precipitation harden at room temperature.

The Aluminum Association publication *Aluminum Standards and Data* shows a minimum tensile strength for 6061-T6 of 42 ksi [290 MPa] and for 6061-T4 of 30 ksi [207 MPa]. Note these are guaranteed minimum strengths and it is not unreasonable to expect that these minimum tensile strengths can be and are normally exceeded.

3.8.2 The Affect of Natural Aging After Solution Heat Treatment

As you suggest in your email, and as shown in your chart (see Figure 3.4), it is possible for the 6061-T4 alloy to naturally age to a tensile strength in the high 30s (ksi).

The chart referenced in your question above, is representative of an aluminum alloy that has been properly solution heat-treated under controlled conditions and then allowed to naturally age over a period of time. The chart indicates a significant increase in the tensile strength of the alloy after solution heat treatment and an extended period of natural aging at room temperature. This chart is intended to show the affect of natural aging, over varying times, on a material that has been properly solution heat-treated to the -T4 condition. This chart is NOT intended to provide any information about the affects on the heat-affected zone (HAZ) of a weld.

3.8.3 The Affect of Aging on the HAZ

The HAZ of a weld made on alloy 6061 is subjected to uncontrolled heating and cooling during welding. For this reason, after welding it is no longer in a fully solution heat-treated condition. After welding, an area adjacent to the weld will be in a

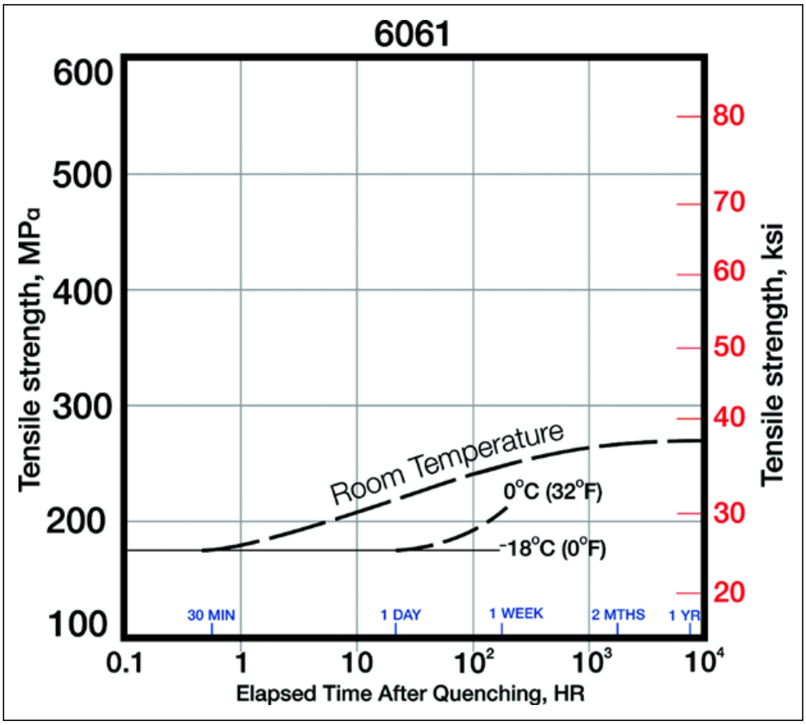


Figure 3.4—The Natural Aging of 6061 Over Varying Periods of Time and at Varying Temperatures

partially annealed condition, therefore, the data within the chart is not relevant to a weld or HAZ and is only relevant to an unwelded plate.

To understand this further, it is important to recognize that welding on an aluminum alloy in the -T4 or -T6 condition, significantly changes the heat-treated condition in the HAZ.

Your question references the alloy 6061, however, you do not specify the particular temper of the material that is to be welded. Most 6061 are welded in the -T6 condition as mentioned above. The 6061 material in the -T6 condition (prior to welding) will have a guaranteed minimum tensile strength of 42 ksi [290 MPa]. After arc welding on this material, the tensile strength in the HAZ is reduced. Dependent on the procedure used and heat input during welding, the as welded strength of the HAZ will be reduced typically to between 24 ksi and 28 ksi [165 MPa to 193 MPa]. The minimum tensile property requirement of the structural welding code AWS D1.2 is 24 ksi [165 MPa]. After welding, the HAZ is no longer in the same solution heat-treated and artificially aged condition; it has undergone a metallurgical change that will permanently reduce its tensile strength.

Regardless of the temper -T4 or -T6, when welding on 6061 material, the temper in the HAZ changes. Welding on these materials, dependent on there original temper, will typically partially anneal and/or overage the HAZ from the heat input during the welding operation.

Figure 3.5 shows that the heat input during welding has a significant affect on the as welded strength of the heat-affected zone of a 6061-T6 alloy. In addition, the figure shows that the higher the heat input, the lower the strength of the HAZ.

Figure 3.6 shows a similar affect, which indicates the reduction in tensile strength of the HAZ in the 6061-T4 alloy.

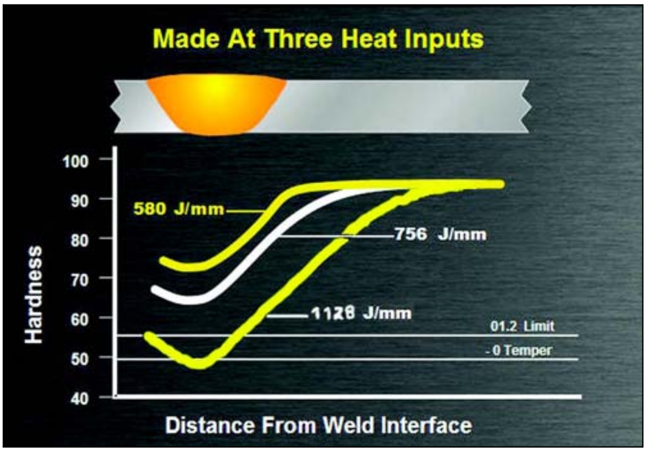


Figure 3.5—The Reduction in Tensile Strength (Hardness) of the HAZ of a 6061-T6 Alloy with Varying Heat Inputs in the As-Welded Condition

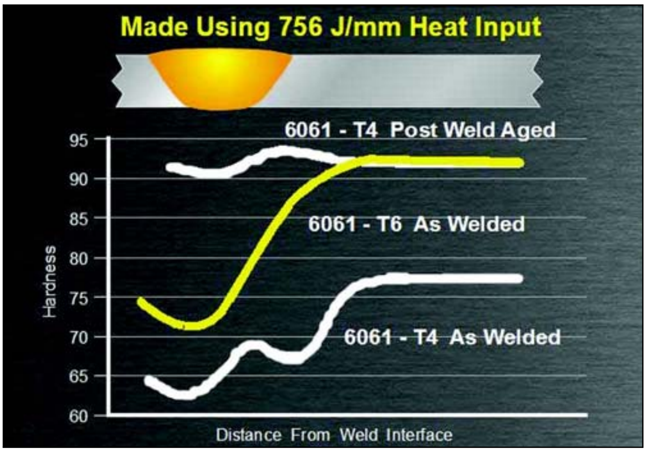


Figure 3.6—The Reduction in Tensile Strength (Hardness) of the HAZ of 6061-T6 and 6061-T4 Alloys in the As-Welded Condition and the Recovery of Strength of a 6061-T4 Alloy After Postweld Artificial Aging

3.8.4 Heat-Treatable Filler Alloy

The use of a heat-treatable filler alloy, such as 4643 that is mentioned in your question, will have no effect on the HAZ and only a minimum effect on joint strength in the as welded condition. The benefits of using the heat-treatable filler alloys, such as 4643, are when the entire unit is subjected to postweld heat treatments.

Two methods are used to regain strength after welding in the 6061 alloys. The first is to use a 6061 base material in the -T6 condition, weld with a heat-treatable filler alloy (4643) and then perform a full solution heat treatment and artificial age on the entire component to return the material to the -T6 condition.

The second option is to start with the 6061 base material in the -T4 condition, weld with a 4643 and then perform artificial aging of the welded component. This option may have the advantage in that it requires a fairly small postweld teat treatment, no quench and has less probability of distorting the fabricated part. By using the heat-treatable filler alloy, there is a good chance of acquiring strength near to the -T6 condition in the weld as well as the HAZ of the base alloy. Figure 3.6 illustrates this method.

3.8.5 Conclusion

Your question: Would 6061 precipitation hardening aluminum alloy, when welded with a heat-treatable filler such as 4643, regain significant tensile strength over time by “naturally aging” similar to what is shown in graphs by the ASM Committee on Heat Treating of Aluminum Alloys? The answer is no it would not for the above reasons.

3.9 What is the Affect of Elevated Service Temperature on 6xxx Series Aluminum Alloys?

? I have been using aluminum extruded tube in one of my processes. This Aluminum tube is made of 6061-T6 alloy. The process in which these tubes are used requires the following heating and cooling profile.

a. Ramp up from room temperature 77°F [25°C] to 797°F [425°C] at the rate of 50°F [10°C] per min.

b. Dwell at 797°F [425°C] for 2 h.

c. Cool down to room temperature at the rate of 34°F [1°C] per min.

The initial hardness of the Aluminum tube is 80 HB. The hardness dropped to approximately 8 HB in 6 cycles of heating and stayed at approximately 8 HB after 30 cycles.

My questions are:

1. What is the reason for this drop in hardness and will the hardness drop further?
2. What is the phenomenon behind the hardness drop?
3. Surface roughness of the aluminum tube is very critical; will the hardness drop affect surface roughness (pitting corrosion, etc.)?

3.9.1 What is the Reason for This Drop in Hardness and Will the Hardness Drop Further?

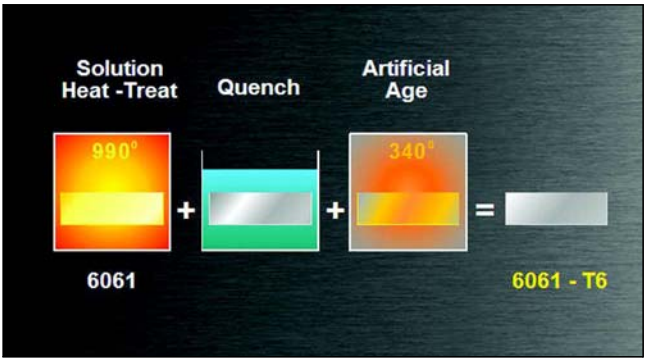
I will first state that I have a problem with the hardness readings that you quote. I question the accuracy of the readings; particularly the lower reading (8 HB) this seems to be a little too low to me.

On examination of the heating and cooling profile you have provided me I was not surprised that you are finding a substantial reduction in hardness in your aluminum tubing. The Aluminum Association publication *Aluminum Standards and Data* provides typical Brinnell hardness numbers and tensile strengths for most aluminum alloys in various strain hardened and heat-treated conditions. ASTM B 918, *Standard Practice for Heat Treatment of Wrought Aluminum Alloys*, provides the times and temperatures recommended for obtaining the various tempers of the aluminum heat-treated conditions. After referring to these documents it was easily confirmed that the times and temperatures used in your heating profile are more than adequate to drastically change the materials strength and hardness. In fact these times and temperatures are sufficient to reduce the material to its lowest strength and hardness, the fully annealed condition. Having reviewed the data which you supplied, and after comparing it with data provided by The Aluminum Association and ASTM, I suspect that your testing method may not have been perfect. The issue of inaccurate hardness test data is probably incidental as the main issue here is that the temperature that you are exposing the material to is going to fully anneal the material. The material will not get any lower in strength and the hardness will not drop any further than it is in this fully annealed condition.

3.9.2 What is the Phenomenon Behind the Hardness Drop After Heating?

To understand this phenomenon, we need to consider the heat-treated condition of the original material and the affect on this condition due to the temperature exposure during your process.

The 6xxx series aluminum alloys are one of the heat-treatable series of aluminum alloys. The 6061 alloy is composed of aluminum alloyed with magnesium and silicon. When subjected to heat treatment the magnesium and silicon produce a compound within the aluminum called magnesium silicide. This magnesium silicide is taken into solution within the material during the heat treatment that is performed to produce the -T6 condition. The -T6 condition denotes that the material has undergone thermal treatment in the form of solution heat treatment and artificial aging (see Figure 3.7). The solution heat treatment part of the -T6 process requires that the material be heated to around 990°F [532°C], followed by quenching in water. The artificial aging or precipitation hardening as it is also known requires that the solution heat-treated material be reheated to around 340°F [171°C] for up to 18 h. This subsequent heating facilitates a controlled precipitation of the magnesium silicide which consequently optimizes the materials mechanical properties. The solution heat-treated and artificial aged condition (-T6) of the 6061 provides a material with the guaranteed minimum ultimate tensile strength of 42 ksi [290 MPa] and a typical Brinnell hardness number of 95.



Note: Artificial aging or precipitation hardening as it is also known requires that the solution heat-treated material be reheated to around 340°F [171°C] for up to 18 h.

Figure 3.7—Solution Heat Treatment Requires that the Material be Heated to Around 990°F [532°C], Followed by Quenching in Water

When the 6061-T6 material is heated in your process it will begin to over-age (lose strength) through the additional precipitation of magnesium silicide. This precipitation will continue during your heating process resulting in the material progressively losing strength and hardness. Eventually all the magnesium silicide will precipitate out of solution and the material will become fully annealed; the annealed condition is the softest condition of this material. The annealed condition of 6061 provides a material with the guaranteed maximum ultimate tensile strength of 20 ksi [138 MPa]. and a typical Brinnell hardness number of 30. A typical annealing temperature as prescribed by ASTM B 918, *The Standard Practice for Heat Treatment of Wrought Aluminum Alloys*, for the 6061 alloy is 765°F [407°C] for 2 h to 3 h. It is therefore apparent that your process is subjecting the material to time at temperature more than adequate to fully anneal its structure.

3.9.3 Will the Hardness Drop Affect Surface Roughness (Pitting, etc.)?

Surface roughness of the part should not be significantly affected; the potential for (pitting) corrosion is generally improved in the annealed condition so this should not be a problem. As the surface condition is very critical I would suggest that further testing is performed to verify the acceptability of this characteristic.

3.9.4 Conclusion

Once we understand the characteristics of the heat-treatable aluminum alloys and the methods used for these materials to gain and retain there strength, it becomes very apparent why we are seeing a significant drop in the mechanical properties of this material after it has been subjected to the temperatures to which it is being exposed during your processing.

3.10 What is Anodized Aluminum?

I have heard the terms “anodized” and “hardcoat anodized” used to describe the surface condition on aluminum. What exactly is this type of coating and can you weld aluminum when it has this type of coating on it?

3.10.1 What is Anodizing?

An oxide film can be grown on certain metals such as aluminum, niobium, tantalum, titanium, tungsten, and zirconium by an electrochemical process called anodizing. For each of these metals there are process conditions which promote growth of a thin, dense barrier oxide of uniform thickness. The thickness of this layer and its properties vary greatly depending on the metal. Aluminum is unique among these metals in that, in addition to the thin barrier oxide, anodizing aluminum alloys in certain acidic electrolytes produces a thick oxide coating, containing a high density of microscopic pores. This coating has diverse and important applications including architectural finishes and prevention of corrosion. When exposed to the atmosphere, aluminum naturally forms a passive oxide layer which provides moderate protection against corrosion. In its pure form aluminum self-passivates very effectively, however, aluminum that is alloyed with other elements is more prone to atmospheric corrosion and can therefore benefit from the protective quality of anodizing. Aluminum alloy parts are anodized to increase the thickness of the oxide layer to improve corrosion resistance, improve abrasion resistance, and/or allow for dyeing of colors (see Figure 3.8). Anodizing is a process that produces an oxide film or coating on metals and alloys by electrolysis. The metal to be treated is made the anode in an electrolytic cell and its surface is electrochemically oxidized. Anodization can improve certain surface properties, such as corrosion resistance, abrasion resistance, hardness, and appearance. The most common material to be anodized is aluminum. All of the above properties are improved when aluminum is anodized. Furthermore, since the surface film is porous after anodizing, the aluminum metal can be easily colored by the application of pigments or dyes into the pores. The most widely used anodizing specification, MIL-A-8625, defines three types of aluminum anodization: Type I (which is Chromic Acid Anodization), Type II (which is Sulfuric Acid Anodization), and Type III (which is Sulfuric Acid Hardcoat Anodization).

3.10.2 How is it Performed?

Before being anodized, wrought aluminum is cleaned in either a hot soak cleaner or in a solvent bath and may be etched in sodium hydroxide (normally with added sodium gluconate), ammonium bifluoride or brightened in a mix of acids. In aluminum anodization, this aluminum oxide layer is made thicker by passing a direct current through an acid solution, with the aluminum object serving as the anode (the positive electrode). The current releases hydrogen at the cathode (the negative electrode) and oxygen at the surface of the aluminum anode, creating a buildup of aluminum oxide. Anodizing at 12 V DC, a piece of aluminum with an area of one square decimeter (about 15.5 in^2) can consume roughly 1 ampere (A) of current. In commercial applications, the voltage used is more normally in the region of 15 V to 21 V.

Figure 3.8—Anodized Aluminum Rings Being Removed from a Processing Tank

Conditions such as acid concentration, solution temperature, and current must be controlled to allow the formation of a consistent oxide layer, which can be many times thicker than would otherwise be formed. This oxide layer increases both the hardness and the corrosion resistance of the aluminum surface. The oxide forms as microscopic hexagonal "pipe" crystals of amorphous alumina, each having a central hexagonal pore (which is also the reason that an anodized part can take on color in the dyeing process).

The film thickness can range from under 5 microns on bright decorative work up to 150 microns for architectural applications.

3.10.3 Different Types of Anodizing

3.10.3.1 Type I—Chromic Acid Anodizing

The oldest anodizing process uses chromic acid. It is widely known as Type I because it is so designated by the MIL-A-8625 standard, but it is also covered by AMS 2470 and MIL-A-8625 Type IB. Chromic acid produces thinner (0.00002 in to 0.0007 in [0.5 microns to 18 microns]), more opaque films that are softer, ductile, and to a degree self-healing. They are harder to dye and may be applied as a pretreatment before painting. The method of film formation is different from using sulfuric acid in that the voltage is ramped up through the process cycle.

3.10.3.2 Type II—Sulfuric Acid Anodizing

Sulfuric acid is the most widely used solution to produce anodized coating. Coatings of moderate thickness (0.00007 in to 0.001 in [1.8 microns to 25 microns]) are known as Type II.

Standards for thin sulfuric acid anodizing are given by MIL-A-8625 Types II and IIB, AMS 2471 (undyed), and AMS 2472 (dyed).

3.10.3.3 Type III—Hardcoat Anodizing

Also produced by using sulfuric acid anodizing, these coatings are thicker than 0.001 in [25 microns] and are known as Type III, hardcoat, or engineered anodizing. Thick coatings require more process control and are produced in a refrigerated tank near the freezing point of water with higher voltages than the thinner coatings. Hardcoat anodizing can be made between 0.001 in to 0.006 in [25 microns to 150 microns] thick. The increased anodizing thickness increases wear resistance, corrosion resistance, ability to retain lubricants, and electrical and thermal insulation. Standards for thick sulfuric acid anodizing are given by MIL-A-8625 Type III, AMS 2469, and the obsolete AMS 2468.

3.10.4 Sealing

Chromic acid and sulfuric acid processes such as Types I, II, and III produce pores in the anodized coat. These pores can absorb dyes and retain lubricants, but are an avenue for corrosion. When lubrication properties are not critical, these pores are usually sealed after dyeing. Long immersion in boiling-hot deionized water is the simplest sealing process, although it is not completely effective and reduces abrasion resistance by 20%. Teflon, nickel acetate, cobalt acetate, and hot sodium or potassium dichromate seals are common. MIL-A-8625 requires sealing for thin coatings (Types I and II) and allows it as an option for thick ones (Type III).

3.10.5 Welding on Anodized Aluminum

Anodized coatings have a much lower thermal conductivity and coefficient of linear expansion than aluminum. As a result, they will have a tendency to crack if exposed to temperatures above 176°F [80°C], although they will not peel. The melting point of an anodized coating is 3722°F [2050°C], and the melting point of pure aluminum is 1216°F [658°C]. The anodized coating on the surface of aluminum acts as an electrical insulator. If we did manage to break through the anodized surface and attempt to arc weld, we would expect to have many problems in stabilizing an arc and would typically produce a weld of very poor quality containing numerous discontinuities. For these reasons, it is not recommended to weld on aluminum that has been anodized without first removing the anodized surface in the area to be welded. The AWS D1.2, *Structural Welding Code—Aluminum*, stipulates within its fabrication section, under preparation of base metals, that all surfaces to be welded shall be free from thick aluminum oxide. Consequently, if aluminum that has been anodized is to be welded, the anodized surfaces in the area to be welded would be required to be removed before welding. Removal can be performed by mechanical means, such as grinding or filing.

3.10.6 Anodizing Material After Welding

One other area of concern relating to the anodizing process is the affect of anodizing on material that has already been welded. The weld area will always be visible, having at least a slightly different appearance than the adjacent aluminum. Because the anodic oxide layer is translucent, the differing substrates will be visible and may in fact be accentuated. If you want the best color match after postweld anodizing, 4043 is not a good choice of filler alloy because it will typically turn dark gray in color after the anodizing process and the weld will become very visible in contrast to the base alloy. The 5356 filler alloy will provide a much closer color match after anodizing, particularly on the 6xxx series base alloys.

3.10.7 Conclusion

Aluminum anodizing has inherent performance qualities including corrosion resistance and decorative options for coloring aluminum. Anyone requiring further information about this finishing process should contact the Aluminum Anodizing Council (AAC) at www.anodizing.org.

3.11 Can Stress Corrosion Cracking (SCC) Affect the 5xxx Series Aluminum Alloys?

? I have been informed that some aluminum alloys can be adversely affected by exposure to sustained temperatures above 150°F [66°C]. Apparently there are some alloy groups that can become susceptible to stress corrosion cracking if exposed to temperatures within a certain range; the 5xxx series (Al Mg) alloys being particularly susceptible. I work with the 5xxx series alloys and I know that they are commonly used in structural applications. What is Stress Corrosion Cracking and is it a problem when using the 5xxx series aluminum alloys? I would like to know more about this subject and how to avoid problems associated with this issue.

3.11.1 What is Stress Corrosion Cracking (SCC)?

Stress Corrosion Cracking (SCC) is an accelerated form of corrosion resulting from exposure of a susceptible material to the combined action of corrosive environment, and high steady tensile stress, either applied or residual (see Figure 3.9).

With the combined action of continuous stress and a corrosive environment, cracking of some aluminum alloys may occur.

In terms of alloy susceptibility, stress corrosion cracking is usually limited to the aluminum alloys with the following chemistry:

- Aluminum-copper-magnesium 2xxx series alloys.
- Aluminum-zinc-magnesium-copper 7xxx series alloys.
- Aluminum-magnesium 5xxx series alloy—that contain more than 3% magnesium.

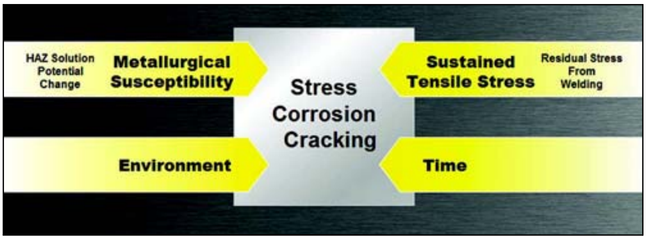


Figure 3.9—Shows the Conditions Required to Promote Stress Corrosion Cracking

SCC is very rarely seen in the aluminum-magnesium-silicon 6xxx series alloys and does not occur in the pure aluminum 1xxx series, aluminum-manganese 3xxx series alloys, or the aluminum-magnesium 5xxx series alloys with less than 3% magnesium.

3.11.2 The Susceptibility of the 5xxx Series Aluminum-Magnesium Alloys to SCC

This series of aluminum alloys has a wide range of magnesium content (from 1% to 5%) and are typically used in work-hardened tempers. Alloys with magnesium content in excess of 3% that have been work-hardened can become susceptible to selective grain boundary precipitation. This grain boundary precipitation can occur to some degree at room temperature, but it is accelerated significantly at moderate elevated temperatures. If these materials are subjected to prolonged exposure to temperature between 150°F to 350°F [66°C to 180°C] precipitate can form that is highly anodic to the aluminum-magnesium matrix, and the continuous grain boundary network of precipitate produces susceptibility to SCC (see Figure 3.10).

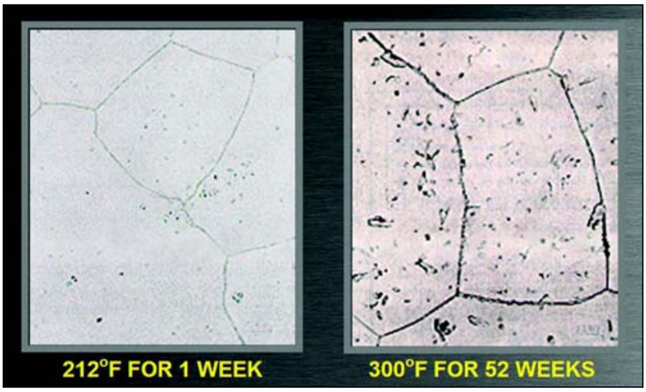


Figure 3.10—Shows the Selective Grain Boundary Precipitation in Two 5% Mg Alloys

The weldable, high-strength 5xxx series aluminum-magnesium alloys were introduced by the aluminum producers after many years of research and development, in which their stress corrosion cracking characteristics were established. The results of this research and of service experience show that stress corrosion cracking is unlikely to occur in welds during normal ambient temperature service of any of the weldable 5xxx series alloys, all those commercially available today from primary producers in the various tempers and forms, including filler alloys.

Research also shows however, that prolonged exposure of alloys containing more than 3% magnesium at temperatures of 150°F to 350°F [66°C to 180°C] should be avoided as this temperature range can produce a material structure very susceptible to SCC. Exposure to higher temperatures (in excess of 350°F [180°C]) results in a coarsening of the precipitates, producing a discontinuous grain boundary precipitate structure and reducing or eliminating SCC susceptibility.

3.11.3 Is SCC a Problem when Using the 5xxx Series Aluminum Alloys?

If we understand and respect this phenomenon and abide by the following rules, there is no reason why we should have problems with SCC when using the 5xxx series alloys.

Base alloys or filler alloys with more than 3% Mg should not be used for applications were prolonged exposure of temperatures between 150°F to 350°F [66°C to 180°C] can be expected.

Filler Alloy ER4043 is a 5% Silicon alloy and is often used for welding the 6xxx series base materials and the 5xxx series base materials with less than 2.5% magnesium. This filler alloy has no magnesium added and is therefore suitable for elevated temperature applications.

The 5554 filler alloy was designed to provide the improved strength and ductility characteristics of a magnesium-based filler alloy that was also suitable for elevated temperature applications. It contains 2.4% to 3.0% magnesium thereby providing an alloy that is not susceptible to stress corrosion cracking, but has improved shear strength and improved ductility when compared to the 4xxx series filler alloys.

There are some base materials and filler alloys of the 5xxx series that are designed specifically for elevated temperature applications, one such combination that is frequently used in industry is 5454 base material welded with a 5554 filler alloy. Both of these alloys have a controlled magnesium range of between 2.4% and 3.0% and are therefore suitable for elevated temperature applications and not susceptible to SCC.

3.11.4 Conclusion

Stress corrosion cracking can be a major issue within the 5xxx series Aluminum Alloys, however, as long as we understand which of these alloys can and can not be used at elevated temperatures, we can easily avoid running into this type of problem.

3.12 What are the Primary Considerations When Evaluating the Design Strength of Welded Aluminum Structures?

? I am about to become involved in the design of an aluminum welded structure. I have a question about the design strength of welded aluminum. I have been informed that there are some considerations relating to the strength of aluminum welded structures that are somewhat unique to this material. If this is indeed correct can you explain what they are?

I would agree with the fact that there are some characteristics associated with the design strength of welded aluminum structures that do require special consideration. Perhaps the two most common being: the reduction in strength of the base material after welding and the effect of filler alloy selection on the strength of fillet welds.

We will consider each of these topics individually.

3.12.1 The Reduction in Strength of the Base Material After Welding

In order to appreciate this occurrence we must first recognize that the majority of welded aluminum structures are manufactured from aluminum base alloys that are in one of two prescribed metallurgical conditions. They are either in the strain hardened conduction, which is generally the case with the non-heat treatable alloys, such as the 5xxx and 3xxx series alloys; or they are in the solution heat treated and precipitation hardened condition, which is generally the case with the heat treatable alloys, such as the 6xxx, 2xxx, and 7xxx series alloys. Aluminum alloys that are in either of the above mentioned conditions, if subjected to adequate elevated temperature from any source, are susceptible to loss of strength through changes to their metallurgical structure. When we arc weld aluminum alloys we certainly subject the base material immediately adjacent to the weld (known as the heat-affected zone or HAZ) to very high temperatures that are more than adequate to change metallurgical structure and consequently reduce strength. Under most circumstances the heat of the welding operation is sufficient to reduce the strength of the base material in the HAZ of the non-heat treatable aluminum alloys to their annealed condition. In the case of the heat treatable alloys, the heat from welding is usually not sustained for a sufficient period of time in order to produce a fully annealed structure within the alloy, however, it is commonly adequate to facilitate over-aging and partial annealing in the HAZ. Both of these metallurgical changes reduce the strength of the base material in the HAZ.

So yes, during the design process it is necessary to consider the change (reduction) in strength that is typically associated with the arc welding process.

One of the most obvious examples of this consideration is seen in the welding procedure qualification requirements of any welding code or standard prescribed for the welding of aluminum structures. The minimum allowable tensile strength required when performing reduced section transverse tensile tests as stipulated by the code is not the material's original strength before welding—it is substantially lower. It is in fact the annealed strength for the non-heat treatable alloys and a strength value based on the partially annealed condition for the heat treatable alloys. The welding engineer should understand these reductions in strength in order to appreciate the mechanical test requirements involved during procedure qualification. The design engineer should understand these reductions in strength in order to appreciate the necessary allowances to be made in load carrying capability of an aluminum welded structure. The Aluminum Association's Aluminum Design Manual, Part I, Section 7 provides methods for determining the strength of welded aluminum members which account for the strength reduction from welding. Table 3.8 shows the unwelded and welded minimum ultimate tensile strength values of some non-heat treatable and heat treatable aluminum base alloys.

Table 3.8—Unwelded and Welded Minimum Ultimate Tensile Strength Values of Some Non-Heat Treatable and Heat Treatable Aluminum Base Alloys

Base Alloy & Temper	Tensile Strength Before Welding (ksi)	Tensile Strength After Welding (ksi)
1100-H16	19	11
1350-H16	16	8
3003-H18	27	14
5005-H16	24	15
5052-H32	31	25
5083-H116	44	40
5086-H34	44	35
2219-T87	64	35
6061-T6	42	24

3.12.2 The Effect of Filler Alloy Selection on the Strength of Fillet Welds

The strength of a fillet weld made in aluminum is determined by its throat size and the shear strength of the filler metal used to deposit the weld. This is the same principle that is used for calculating the strength of fillet welds made in other materials. The difference with fillet welds made in aluminum, however, is that it is not unusual to have a situation where we are able to select one of a number of different filler alloys that may be available to weld a particular aluminum base material. For example, many 6xxx series base materials and some 5xxx series base materials can be welded with 4043, 4047, 4643, 5183, 5356, 5554, 5556, and 5654 filler metals. From a design standpoint it should be realized that in making the selection of the most appropriate filler metal the shear strength of that particular filler metal is an important variable to consider. There are significant differences between various aluminum filler alloys. In almost all cases, the strength of a fillet weld is dictated by the strength of the filler alloy selected and the weld size. (The opposite holds for groove welds: for groove welds, the strength is usually dictated by the base metal). See Table 3.9, which shows the minimum shear strength values for aluminum filler alloys.

Table 3.9—Minimum Shear Strength Values for Aluminum Filler Alloys

Filler Alloy	Shear Strength (ksi)
1100	7.5
2319	16.0
4043	11.5
4047	13
4643	13.5
5183	21.0
5356	17.0
5554	17.0
5556	20.0
5654	12.0

Note: These minimum shear strength values are divided by a safety factor when used to design the size of welds for aluminum structures.

3.12.3 Conclusion

When designing arc welded aluminum structures we should make allowances for the fact that the heat of the welding operation can reduce the strength of the aluminum base material in the HAZ to a strength that is substantially lower than that of the original base material. We should also recognize that filler alloy selection is a more complex subject for aluminum than it is for most other materials. In aluminum welding, filler alloy selection can influence a number of weld performance characteristics, one of which is the strength of fillet welds. Therefore, from a strength standpoint, we should give serious consideration to filler alloy selection when designing welded aluminum structures.

The Aluminum Associations publication—Aluminum Design Manual—Specification & Guidelines for Aluminum Structures, is the industry's accepted guide for the design of welded aluminum structures and is available from the www.aluminum.org book store.

For assistance with filler alloy selection for aluminum welding a filler alloy selection chart can be used (see Figure 4.4).

3.13 What Can be Done to Restore the Lost Strength in Aluminum Weldments After Welding?

? After reading your Q&A column about design considerations of welded aluminum structures (Section 3.12) I have a question related to the section on the reduction in strength of the base material after welding. It is apparent from Table 3.8 in your article that the loss of strength in the HAZ after arc welding, particularly in the heat treatable alloys, can be very significant. What I would like to know is what, if anything can be done after welding to regain this lost strength and return the material to its original condition?

You are correct the reduction in strength after arc welding can be very significant in both the heat-treatable and nonheat-treatable alloys dependant on the particular alloy and its original temper condition prior to welding.

In order to consider the possibility of returning a welded base alloy back to its original condition we need to evaluate both the effect of arc welding on the various tempers and the options available for postweld treatment.

3.13.1 The Affect of Arc Welding on Material Temper

The amount of heat developed in a base material during arc welding is generally sufficient to reduce the strength of the temper condition of the base alloy. The one exception to this is that no reduction in strength will be experienced in either a heat-treatable or nonheat-treatable aluminum alloy when welded in the “O” temper. The “O” temper is the annealed condition and is sometimes referred to as dead soft. Unfortunately this fact is of very little practical consequence because owing to its low strength “O” temper material is very seldom chosen for structural applications. The effect of welding on the various tempers is different when considering the heat-treatable and nonheat-treatable alloys so we will evaluate then independently. *Figure 3.11 shows the affect of arc welding on both the heat-treatable and nonheat-treatable alloys.*

3.13.1.1 Nonheat-Treatable Alloys

The strength of these alloys is initially produced by alloying the aluminum with additions of other elements. These alloys consist of the pure aluminum alloys (1xxx series), manganese alloys (3xxx series), silicon alloys (4xxx series) and magnesium alloys (5xxx series). A further increase in strength of these alloys is obtained through various degrees of cold working or strain hardening. Strain hardening is a process used to increase the strength of aluminum alloys that cannot be strengthened by heat treatment. Strain hardening is accomplished through change of shape by the application of mechanical energy. As this physical deformation progresses (typically through rolling or drawing) it produces an elongation of the materials grain structure in the direction of working that provides a preferred grain orientation, high level of internal stress, and resultant increase in strength.

When these strain hardened alloys are heated during arc welding, recrystallization takes place in the heat-affected zone (HAZ), the work hardened and deformed crystals

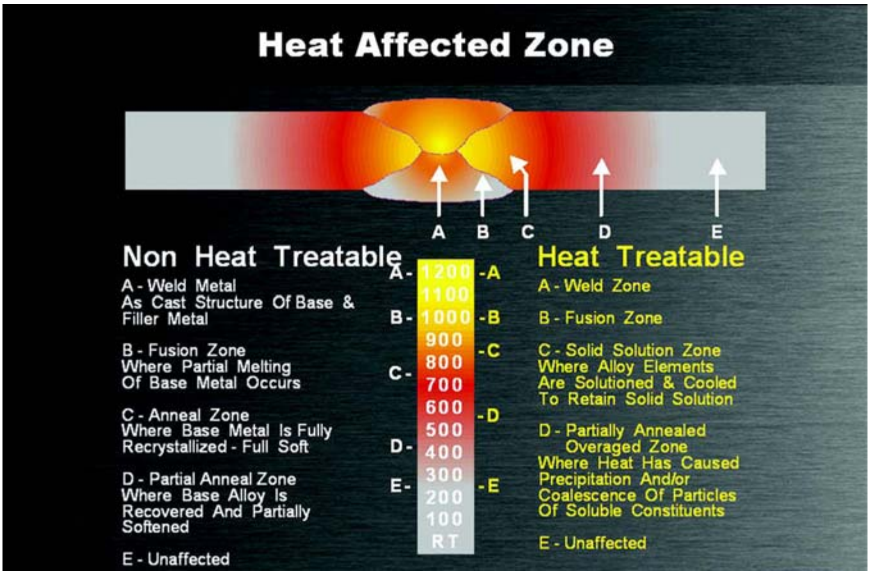


Figure 3.11—Affect of Arc Welding on Both Heat-Treatable and Nonheat-Treatable Alloys

are replaced by new strain-free crystals, and the base material within the HAZ is transformed into the annealed (dead soft) condition. This transformation is unavoidable in the nonheat-treatable alloys; regardless of the original pre-welded temper the postweld condition of the HAZ will always be annealed.

3.13.1.2 Heat-Treatable Alloys

The initial strength of these alloys is also produced by the addition of alloying elements to pure aluminum. These elements include copper (2xxx series), magnesium and silicon, which is able to form the compound magnesium silicide (6xxx series), and zinc (7xxx series). When present in a given alloy, singly or in various combinations, these elements exhibit increasing solid solubility in aluminum as the temperature increases. Because of this reaction, it is possible to produce significant additional strengthening to the heat-treatable alloys by subjecting them to an elevated thermal treatment, quenching, and, when applicable, precipitation heat-treatment known also as artificial aging.

In *solution heat-treatment*, the material is heated to temperatures around 900°F to 1000°F, depending upon the alloy. This causes the alloying elements within the material to go into solid solution. Immediately following this heating process the material is rapidly quenched, usually in water, this freezes or traps the alloying elements in solution. A material in this finished condition is said to be “*solution heat treated and naturally aged*” and given the –T4 designation.

Precipitation heat-treatment also known as *artificial aging* is often used after *solution heat-treatment.* This involves heating the material for a controlled time (8 hrs to 18 hrs) at a lower temperature (around 250°F to 500°F) depending upon the alloy. This process, used after *solution heat-treatment*, both increases strength and stabilizes the material. A material in this finished condition is said to be "*solution heat treated and artificially aged*" and given the –T6 designation.

When these heat-treatable alloys are heated during arc welding they are typically not heated for a sufficient period of time to fully anneal their structure. However, they are usually subjected to sufficient heating to reduce their strength considerably.

Whilst the duration of the heating from the arc welding process is normally insufficient to fully anneal the base material in the HAZ it is sufficient to partially precipitate alloying elements out of solution. This will typically result in the base alloy HAZ becoming *overaged* and the appropriate loss of strength associated with this process. An example of this reduction in ultimate tensile strength can be appreciated when considering the 6061-T6 base alloy in the pre-welded condition (45 ksi) postweld condition (24 ksi) and in the annealed condition (18 ksi).

3.13.2 Options Available for Postweld Treatment

3.13.2.1 Nonheat-Treatable Alloys

Unfortunately in the case of the nonheat-treatable aluminum alloys there is no practical way to rework the annealed heat-affected zone to its original strain hardened condition. It is customary therefore when using these alloys to design around the as-welded strength.

3.13.2.2 Heat-Treatable Alloys

In the case of the heat-treatable alloys there are procedures that can be used to return the pre-welded strength to the heat-affected zone.

3.13.2.3 The –T6 Temper

In order to fully recover the original pre-welded strength of a material that was in a -T6 temper prior to welding; a postweld heat treatment similar to that described above for solution heat-treatment and artificial aging is required. It can be appreciated that in many situations heating a welded structure to around 1,000°F followed by quenching in water and re-heating to around 350°F. for extended periods may not be entirely practical. This type of postweld heat treatment is not suited to localized application; the entire structure is typically required to be subjected to the procedure. When we consider the cost of conducting such postweld heat treatment, size limitations, and the possibility of producing residual stress and or distortion into the structure, it is not surprising that we do not see this type of heat treatment conducted extensively in the aluminum welding fabrication industry.

However, this type of post weld heat treatment is conducted for some specialized applications. If full solution heat treatment and artificial aging is to be performed on a welded structure it is advisable to consider the use of a heat treatable filler alloy. In the case of 6061-T6 a suitable heat treatable filler alloy would be alloy 4643. A small addition of magnesium to this silicon based alloy allows it to produce magnesium silicide and respond to this form of heat treatment. Using the correct filler alloy and conducting the appropriate post weld heat treatment can return an arc welded component that was originally in the –T6 condition prior to welding to its original strength.

3.13.2.4 The –T4 Temper

One other option that is sometimes seen as a more practical method of post weld heat treatment for the heat treatable aluminum alloys is to choose a base alloy in the –T4 temper. In the –T4 temper the base material has been solution heat treated and naturally aged, no artificial aging has been performed on this material. The typical ultimate tensile strength of 6061-T4 is (35 ksi) as compared with (45 ksi) of 6061-T6. After arc welding on the 6061-T4 material a considerable loss in strength is seen in the HAZ. However, the postweld heat treatment required in order for the 6061-T4 material to regain substantial strength in the HAZ (as well as the entire structure) can be far less complex than that required for 6061-T6 (see Figure 3.12).

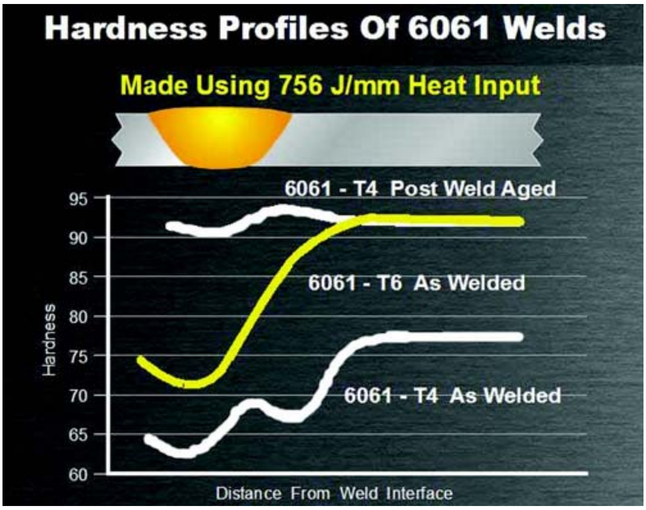


Figure 3.12—Three Examples of Strength Levels; 6061-T4 in the As-Welded Condition, 6061-T6 in the As-Welded Condition, and 6061-T4 in the Postweld Aged Only Condition. As Can be Seen, the 6061-T4 Postweld Aged Condition Exhibits Excellent Recovery of Strength Within the HAZ Along with Typical –T6 Properties Throughout the Structure.

As can be seen, the 6061-T4 postweld aged condition exhibits excellent recovery of strength within the HAZ along with typical –T6 properties throughout the structure. The benefits associated with this processing are related to the fact that no high temperature solution heat treatment and quenching are required only more moderate lower temperature artificial aging. This method of postweld processing is carried out by some manufacturers as a successful alternative to full solution heat-treatment and artificial aging.

3.13.3 Conclusion

So in answer to the question; what, if anything can be done after arc welding to regain lost strength and return aluminum alloys to there original unwelded condition?

For the nonheat-treatable alloys, no practical method of postweld processing is available. For the heat-treatable alloys variations of postweld heat-treatment are available for consideration. However, after explaining these methods I feel that it is reasonable to say that in reality the majority of the heat-treatable alloys that are used for structural welding applications are used in the same way as the nonheat-treatable alloys, in the as-welded condition.

3.14 What are the Types of Heat Treatment Used on Aluminum Alloys and How Do They Influence Manufacturing Procedures?

? I have worked with aluminum and aluminum welding for many years and have often heard many different metallurgical terms used for describing the various heat treating techniques and conditions used for aluminum alloys. Terms such as; solid-solution hardening, solution heat treatment, precipitation hardening, age hardening, natural aging, artificial aging, annealing, stabilizing, and stress-relieving. Can you explain the different heat treatments and how they can influence manufacturing procedures used for welding, forming and machining?

In order to appreciate the affect of thermal treatment on aluminum alloys we should first understand the principal effects of alloying elements and solid-solution hardening.

Pure aluminum is not heat-treatable but it “work hardens” or gains strength when mechanically worked such as bending or stretching. The addition of alloying elements to aluminum does not remove this characteristic, all aluminum alloys gain strength when cold worked. Adding elements to aluminum affect the metal in many respects, one of the most significant affects is that some aluminum alloys can now be made stronger through the use of thermal treatments.

3.14.1 Solid-Solution Hardening

Aluminum alloys are made by dissolving other metals in aluminum to form solid solutions. Some atoms of the alloying metals replace certain aluminum atoms in the metallurgical structure; this is called substitutional solid solution.

Other atoms of alloying elements occupy spaces between the base metal atoms in its metallurgical structure (lattice); this is termed interstitial solid solution. In both cases, the metallurgical structure is usually distorted by the new atoms in the structure, thus increasing strength. These alloys may then be further strengthened by heat treating and/or work hardening.

3.14.2 Precipitation Hardening

Heat-treatable aluminum alloys contain alloying elements that are more soluble at elevated temperatures than at room temperatures. When these alloys are solution-heat treated to put these elements back into solid solution and then rapidly quenched, a supersaturated condition is produced.

The strength of the alloy is developed as the alloying elements precipitate out of the solution during the passage of time. This effect is referred to as precipitation or age hardening. Varying degrees of age hardening occur at room temperature (natural aging), but artificial aging (or precipitation heat treatment at higher temperatures) usually is employed to develop maximum strengths as quickly as possible. Close control is essential to assure the correct metallurgical structure which will produce the desired properties.

Solid-solution hardening followed by precipitation hardening is the principal heat treatment method used for strengthening the heat treatable aluminum alloys.

Other thermal treatments used to prepare various aluminum alloys for optimum workability and application requirements include annealing, stabilizing, stress-relieving, and refrigeration.

3.14.3 Annealing

Aluminum and all of its alloys may be annealed to remove the hardening or strengthening effects of cold working or heat-treatment described above. Annealing is accomplished by heating the metal above its recrystallization temperature 650°F–800°F (345°–425°C), depending upon the alloy, and maintaining the required level until recrystallization is complete in work-hardened alloys. For heat treatable alloys either a controlled cooling rate or a low temperature soaking treatment is necessary in order to precipitate particles of the alloying elements.

Annealing is used to restore ductility to make the alloy easier to work, both at intermediate stages of fabrication, in which extensive metal deformation (work hardening) has taken place, or whenever metalworking procedures or end use requirements call for maximum ductility. In Figure 3.13 we see spools of aluminum welding wire positioned in a furnace. These spools are about to undergo an annealing operation to remove the work hardening affect of the previous wire drawing operation before subsequent manufacturing operations are carried out.

3.14.4 Stabilizing

Certain non-heat-treatable, work-hardening alloys containing magnesium, such as 5052, gain ductility but lose strength upon room temperature aging. Such age-softening alloys often are stabilized by heating to 225°F to 350°F (110°C to 180°C) to accelerate the softening to its ultimate limit.

3.14.5 Stress-Relieving

Internal stresses built up by temperature gradients in aluminum may be caused by many factors: during quenching (rapid cooling), after heat treatment, cooling after welding or casting, from distortion of rolling, forging, extruding, bending, or drawing

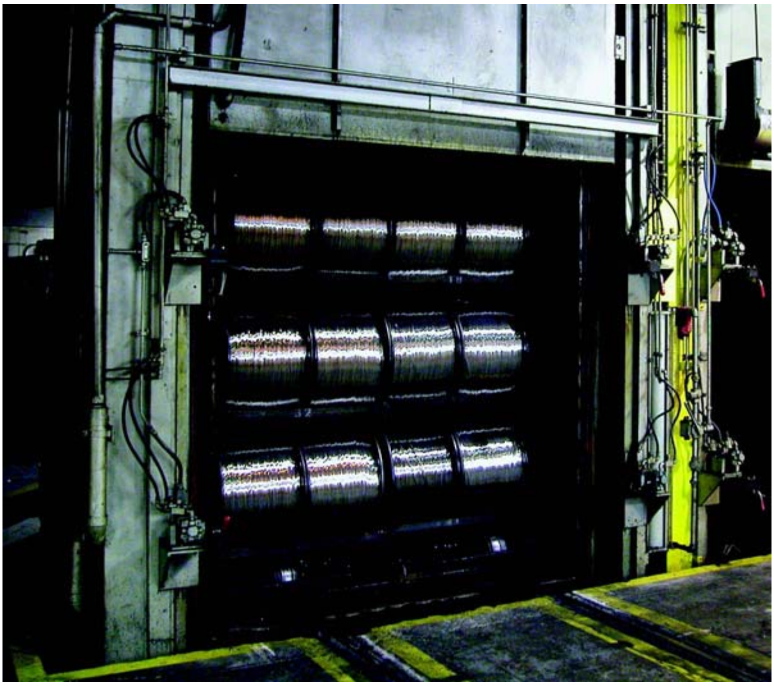


Figure 3.13—These 600 Pound Spools of Aluminum Welding Wire are About to Undergo an Annealing Operation to Remove the Work Hardening Affect Produced by Previous Wire Drawing Operations

operations. These internal stresses can be reduced by either thermal or mechanical treatments.

Thermal treatments employing temperatures below those required for annealing often are used for non-heat-treatable wrought alloys, with some loss of strength and an increase in ductility.

Where applicable, the metallurgically superior procedure of stressing the metal mechanically is used. This produces a small, controlled amount of plastic deformation (1–3%) to effect employed stress relief, with no resultant loss of strength.

This treatment aligns the residual stress in the direction of working and also reduces the differences between compressive stresses in the outer layer of the metal and the interior tensile stresses within. Mechanical stress-relieving is accomplished by stretching or compressing the metal in hydraulic machines.

3.14.6 Refrigeration

Hardening of naturally aging heat-treatable alloys can be retarded significantly by refrigeration immediately after solution heat treatment, the lower the temperature the longer the "workable life," within limits. Some applications of this practice are quite sophisticated, particularly where aerospace components, for example, are being fabricated. However, a typical simple use of refrigeration is for storage of alloy 2024 wire or rod to gain maximum workability when cold-heading rivets are produced from this alloy.

3.14.7 The Influence of Heat Treatment on Manufacturing Procedures

3.14.7.1 Welding

Typically the same welding procedures can be used for heat treatable alloys in various tempers. While the original temper of a base material can have some direct effect on the strength of the completed weld, the predominant effect on the weld strength is from the heat introduced into the base material during welding. Regardless of the heat treated condition, the heat-affected zone (HAZ) of the base material will determine the welded transverse tensile strength of a groove weld. The design engineer will usually select a specific heat treated temper based on its physical properties and suitability for the specific application. The welding engineer will then design a welding procedure to best achieve the required mechanical results after welding. Regardless of the heat treated condition of the base material used, welding procedures should be qualified to establish the suitability of the completed weld for its intended service.

3.14.7.2 Forming and Machining

The heat treated condition of aluminum alloys can certainly influence the procedures used for forming and machining of these materials. In forming operations, such as bending, using the correct bend radii is essential to prevent fracturing during this manufacturing process. Tables are available that provide the approximate bend radii for various aluminum alloys of different thicknesses and tempers for plate and tubes. These requirements differ dependent on the heat treated condition of the alloy.

The correct tooling for machining of aluminum alloys is dependant on its machineability rating, designated as A through E. Tables are available that provide this information as well, based on aluminum alloy type and designated heat treated temper.

3.14.8 Conclusion

There are a number of forms of thermal treatment associated with the processing of aluminum alloys, particularly the heat treatable alloys. Some treatments are designed to strengthen the alloy and others to remove strength and or residual stress. The heat treated condition of an aluminum alloy is usually chosen in order to correspond with the design criteria of the product, assist in manufacturing processing and produce a finished product that is best suited to its operating conditions and environment.

Acknowledgment

I would like to thank the Aluminum Association for allowing me to use information from their publication “Forming and Machining Aluminum” which is a popular resource to persons interested in forming and machining aluminum and is available from www.aluminum.org.

3.15 Why are Aluminum Alloys Suitable for Low Temperature Application and Why are There No Impact Toughness Requirements for Aluminum Filler Alloys?

? Many filler alloys used for welding steel are required to have a guaranteed minimum Charpy V-Notch impact toughness value, especially for applications where low temperature service is to be experienced. How is this issue addressed in aluminum? I know that aluminum is used in cryogenic applications. Are the aluminum filler alloys that are used in these very low temperature applications required to be tested in order to meet minimum impact toughness requirements?

3.15.1 Cryogenic Applications

You are correct aluminum is used in cryogenic applications. In physics or engineering, ***cryogenics*** is the study of the production of very low temperatures (below –150°C, –238°F or 123K) and the behavior of materials at those temperatures. The word cryogenic originates from the Greek word Kryos which means very cold. Aluminum is used in many applications that are very cold. One of the most well known is probably LNG Tankers, LNG Tankers are large ships that carry vast amounts of Liquid Natural Gas (LNG) in very large welded aluminum spheres (see Figure 3.14).

Figure 3.14—Liquid Natural Gas (LNG) Tanker with Four Large Welded Aluminum Spheres (Tanks)

Many materials when subjected to these very low temperatures undergo changes in their physical structure which severely limit their usefulness in cryogenic applications. Some metals, like many steels for example, become extremely brittle.

Aluminum alloys, however, have been demonstrated to have an unusual ability to maintain their ductility and resistance to shock loading at extremely low temperatures approaching absolute zero –459°F (–273°C). As temperature decreases below room temperature, aluminum's tensile and yield strength actually increase as the temperature decreases, and the ductility and toughness of most alloys increase as well. Even at the lowest test temperatures available, in liquid helium at –452°F (–273°C), strength remains high and ductility and toughness remain well above values at room temperature for most alloys (see Table 3.10).

Consequently, aluminum alloys offer distinct advantages over most steels when used as material for construction of cryogenic equipment or for structures that will experience cryogenic cold.

Table 3.10—Average Results of Tensile Tests of Some Aluminum Alloys for Low-Temperature Service

Alloy and Temper	Temperature °F	Tensile Strength psi	Yield Strength psi	Elongation in 2 in %	Reduction of Area %	Notch Tensile Strength psi
2219-T851	Room Temp	67,600	53,800	11.0	27	79,400
2219-T851	–320	82,500	63,800	13.8	30	94,500
2219-T851	–452	96,100	69,000	14.0	26	102,100
3003-H14	Room Temp	22,900	21,100	16.8	68	Not available
3003-H14	–320	36,600	25,900	32.5	56	Not available
3003-H14	–452	58,100	30,100	32.0	49	65,100
5083-0	Room Temp	46,800	20,400	19.5	26	54,000
5083-0	–320	63,000	23,000	34.0	34	61,000
5083-0	–452	80,800	25,800	32.0	33	62,300
5083-H321	Room Temp	48,600	34,100	15.0	23	61,100
5083-H321	–320	66,100	39,700	31.5	33	70,400
5083-H321	–452	85,800	40,500	29.0	33	73.700
6061-T6	Room Temp	44,900	42,200	16.5	50	69,200
6061-T6	–320	58,300	48,900	23.0	48	83,400
6061-T6	–452	70,100	55,000	25.5	42	89,900

Note: These values are minimum values and are not intended to be used for design calculations; values used for design have a safety factor incorporated and are therefore much lower).

3.15.2 Test Data Available for Low Temperature Applications

One type of test used to establish the ability of a material to deform plastically in the presence of a severe stress raiser is the notch tensile test, conducted in accordance with ASTM Standard Method E 338 and E 602. The notch-yield ratio from such tests, the ratio of the fracture strength of a severely notched specimen to the tensile yield strength of the material, illustrates whether or not the material yields before fracturing in the presence of a severe crack or flaw, and comparison of values over a range of temperature illustrates susceptibility to embrittlement effects if deterioration is evidenced.

Tests have shown that alloy 5083-0, which is often chosen for cryogenic applications, sustains more than twice its tensile yield strength before fracturing, even at temperatures approaching absolute zero. Data for many other aluminum alloys illustrates that they too are free of any type of brittle-to-ductile transition in fracture behavior.

Much technical data is available that demonstrates outstanding cryogenic performance of aluminum alloys. Tensile, compressive yield, and shear ultimate strengths increase with the decrease in temperature; at –320°F (–196°C) ultimate strengths are 35%–50% above room temperature values and yield strengths are 15%–25% higher. The moduli of elasticity increases with decrease in temperature; precise measurements at –320°F (–196°C) have shown that moduli are 15%–17% above the room temperature values. Fatigue strengths, like static tensile and shear strengths, increase with decrease in temperature; at –320°F (–196°C), for 5xxx alloys, both parent metal and weldments have fatigue strengths about 25% above room temperature values. Toughness as measured by notch-yield ratio (notch tensile strength/tensile yield strength), unit propagation energy (tear resistance) and plane stress or plane strain fracture toughness, remains high over the entire range of cryogenic temperatures; for those alloys recommended most often for cryogenic service, toughness by any indicator is well above the room temperature value, even near absolute zero. As mentioned earlier, there is no indication of a ductile-to-brittle fracture transition with aluminum, as often exhibited by some ferritic materials, even for the highest strength aluminum alloys.

3.15.3 Conclusion

In response to the original question—Are the aluminum filler alloys that are used in these very low temperature applications required to be tested in order to meet minimum impact toughness requirements?

As seen above, at very low temperatures aluminum alloys show an improvement in their mechanical properties, yield and tensile strengths can increase significantly, and elongation and impact strength remains relatively constant. Because aluminum alloys exhibit these characteristics and the fact that aluminum has no ductile-to-brittle transition, neither the AWS or ASME welding standards require low-temperature Charpy or Izod impact testing for aluminum filler alloys.

Acknowledgment

I would like to thank the Aluminum Association for allowing me to reproduce material from their publication “Aluminum Alloys for Cryogenic Applications.”

3.16 How Can I be Assured that I am Using the Correct 5xxx Series Aluminum Alloy for Marine Applications and Thereby Prevent Sensitization and Intergranular Corrosion?

? I was informed that some years ago there was a significant problem associated with the aluminum alloy 5083 that was used for the manufacturing of some large boats that were fabricated in the Washington State vicinity. The 5083 aluminum alloy that was used for the fabrication of these boats was not suitable for marine applications, causing corrosion and fracturing in the material after welding and when in service. What exactly was the problem with the aluminum and how can a manufacturer of aluminum boats be assured that they are using the correct aluminum alloy in marine applications so that this problem will not arise again?

I think I am aware of the problem that you are referring, and believe that I may have information about specific actions that were taken in an attempt to prevent its reoccurrence.

3.16.1 The Problem

Around 2002 I was visiting a number of ship and boat building manufactures in and around the Puget Sound area of Washington State. It was there that I came across a number of aluminum vessels that had been found to have discontinuities in the parent material, typically at the edge of welds in and around the heat-affected zone. I actually inspected some of these vessels and found surface pitting and crescent-shaped cracks near some welds on their hulls. At the time of inspection I was unaware of what was causing this problem, so after my visit I immediately contacted a colleague from an aluminum manufacture to discuss the situation. I was informed that some 5083-H321 cold rolled aluminum plate that was not guaranteed for marine application by the manufacturer had been used for the construction of the vessels I had inspected and I was directed to a report issued by the U.S. Coast Guard that contained questions and answers specifically addressing this problem.

In summary this report reflected the following:

The 5083-H321 temper material can be produced using a variety of mill processes. In the case of the 5083-H321 material in question it was produced using a non-marine process that made it susceptible to intergranular corrosion. This corrosion occurs as a result of exposure of the material to corrosive environments such as saltwater. The saltwater attacks certain sensitized areas at the aluminum grain boundaries, and can result in pitting and/or cracking. It also stated that the -H3XX tempers should be considered for marine applications only if both the individual producer is qualified and approved by the marine classification organization and the producer certifies that the particular product (aluminum plate) is suitable for the intended use (marine application). In an attempt to prevent further situations of this kind, at the time of this report (October 2002) the Aluminum Association Task Group on Marine Alloys was working on a draft specification that was submitted to ASTM for further development.

3.16.2 The Action Taken to Prevent Reoccurrence

The predominant action to prevent the reoccurrence of this type of problem was from the development and introduction of the ASTM document designation: *B 928/B 928M Standard Specification for High Magnesium Aluminum-Alloy Sheet and Plate for Marine Service and Similar Environments.* The B 928/B 928M document was originally approved in 2003.

I consider this Standard Specification to be very important to the manufacturing environment that is involved in the fabrication of aluminum products used in marine applications or similar environments. Material used for these applications should be specifically required to meet the requirements of this Specification. The Specification contains the chemical composition limits and minimum mechanical property limits for 5059, 5083, 5086, 5383, and 5456 in the H116 and the H321 tempers. The standard provides some excellent definitions of some of the terms used in its text; these appear in section 3 Terminology:

Exfoliation—Corrosion that proceeds laterally from the site of initiation along planes parallel to the original rolling surface, generally at the grain boundaries, forming corrosion products that force metal away from the body of the material, giving rise to a layered appearance.

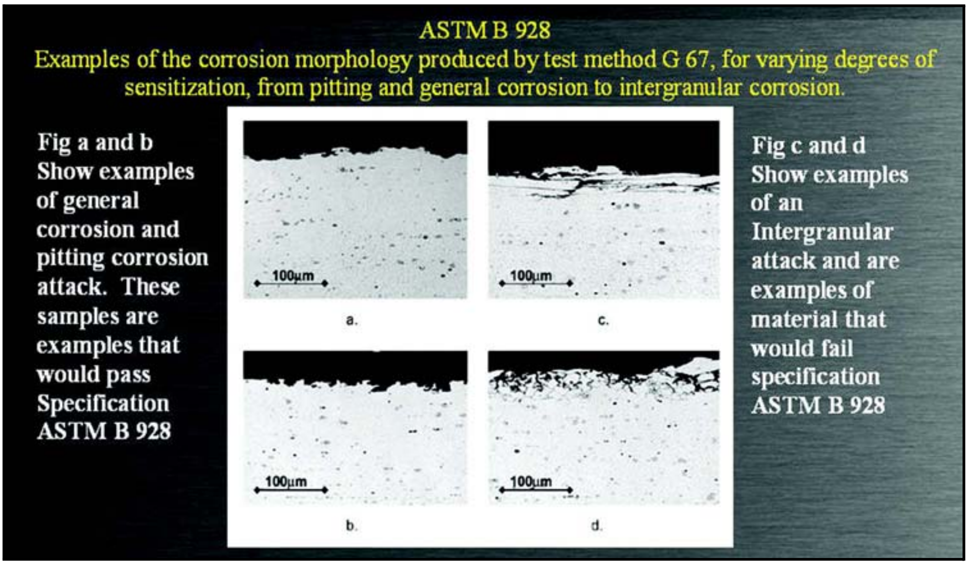
Intergranular corrosion—Corrosion that preferentially occurs at, or adjacent to, the grain boundaries of a metal or alloy.

Sensitization—The development of a continuous or nearly continuous boundary precipitate in 5xxx alloy temper material, which causes the material to be susceptible to intergranular forms of corrosion.

Stress-corrosion cracking—A cracking process that requires the simultaneous action of a corrodent, and sustained tensile stress. (This excludes corrosion-reduced sections, which fail by fast fracture. It also excludes intercrystalline or transcrystalline corrosion which can disintegrate an ally without either applied or residual stress.)

3.16.3 More About the B 928 Standard

The standard explains that the aluminum-magnesium alloy products that have a continuous or nearly continuous grain boundary precipitate are susceptible to intergranular forms of corrosion, (that is intergranular corrosion, stress corrosion cracking or exfoliation corrosion) and provides examples of varying degrees of grain boundary precipitate. It explains how the term “sensitization” is used to describe the development of a susceptible microstructure and how the extent of corrosion that will occur is dependent on the degree of continuity of the grain boundary precipitation and the corrosiveness of the environment. It also explains how 5xxx alloys that have been sensitized, are susceptible to intergranular corrosion, and when subjected to sustained tensile stress, may exhibit intergranular stress corrosion cracking. Perhaps the most significant section of the specification addresses the testing of materials to determine if the loss of mass experienced after accelerated corrosion testing is a result of intergranular attack or general corrosion and pitting attack (See examples shown in Figure 3.15).



ASTM B 928

Examples of the corrosion morphology produced by test method G 67, for varying degrees of sensitization, from pitting and general corrosion to intergranular corrosion.

Fig a and b Show examples of general corrosion and pitting corrosion attack. These samples are examples that would pass Specification ASTM B 928

Fig c and d Show examples of an Intergranular attack and are examples of material that would fail specification ASTM B 928

Figure 3.15—Examples of the Corrosion Morphology Produced by Test Method G 67

ASTM B 928/B 928M requires that material is tested by test methods G 66 — *Test Method for Visual Assessment of Exfoliation Corrosion Susceptibility of 5xxx Series Aluminum Alloys (ASSET Test)* and G 67 — *Test Methods for Determining the Susceptibility to Intergranular Corrosion of 5xxx Series Aluminum Alloys (ASSET Test).*

One other action that was taken directly related to this same problem was a change to *ANSI H35.1/H35.1(M) — Alloy and Temper Designation Systems for Aluminum.* The H116 and H321 temper designations were redefined to identify that these tempers are only assigned for wrought products in the 5xxx series of which the magnesium content is 3% nominal or more. These alloys are suitable for continuous service temperature no greater than 150°F (66°C) and there is a requirement for these alloy tempers to meet specified levels of corrosion resistance in accelerated type corrosion tests including tests for both inter-granular and exfoliation corrosion.

3.16.4 Conclusion

When procuring 5xxx series aluminum alloys for marine applications, ensure that they are ordered to the correct temper and that they are manufactured and tested in accordance with the requirements of ASTM B 928/B 928M

Acknowledgment

I would like to thank the ASTM for allowing me to use some of their material including the pictures in Figure 3.15. Reprinted, with permission, from B 928/B 928M-07 *Standard Specification for High Magnesium Aluminum-Alloy Sheet and Plate for Marine Service and Similar Environments*, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

3.17 Where Can I Find Technical Information and Training on Aluminum Welding?

? Where can I find technical information that can help me improve my understanding of welding aluminum? Are there any useful textbooks and/or training programs available on this subject?

3.17.1 Useful Textbooks

This is a fairly common question, usually asked by an individual who is moving into the welding of aluminum for the first time. Typically, they are experienced in steel fabrication, but have heard that welding of aluminum is difficult or different. Apart from being fairly common, it is also a question I like to hear, as it usually indicates that the individual is attempting to prepare for a change in environment, and is, therefore, much more likely to be successful in his venture.

There are a number of publications available that address the welding of aluminum. I will suggest two which I believe provide useful information for the fabricator moving to aluminum.

1. **The American Welding Society—*Welding Handbook* Chapter on Aluminum and Aluminum Alloys**

This chapter is dedicated to aluminum and contains excellent information about aluminum welding. If you are a member of the AWS, you may have this one already on your shelf. If you do not you may want to acquire it along with the rest of the set.

2. **The Aluminum Association—*Welding Aluminum: Theory and Practice***

If you are looking for a textbook exclusively dedicated to the practical aspects of welding aluminum, then you should seriously consider acquiring this publication.

This textbook is perhaps the best-recognized publication, currently in print, that relates exclusively to the welding of aluminum.

I came across a reference in a past edition of the American Welding Society's *Welding Journal*. The one section in particular that attracted my attention was the reference to a book review, performed by Secat Inc., for the latest edition of *Welding Aluminum: Theory and Practice*.

I would like to quote from the independent book review by Secat that I found on their web site, www.secat.net:

> "To be competitive in the modern industrial world, a structural metal must be readily weldable." So starts The Aluminum Association's flagship publication in the area of joining, which has just been revised and published. The information it contains addresses both the "whys" and "hows" of the important processes that have partly enabled aluminum to achieve its stature as a widely used structural metal.

> *Welding Aluminum: Theory and Practice* has traditionally been the "go to" publication for information on joining aluminum. While it is not comprehensive in every aspect of joining, it gathers in one place the key topics. Perhaps the main accomplishment of this publication is its ability to bring together the metallurgical aspects of welding processes on a reasonably theoretical level with the practical elements of actually carrying out those processes in the real world. The book has been edited, revised, and expanded by The Aluminum Association's Technical Committee on Welding and Joining."

The above quote was taken from the initial chapter of the book review. The remainder continued to provide a fairly comprehensive overview of the entire book's content. I considered the book review to be favorable, which was extremely satisfying considering the hours I spent, along with other members of The Aluminum Association's Technical Committee, writing, reviewing and editing the 4th edition.

Where is this book used? This publication has become the document that is traditionally provided to students attending aluminum welding seminars and/or aluminum welding training programs. Many welding engineers and welding educators are using this document as both a technical reference document and as training material for aluminum welding technology.

If you are an engineer, a metal fabricator, a structural designer, a welder, or anyone who is serious about joining aluminum, *Welding Aluminum: Theory and Practice* is a reference that you cannot afford to be without.

Welding Aluminum: Theory and Practice can be ordered from the electronic bookstore at:www.aluminum.org.

3.17.2 Training Programs for Aluminum Welding

Traditionally, there has been limited training in aluminum welding available when compared to what is available for welding steel. The more recent advancement of aluminum into the automotive industry, along with its increased use within the welding fabrication industry in general, has certainly promoted the need for additional training in aluminum welding. The requirement for welding engineers, technicians, inspectors, supervisors and welders who have experience and technical training in aluminum welding technology has increased. Where do we find this training? Unfortunately, you will still find that the typical technical school has little, if any, formal training programs available in aluminum welding, although this situation would appear to be slowly improving. One method to help promote this change is for manufacturing organizations involved in aluminum welding to exert pressure and provide assistance to their local technical training centers to introduce training in aluminum welding. There are some well-established training programs available that specialize specifically in aluminum welding technology, and there are a few newcomers to the aluminum welding training scene. One organization who has been performing both practical and theoretical training in aluminum welding exclusively, for the last 20 years, is AlcoTec Wire Corporation. Information on their training programs is available through their web site, www.alcotec.com.

3.17.3 Conclusion

Because the welding of aluminum is different than welding steel, it is very wise to seek information and/or training in aluminum welding before embarking onto an aluminum welding project for the first time.

Yes, there is training literature, and there are training courses available for welding aluminum. However, because aluminum welding is a smaller and more specialized section of the welding industry, there are typically fewer available than that for steel.

Chapter 4

Aluminum Filler Alloys

4.1 Filler Alloy Selection for Aluminum Welding

4.1.1 Introduction

Typically, filler alloy selection for welding steel is based on matching the tensile strength of the base alloy alone. Aluminum, on the other hand, often has a variety of filler alloys, which can meet or exceed the tensile strength of the base material heat-affected zone in the as-welded condition. The selection of a filler alloy for aluminum typically is based on other variables, which may be as important, or possibly more important, than that of tensile strength. Choosing the correct filler alloy for aluminum is based on the operating conditions of the finished welded component and consideration of a number of variables that can affect the operating condition of the weld. Section 4.8 provides a filler alloy selection chart that compares the performance of each filler alloy against each of the following variables.

4.1.2 Ease of Welding

Ease of welding is often an important consideration in filler alloy selection. Its significance is based on the filler/base alloy combination (chemistry) and its relative crack sensitivity. For base alloys with a high susceptibility to hot cracking, such as many in the 2xxx series alloys, a 4xxx series filler may be chosen, such as 4145, which has an extremely low solidification temperature (970°F [521°C]). This low solidification temperature of the filler alloy ensures that the 4145 weld is the last area to solidify and thereby allows the base material to solidify completely and reach its maximum strength before the solidification/shrinkage stresses of the weld are applied.

By using a filler alloy such as 4047, which has a freezing range of around 10°F [–12°C], welds can be made which solidify quickly. This reduces the time that liquid metal is subjected to shrinkage during the solidification process.

4.1.3 Critical Chemistry Ranges

The critical chemistry ranges and the effects of alloy content on cracking sensitivity are discussed in this section. See also Section 5.1 for additional information on the effects of alloy content on cracking sensitivity.

4.1.3.1 Aluminum/Silicon Alloys—4xxx Series

The 4xxx series aluminum/silicon alloys are used predominately for filler alloys and are found as nonheat-treatable and heat-treatable alloys containing 4.5% to 13% silicon. Silicon in an aluminum filler/base alloy mixture of 0.5% to 2% produces a weld metal composition that is crack sensitive. A weld with this chemistry usually will crack during solidification. Care must be exercised if welding a 1xxx series (pure Al) base alloy with a 4xxx series (Al/Si) filler alloy to prevent a weld metal chemistry mixture within this crack sensitive range.

4.1.3.2 Aluminum/Copper Alloys—2xxx Series

Aluminum/copper alloys (2xxx series) are heat-treatable high-strength materials often used in specialized applications. They exhibit a wide range of crack-sensitive characteristics. Some of these base alloys are considered poor for arc welding because of their sensitivity to hot cracking, but others are welded easily using the correct filler alloy and procedure.

4.1.3.3 Aluminum/Magnesium Alloys—5xxx Series

The aluminum/magnesium alloys (5xxx series) have the highest strengths of the nonheat-treatable aluminum alloys and, for this reason, are very important for structural applications (see Figure 4.1). Magnesium (0.5% to 3.0%) in an aluminum weld produces a crack-sensitive weld metal composition. As a rule, the Al/Mg base alloys with less then 2.5% Mg content can be welded with either the Al/Si (4xxx series) or the Al/Mg (5xxx series) filler alloys dependent on weld performance requirements. The Al/Mg base alloys with more than about 2.5% Mg typically cannot be welded successfully with the Al/Si (4xxx series) filler alloys because excessive amounts of magnesium silicide Mg_2Si develop in the weld structure, decreasing ductility and increasing crack sensitivity. The base alloys with more than 2.5% Mg are welded with the Al/Mg (5xxx series) filler alloys, usually with a similar chemistry to the base alloy.

4.1.3.4 Aluminum/Magnesium/Silicon Alloys—6xxx Series

The aluminum/magnesium/silicon alloys (6xxx series) are heat-treatable. The 6xxx series base alloys, typically containing around 1.0% magnesium silicide Mg_2Si, cannot be arc welded successfully without filler alloy. These alloys can be welded with 4xxx series (Al/Si) or 5xxx series (Al/Mg) filler alloys depending on weld performance requirements. It is important to dilute the Mg_2Si percentage in the base material with sufficient filler alloy to reduce weld metal crack sensitivity.

4.1.4 Crack Sensitivity

When we consider the aluminum alloys that fall into this difficult-to-weld category, we can divide them into different groups. We will first consider the small selection of aluminum alloys, which were designed for machinability not weldability. Alloys such as 2011 and 6262, which contain 0.20–0.6 Bi, 0.20–0.6 Pb and 0.40-0.7 Bi, 0.40–0.7 Pb, respectively. The edition of these elements (Bismuth and Lead) to these materials greatly assists in chip formation in these free machining alloys. However, because of the low solidification temperatures of these elements, they can seriously reduce the ability to produce sound welds in these materials.

Figure 4.1—Gas Metal Arc Welding on an Aluminum Wheel Uses 5454 Base Material Welded with an ER5554 Filler Alloy that is Made Specifically to Match the Base Alloy Content

There are a number of aluminum alloys that are quite susceptible to hot cracking if arc welded, these alloys are usually heat-treatable alloys and are most commonly found in the 2xxx series (Al-Cu) and 7xxx series (Al-Zn) groups of materials.

To understand why some of these alloys are unsuitable for arc welding (unweldable), we need to consider the reasons why some aluminum alloys can be more susceptible to hot cracking.

Hot cracking or solidification cracking occurs in aluminum welds when high levels of thermal stress and solidification shrinkage are present while the weld is undergoing various degrees of solidification. The hot cracking sensitivity of any aluminum alloy is influenced by a combination of mechanical, thermal, and metallurgical factors.

A number of high-performance, heat-treatable aluminum alloys have been developed by combining various alloying elements to improve the materials mechanical properties. In some cases the combination of the required alloying elements has produced materials with high hot cracking sensitivity.

4.1.4.1 Coherence Range

Perhaps the most important factor affecting the hot crack sensitivity of aluminum welds is the temperature range of dendrite coherence, plus the type and amount of liquid available during the freezing process. Coherence is when the dendrites begin to interlock with one another to the point that the melted material begins to form a mushy stage.

The coherence range is the temperature between the formation of coherent interlocking dendrites and the solidus temperature. This could be referred to as the mushy range during solidification. The wider the coherence range, the more likely hot cracking will occur because of the accumulating strain of solidification.

4.1.4.2 The 2xxx Series Alloys (Al-Cu)

Hot cracking sensitivity in the Al-Cu alloys increases as we add up to approximately 3% Cu and then decreases to a relatively low level at 4.5% Cu and above. Alloy 2219 with 6.3% Cu shows good resistance to hot cracking because of its relatively narrow coherence range. Alloy 2024 contains approximately 4.5% Cu which may initially encourage us to suppose that it would have relatively low crack sensitivity. However, alloy 2024 also contains a small amount of Magnesium (Mg). The small amount of Mg in this alloy depresses the solidus temperature but it does not affect the coherence temperature, therefore the coherence range is extended and the hot cracking tendency is increased. The problem to be considered when welding 2024 is that the heat of the welding operation will allow segregation of the alloying constituents at the grain boundaries and the presence of Mg, as stated above, will depress the solidus temperature. Because these alloying constituents have lower melting phases, the stress of solidification may cause cracking at the grain boundaries and/or establish the condition within the material conducive to stress corrosion cracking later. High heat input during welding, repeated weld passes, and larger weld sizes can all increase the grain boundary segregation problem (segregation is a time-temperature relationship) and subsequent cracking tendency.

4.1.4.3 The 7xxx Series Alloys (Al-Zn)

The 7xxx series of alloys can also be separated into two groups as far as weldability is concerned. These are the Al-Zn-Mg and the Al-Zn-Mg-Cu types. Al-Zn-Mg Alloys such as 7005 will resist hot cracking better and exhibit better joint performance than the Al-Zn-Mg-Cu alloys such as 7075. The Mg content in this group (Al-Zn-Mg) of alloys would generally increase the cracking sensitivity. However, Zr is added to refine grain size and this effectively reduces the cracking tendency. This alloy group is easily welded with the high magnesium filler alloys such as 5356, which ensures the weld contains sufficient magnesium to prevent cracking. Silicon based filler alloys such as 4043 are not generally recommended for these alloys because the excess Si introduced by the filler alloy can result in the formation of excessive amounts of brittle Mg_2Si particles in the weld.

Al-Zn-Mg-Cu Alloys such as 7075 have small amounts Cu added. The small amounts of Cu, along with the Mg, extend the coherence range and therefore increase the crack sensitivity. A similar situation can occur with these materials as with the 2024 type alloys. The stress of solidification may cause cracking at the grain boundaries and/or establish the condition within the material conducive to stress corrosion cracking later.

It should be stressed that the problem of higher susceptibility to hot cracking from increasing the coherence range is not only confined to the welding of these more susceptible base alloys such as 2024 and 7075. Crack sensitivity can be substantially increased when welding incompatible dissimilar base alloys (which are normally easily welded to themselves) and/or through the selection of an incompatible filler alloy. For example; by joining a perfectly weldable 2xxx series base alloy to a perfectly weldable 5xxx series base alloy, or by using a 5xxx series filler alloy to weld a 2xxx series base alloy, or a 2xxx series filler alloy on a 5xxx series base alloy, we can create the same scenario. If we mix the high Cu and high Mg we can extend the coherence range and therefore increase the crack sensitivity.

4.1.5 Groove Weld Tensile Strength

Typically the HAZ of the groove weld dictates the strength of the joint, and many filler alloys can satisfy this strength requirement. However, two factors should be considered when developing welding procedures for the nonheat-treatable and the heat-treatable alloys.

For nonheat-treatable alloys, the area adjacent to the weld will be annealed completely. These alloys are annealed by heating to 600°F to 700°F [316°C to 371°C] for a short time. The welding procedure has little effect on the transverse ultimate tensile strength of the groove weld because the annealed HAZ typically is the weakest area of the joint. Welding procedure qualification for these alloys is based on the minimum tensile strength of the base alloy in its annealed condition.

Heat-treatable alloys must be heated for a longer time to fully reduce their strength. This typically does not occur during welding, and the strength of the HAZ will only be reduced partially. The amount of strength loss is both time and temperature-related in these alloys. The faster the welding process and heat dissipation, the smaller the HAZ will be and the higher the as-welded strength will be.

Excessive preheating, lack of interpass cooling, and excessive heat input all increase peak temperature and time at temperature. These factors alone or the use of too small a specimen to provide adequate heat sink can create overheating so that minimum strength values are not met.

Unlike groove welds, fillet weld strength largely depends on the composition of the filler alloy. The joint strength of fillet welds is based on shear strength, which can be affected considerably by the filler alloy.

In structural applications, the selection between 5xxx series filler or 4xxx series filler may not be so significant regarding groove welds' tensile strength. However, this may not be the case when considering the shear strength of fillet welds.

Typically, the 4xxx series filler alloys have lower ductility and provide less shear strength in fillet-welded joints. The 5xxx series fillers typically have more ductility and can provide close to twice the shear strength of a 4xxx series filler alloy in some circumstances.

Tests have shown that a required shear strength value in a fillet weld in 6061 base alloy required a 1/4 in [6.4 mm] fillet weld with 5556 filler, compared to a 7/16 in [11.11 mm] fillet with 4043 filler, to meet the same required shear strength. This can mean the difference between a one-run and a three-run fillet to achieve the same strength.

4.1.6 Ductility

Ductility is a property that describes the ability of a material to flow plastically before fracturing. Fracture characteristics are described in terms of ability to undergo elastic stretching and plastic deformation in the presence of stress raisers (weld discontinuities).

Increased ductility ratings for a filler alloy indicate greater ability to deform plastically and to redistribute load and thereby decrease the crack propagation sensitivity. Ductility may be a consideration if forming is performed after welding or if the weld is subjected to impact loading. It is considered when conducting bend tests during procedure qualifications.

The 4xxx series filler alloys and 6xxx series base alloys have relatively low ductility. This is addressed with special requirements within the code or standard relating to test sample thickness, bending radius and/or material condition.

4.1.7 Corrosion Resistance

Most unprotected aluminum base filler alloy combinations are satisfactory for general exposure to the atmosphere. When a dissimilar aluminum alloy combination of base and filler is used and electrolyte is present, galvanic action between the dissimilar compositions can occur.

The difference in alloy performance can vary based on the type of exposure. Filler alloy ratings typically are based on fresh and salt water exposure only. Corrosion resistance can be a complex subject. When welding in a specialized highly corrosive environment, it may be necessary to consult an engineer with experience within this field.

4.1.8 Service Temperature

Stress corrosion cracking is a condition that can result in premature weld failure. This condition can be developed through magnesium segregation at the grain boundaries of the material. This typically will only occur in alloys of more than 3% magnesium when exposed to prolonged elevated temperature (above 150°F [66°C]).

The 5356, 5183, 5654, and 5556 filler alloys all contain more than 3% Mg (typically around 5%). Therefore, they are not suitable for elevated temperature service. Alloy 5554 has less than 3% Mg and was developed for high-temperature applications.

Alloy 5554 is used for welding 5454 base alloy, which also is used for high-temperature applications. The Al/Si (4xxx series) filler alloys may be used for some service temperature applications depending on weld performance requirements (see Figure 4.2).

4.1.9 Postweld Heat Treatment

Typically, the common heat-treatable base alloys, such as 6061-T6, lose a substantial proportion of their mechanical strength after welding. For example, 6061-T6 typically has 45 000 psi tensile strength prior to welding and around 27 000 psi in the as-welded condition.

Note: The 4047 filler alloy is also suitable for temperature applications.

Figure 4.2—Automotive Components Welded with 4047 Filler Alloy Produces Welds that are Extremely Fluid and Easily Create Leak-Tight Joints

Consequently, on occasion, it's desirable to perform postweld heat treatment to return the mechanical strength to the manufactured component. When postweld heat treating, the filler alloy's ability to respond to the heat treatment should be evaluated.

Most of the commonly used filler alloys will not respond to postweld heat treatment without substantial dilution with the heat-treatable base alloy. This is not always easy to achieve and can be difficult to control consistently. For this reason, filler alloys have been developed to independently respond to heat treatment.

Filler alloy 4643 was developed for welding 6xxx series base alloys and developing high mechanical properties in the postweld heat-treated condition. It was developed by taking the well-known alloy 4043, reducing the silicon, and adding 0.10% to 0.30% magnesium.

Filler alloy 5180 was developed for welding 7xxx series base alloys. It falls within the Al/Zn/Mg alloy family and responds well to postweld thermal treatments. This alloy is used to weld 7005 bicycle frames and responds to heat treatment without dilution of the thin-walled tubing used for this high-performance application.

A number of other heat-treatable filler alloys are available for welding some of the heat-treatable cast aluminum alloys.

4.1.10 Conclusion

Selecting the most suitable filler alloy can only be achieved successfully after a full analysis of the many variables associated with welding of aluminum components and their applications. Firstly, consideration must be given to the type and chemistry of the base material to be welded, and secondly, consideration of the welded components performance requirements. Filler alloy selection for welding aluminum is an essential part of the development and qualification of a suitable welding procedure specification.

4.2 What Filler Alloy Should be Used to Weld 6061?

? I need to weld aluminum base metal 6061-T6. What filler metal should I use for welding this base material?

4.2.1 How to Choose the Best Filler Alloy

This question is characteristic of many I receive on a regular basis. The base metal type may vary but, in essence, the question remains the same: “How do I choose the most suitable filler metal for welding a particular base material?” A fundamental difference between arc welding of steel and aluminum is the evaluation method used during the filler metal selection process. Many aluminum base materials can be successfully welded with any number of different filler metals. For instance, 6061-T6, the base metal referenced in the above question, is commonly welded with at least four totally different filler metals and can be successfully welded with even more.

So how do you choose the filler metal that will work best? The answer is the most appropriate filler material cannot be selected with any certainty without understanding the welded component’s application and expected performance in service. When an aluminum filler metal is chosen, you need to ask yourself which of the variables associated with weld performance are most important. Also, recognition that the selection of filler metal that is not recommended for a specific application may result in inadequate service performance and possibly premature failure of the welded joint. Filler metals for arc welding aluminum are evaluated against the following variables:

1. **Ease of Welding.** This is the relative freedom from weld cracking. By use of hot cracking sensitivity curves for the various aluminum alloys, and through the consideration of dilution between filler metal and base metal, the filler metal/base metal crack sensitivity rating can be established.

2. **Strength of Welded Joint.** Consideration of the tensile strength of groove welds and shear strength of fillet welds, when welded with different filler metals, can prove to be extremely important during weld design. Different filler metals, which may both exceed the as-welded tensile strength of the base material, can be significantly different in shear strength performance.

3. **Ductility.** This is a consideration if forming operations are to be used during fabrication and may also be a design consideration for service if fatigue and/or shock loading are of importance.

4. **Corrosion Resistance.** This is a consideration for some environmental conditions and is typically based on exposure to fresh and salt water.

5. **Sustained Temperature Service.** The reaction of some filler metals at sustained elevated temperatures (above 150°F [66°C]). This may promote premature component failure due to stress corrosion cracking.

6. **Color Match.** Base metal and filler metal color match after anodizing can be of major concern in some cosmetic applications.

7. **Postweld Heat Treatment.** The ability of the filler metal to respond to postweld heat treatment associated with filler metal chemistry and joint design.

4.2.2 Making the Choice

As an example of the extent and complexity of this situation, let's take a look at one aluminum base metal and three of the many applications in which it may be used. If you consider the base metal in the original question, 6061-T6, and its use in the following applications, you can appreciate how the filler metal selected can seriously affect the component's performance.

1. The first application uses 6061-T6 tubing for a hand railing that is to be clear coat anodized after welding. You will need to select a filler metal that will provide the best color match after anodizing. With color match as the prime consideration, the most appropriate filler for this application is alloy 5356. If you selected filler metals 4043, 4047, or 4643, which are often shown as being suitable for this base material, you would find that after anodizing, the weld would become dark gray in color and would not provide a suitable match to the bright silver appearance of the hand rail tubing (see Figure 4.3).
2. The second application uses 6061-T6 extruded angle bar as a welded attachment bracket for a heating component that will be operating consistently at 250°F [121°C]. For this application, investigate filler metals suitable for elevated temperature service such as 5554, 4043, or 4047. If 5356, 5183, or 5556 filler metals are used, which are often shown as being suitable for this base material, the possibility of sensitization of magnesium in these metals would be introduced, running the risk of stress corrosion cracking and premature failure of the welded component.

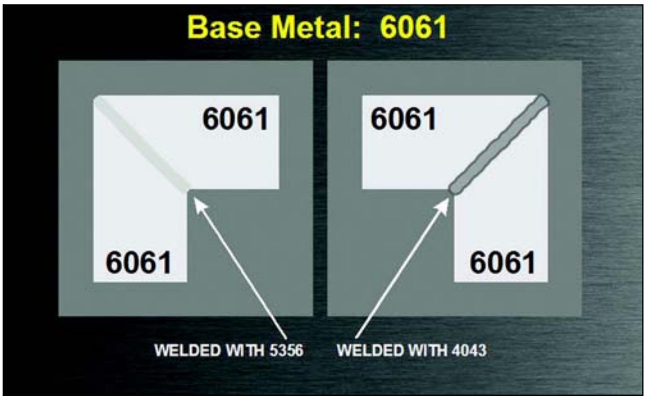


Figure 4.3—Weld Made Using 6061-T6 Base Metal and 4043 Filler Metal Would Not Produce a Good Color Match After Anodizing

3. The third application uses 6061-T6 to fabricate a large safety-critical lifting device that is required to undergo extensive welding during fabrication, followed by postweld solution heat treatment and artificial aging to restore strength and return the structure to the -T6 temper. For this application, our concern would be the strength of the weld after it has been exposed to postweld heat treatment. Most filler metals commonly used for welding this base material will not respond favorably to this type of heat treatment. The 5356, 5183, and 5556 filler metals are nonheat-treatable alloys that may undergo undesirable changes if subjected to this form of heat treatment. The 4043 filler metal, on its own, is nonheat-treatable and would be totally dependent on dilution with the base material to achieve any significant response to the heat treatment. For this application, you should seriously consider the use of filler metal 4643, which is a heat-treatable filler metal and will, therefore, respond to the heat treatment after welding and provide a weld of comparable strength to that of the base material.

4.2.3 Conclusion

Each variable specific to your application should be evaluated in detail to establish the most suitable filler metal. Fortunately, there are aluminum filler metal selection charts available that have been developed to help you make the most appropriate filler metal choice. These charts have been developed through careful consideration of all the variables and often provide a rating system for each variable to help with the selection process. If you are unsure what the most suitable filler metal is, consult the experts (see also the Filler Alloy Selection Chart in Section 4.8).

4.3 What are the Advantages of 4047 Filler Alloy over 4043?

? I have been informed that there is a filler metal, 4047, that can sometimes be used in lieu of the commonly used filler metal 4043. What are the advantages of using the 4047 filler metal and when would it make sense to substitute it for 4043?

4.3.1 The Difference Between 4043 and 4047 Filler Alloys

You are correct that there is a filler metal 4047. The filler metal 4047 was originally developed as a brazing alloy (BAlSi-4 or 718), taking advantage of its low melting point and narrow freezing range (1070°F to 1080°F [577°C to 582°C]). The main difference between 4043 and 4047 is the silicon content of these alloys. The 4043 filler metals contain 4.5% to 6.0% silicon and the 4047 contain 11.0% to 13.0%. The higher silicon additions in the 4047 alloy result in improved fluidity (wetting action) during the welding operation. This characteristic has proven itself to be extremely desirable when welding thinner materials that are required to have leak-tight joints. Welding procedures used in the heat exchanger fabrication industry have been improved by changing from 4043 to 4047 filler metal. The 4047 provides exceptional fluidity, which helps to reduce weld leakage rates during the manufacturing process, thereby substantially improving productivity. Additional benefits from the 4047 filler metal over the 4043 are minimization of solidification cracking and slightly higher fillet weld shear strength. Other advantages have been found in moving from 4043 to 4047. One such advantage is improved cosmetic appearance, particularly when welding thin material. The improved fluidity from the additional silicon within the 4047 filler metal can produce exceptionally smooth welds that are cosmetically pleasing.

In terms of AWS D1.2, *Structural Welding Code—Aluminum*, 4047 is acceptable as a replacement for 4043 as both of these filler metals have the same “F” number (F23). The 4047 filler metal, like the 4043, is suitable for elevated-temperature service. However, the same problem with both 4047 and 4043 can occur if postweld anodizing is to be performed. Because of their silicon content, both of these alloys will typically turn dark gray after anodizing, and for this reason, they are usually not recommended for products requiring this type of postweld surface treatment.

4.3.2 Conclusion

Both these silicon based filler alloys are generally accepted as being interchangeable. However, the 4047 does have some characteristics that may be used to your advantage on some types of applications.

4.4 What is the Correct Filler Alloy for Welding 5083 Base Alloy, and is the Filler Alloy I am Using the Reason Why I am Failing the Guided-Bend Tests?

? I have a situation where my customer is experiencing failures in their guided-bend tests. The base metal is 5083 and the filler metal is ER5556. The test plate is a 5-mm-thick single groove weld with a 70° included angle, no root opening, and a 2 mm nose. The weld is backgouged and welded from the second side. We are not sure if we are using the correct welding wire; our welding equipment supplier has suggested that we change to an ER5356 type wire. What is your professional advice on this issue?

4.4.1 What is the Most Appropriate Filler Alloy?

Base Alloy 5083 can be successfully welded with filler metals 5356, 5183, or 5556; any of these three filler metals may be suitable for welding this base alloy. The reason to choose one of these filler metals over the others depends on the application and service requirements of the component being welded.

Used in a number of applications, base alloy 5083 aids in shipbuilding, cryogenic tanks, military vehicles, and structural fabrications, just to name a few.

The 5356 filler is normally used only on 5083 base alloy when there is no requirement for groove weld welding procedure qualifications, in accordance with the Structural Welding Code; this is because the 5083 base/5356 filler combination will typically not obtain the minimum tensile strength requirements of the code (40 ksi [276 MPa]) for groove weld transverse tensile strength. The 5356 filler metal is often used on the slightly lower strength 5086 base alloy and will typically obtain its required minimum transverse tensile strength for groove welds (35 ksi [241 MPa]).

The 5183 and the 5556 filler alloys will both typically meet the code tensile strength requirements for groove welds in 5083 base alloy. Developed specifically for welding the 5083 base alloy, the 5183 filler meets the mechanical property requirements for groove weld procedure qualification. The 5556 base alloy, with slightly higher mechanical properties than the 5183, will meet the minimum requirements for the 5083 base alloy. The 5556 filler alloy was developed for obtaining slightly higher tensile strength requirements (42 ksi [290 MPa]) of groove welds in 5456 base alloy.

In my opinion, the filler alloy selection is not the problem causing the guided-bend test failures; however, I do think you need to understand the application/welding standard requirements when selecting the most appropriate filler alloy.

4.4.2 Why Did the Welded Samples Fail the Guided-Bend Test?

Start by considering the actual test itself and the differences between testing aluminum and other more common materials, such as steel, with this testing method.

Utilized for many years, the guided-bend is a common method of testing the integrity of welds made in many different material types. The guided-bend test is relatively quick and is usually a comparatively economical method of establishing the soundness of a groove weld. Where properly used, it can be very revealing; however, in order for the test results to be of meaningful importance when testing aluminum, it is imperative that the testing methods implemented be thoroughly understood.

There are various types of bend tests used to evaluate welds. Guided-bend specimens may be longitudinal or transverse to the weld axis and may be of the root bend, face bend, or side bend type. The type of bend test (root, face, or side) used is determined by which surface of the weld sample (root, face, or side) is on the convex (outer) side of the bent specimen and, consequently, subjected to tension load during the testing operation. Probably the most common combination of bend tests used for welder performance and welding procedure test samples are two transverse root bend tests and two transverse face bend tests per test plate.

4.4.3 Reasons Why a Welded Sample May Fail the Guided-Bend Test

4.4.3.1 Discontinuities in the Welded Joint

The most obvious reason a welded sample may fail a guided-bend test is because it has been weakened by the presence of significant discontinuities. The test helps determine whether the weldment tested contains discontinuities such as cracks, incomplete fusion, inadequate penetration, or severe porosity. If significant discontinuities in the weldment were present, we would expect the bend test sample to fail. If inspected after testing, it is often possible to identify the type and extent of discontinuity present in the weldment.

If this were the reason for your bend test failure, you would need to evaluate your welding procedure and make the necessary adjustments to improve the weld integrity.

4.4.3.2 Using an Incorrect Testing Fixture

The most common way to conduct guided-bend testing of welded steel samples is the use of a die and plunger arrangement, often referred to as the plunger-type guided-bend test fixture. Using the plunger-type guided-bend test fixture for testing aluminum is not appropriate. The heat-affected zones of welds in aluminum alloys can be significantly softer and weaker than the surrounding material. If these welds bend around a plunger, the bend sample may bend sharply in the heat-affected zones and kink and/or break without adequately bending the weld metal, resulting in a test failure. To avoid test failures, always use the wraparound bend test fixture for testing aluminum. This testing method forces the test specimen to bend progressively around a pin or mandrel so that all portions of the weld zone achieve the same radius of curvature and, therefore, the same strain level.

4.4.3.3 Improper Sample Preparation

You should be concerned about bend test sample preparation prior to bending. A common mistake is to leave the corners of the sample square. Most codes allow up to a 1/8-in [3-mm] radius on the corners of the test specimens. For best results, samples should have rounded corners, a smooth surface, and be free of sharp notches that may provide stress concentration during the bending operation.

4.4.4 Conclusion

With complete understanding and proper use, the guided-bend test can be a very effective testing method for aluminum weldments. It is difficult to say why you are having this problem without knowing the extent of sample preparation, seeing the test samples before and after testing, and knowing the testing fixture used. I hope you are able to use the information here to investigate your problem further and successfully resolve it.

4.5 Should I Use 4043 or 5356 Filler Alloy?

? With regard to the most appropriate filler metal to use on a particular aluminum fabrication project, the most common question is, “Should I use a 4043 or a 5356 filler metal?”

4.5.1 Choosing Between 4043 and 5356

Occasionally, I find misconceptions within the aluminum welding industry. One such erroneous belief is that you can successfully weld all aluminum base alloys with either 4043 or 5356 filler metal. This is not correct, and there are often applications where other filler materials are required to produce welding procedures suitable to the requirements.

However, I understand how this misunderstanding could take place. The most commonly used aluminum filler metals within the industry are, by far, 4043 and 5356. In addition, many commonly used structural aluminum base alloys can be welded with either 4043 or 5356. The 5xxx series base alloys with less than 2.5% magnesium (Mg) such as 5052, a commonly used material, can be welded successfully with both the 4043 or 5356 filler metal. The 6xxx series (Al-Mg-Si) base alloys, such as 6061 and 6063, which are extensively used in aluminum fabrication, can be welded with either the 4043 or the 5356 filler metals. If the filler metal selection chart (see Figure 4.4) lists both 4043 and 5356 as acceptable for a particular base material, how do you choose between the two? As a guide, consider the following facts about each of these popular filler metals before making your choice:

- As a basic description, 4043 is an aluminum filler metal with 5% silicon added and 5356 is an aluminum filler metal with 5% magnesium added.
- If you want the best color match after postweld anodizing, 4043 is not a good choice because it will typically turn dark gray in color after the anodizing process. A much closer color match after anodizing will be provided by 5356, particularly on the 6xxx series base alloys (see Figure 4.3).
- For service temperatures above 150°F [66°C], 4043 is appropriate. However, 5356, because of its 5% magnesium content, is not suitable for prolonged elevated-temperature applications and, if used in such environments, may result in premature failure of the welded structure (see Figure 3.10).
- In the as-welded condition, 4043 has a lower ductility than that of 5356. If forming after welding, consider this fact when choosing the appropriate filler metal. In addition, if 4043 is used, special bending requirements may be necessary when conducting guided-bend tests for welding procedure and welder performance qualification (see 4.1 6 and 5.5.3).
- The shear strength of 4043 is lower than that of 5356. This is important when calculating the size of fillet welds. The typical transverse shear strength of 4043 is around 15 ksi [103 MPa], and the shear strength of 5356 is around 26 ksi [179 MPa] when loaded in the same transverse direction. These differences are substantial and, if not fully understood and taken into consideration, may affect the service performance of a welded structure (see Table 4.1).
- When compared to 5356, 4043 is a softer alloy in the form of spooled welding wire. Typically, when gas metal arc welding (GMAW), feedability will not be as critical when feeding the more rigid 5356 alloy. Feedability of any aluminum welding wire, when compared to steel, can be an issue, especially with the smaller-diameter wires. The less rigid alloys, such as 1100 and 4043, can compound this problem (see 6.2.1).
- For welding any of the magnesium base metals (5xxx series) that contain more than 2.5% Mg, such as 5086 or 5083 materials, 4043 is not recommended. The 5% silicon in the 4043 filler metal when combined with the higher magnesium in these base alloys can produce undesirable mechanical properties in the weld.
- For weldability and slightly lower crack sensitivity, 4043 will typically provide a higher rating. Also, 4043 will also generally produce welds with improved cosmetic appearance, smoother surfaces, less spatter, and less smut. For this reason, 4043 is sometimes more appealing to the welder.

4.5.2 Conclusion

There are many aluminum base metals that provide the option of welding with either 4043 or 5356 filler metal. However, based on the facts listed above, understand and select the most appropriate filler metal for the job. The application and service conditions of the finished welded structure is generally a governing factor, and will often dictate the most suitable filler metal selection.

Use a filler metal selection chart to assist with choosing the most appropriate filler metal. In addition, conduct procedure qualification testing to evaluate the filler metal selected, and verify its performance characteristics. AWS D1.2, *Structural Welding Code—Aluminum*, is an excellent resource for welding procedure development and testing.

4.6 Are the 4xxx Series Aluminum Alloys Heat-Treatable Alloys or Nonheat-Treatable Alloys?

I recently received a letter asking for an explanation about the heat treatment ability of the 4xxx series alloys. The letter stated that there was a discrepancy in the way the writer was taught and an article he had read. He had been instructed that the 4xxx series alloys are nonheat-treatable alloys only. However, the article said that some 4xxx series aluminum alloys could be heat-treatable alloys. The writer was looking for clarification on the subject.

4.6.1 Postweld Heat Treatment

I would like to address this issue and hope this will clear up any preconceived beliefs about the heat-treatable and nonheat-treatable 4xxx series aluminum alloys. The 4xxx series alloys are most often encountered when they are being used as filler material within the welding or brazing processes. The most common of these alloys are 4043 and 4047. The 4043, which is a 5.0% Si (silicon) alloy, is extensively used as a welding filler metal. The 4047, which is a 12.0% Si alloy, is used for welding and brazing. Both of these 4xxx series alloys are nonheat-treatable. To be precise, these alloys alone will not respond to precipitation hardening. Consideration may be required when using these nonheat-treatable filler metals if it is our intent to weld a heat-treatable base material such as the 6xxx series alloys or one of the heat-treatable cast aluminum alloys such as 356.0 or 357.0, and then perform postweld heat treatment, such as solution heat treatment and/or artificial aging. The heat-treatable 4xxx series aluminum alloys are most often encountered when involved with the postweld heat treatment of the welded, heat-treatable, aluminum base alloys. Typically, the heat-treatable base alloys, such as 6061-T6, lose a substantial proportion of their mechanical strength after welding. For example, 6061-T6 typically has 45 000 lb/in^2 tensile strength prior to welding and around 27 000 lb/in^2 in the as-welded condition. Consequently, on occasion, it may be desirable to perform postweld heat treatment to return the mechanical strength to the manufactured component. When postweld heat treating, the filler metal's ability to respond to the heat treatment must be evaluated.

It is important to understand that the common 4xxx series filler metals, such as 4043 and 4047, are not heat-treatable and these filler metals may or may not respond to heat treatment when deposited as weld metal. Their response to postweld heat treatment is largely dependent on the welding procedure used and whether the filler metal can obtain a sufficient amount of alloying elements from the base material during welding. Consistent results after heat treatment may be difficult to achieve from the nonheat-treatable filler metals because of the number of variables within the welding procedure that affect the amount of base dilution during welding.

When performing postweld heat treatment on a welded heat-treatable base alloy, it may be important to consider using a filler metal that is heat-treatable. The heat-treatable filler metal 4643 was designed for welding 6xxx series base alloys and developing high mechanical properties in the postweld heat-treated condition. It was formulated by taking the well-known Alloy 4043, reducing the silicon, and adding 0.10% to 0.30% magnesium. This modification to its chemistry produces a 4xxx series alloy, which will form the magnesium silicide compound required to respond to postweld heat treatment.

Other heat-treatable 4xxx series filler metals have been developed for some of the cast aluminum base alloys. Alloys 356.0 and A356.0 (Al-Si-Mg) are used in large quantities for sand and permanent mold castings. A variety of heat treatments can be used to produce the desired combinations of mechanical properties in these castings. Alloy A356.0 has a lower iron content than 356.0, which, in effect, provides higher tensile properties in premium quality castings. Alloy A356.0 filler wire is optimum for joining and repairing both 356.0 and A356.0 castings. Alloy A356.0, when fabricated as a wrought wire product, is registered by The Aluminum Association as the heat-treatable alloy 4010. Filler metal 4008 is also available; this is a tightly controlled chemistry version of the A356.0 (4010) alloy and is heat-treatable. The 4008 alloy is generally formulated to meet the requirements of AMS 4181 specification.

Aluminum casting Alloys 355.0, A355.0, and C355.0 (Al-Si-Cu-Mg) are alloyed with copper to afford a greater response to heat treatment. Alloy C355.0 contains a low amount of iron to create higher tensile properties in premium-quality castings. Aluminum filler metal C355.0 was designed for joining and repairing 355.0, A355.0, and C355.0 castings. Alloy A355.0, when fabricated as a wrought wire product, is registered by The Aluminum Association as heat-treatable Alloy 4009. Alloy 4145 is one other 4xxx series metal that is alloyed with copper and is therefore heat treatable.

4.6.2 Conclusion

Aluminum Alloys within the 4xxx series group are both heat-treatable and nonheat-treatable alloys. The primary difference is that the nonheat-treatable alloys contain aluminum with silicon as the principal alloying element with no other elements added that could allow heat treatability. The heat-treatable 4xxx series alloys contain silicon and also controlled additions of magnesium and/or copper, which provide the material the opportunity to respond to, and increase its strength through, heat treatment.

4.7 Which Aluminum Filler Alloys are Suitable for Sustained High-Temperature Service?

? I am looking for some assistance with the selection of the most suitable filler alloy for a particular gas metal arc welded aluminum structure. The application is a structural component used for material handling manufactured from 6061-T6 in material thicknesses of 1/8 in to 1/2 in. The joint design is fillet welds. Special operating considerations are the welding filler alloy should be suitable for sustained high-temperature application (250°F [121°C]) provide good structural integrity, and suitable feedability characteristics. This component is to be used in the as-welded condition and will not undergo any postweld heat treatment.

4.7.1 Introduction

The sustained high-temperature application (above 150°F [66°C]) requirement for this component is probably your main consideration and will definitely influence your filler alloy selection. Also, as this component is intended to be used for handling material and the welds being used are fillet welds, I would most certainly consider the shear strength characteristics of the filler alloy.

The high service temperature requirement eliminates the use of any filler alloy with more than 3% Mg, such as the frequently used 5356 and the higher-strength filler alloys 5183 and 5556. This provides you with 4643, 4043, 4047, and 5554 as possible filler alloys for your application.

4.7.2 Evaluation of Most Appropriate Filler Alloy

Let us evaluate each of these four filler alloys based on their features and characteristics. Considerations are relating to the four filler alloys that may be used for this application—4643, 4043, 4047, and 5554.

4.7.2.1 Filler Alloy ER4643

This filler alloys was developed for welding 6xxx series base alloys and developing high mechanical properties in the postweld heat-treated condition. This alloy was produced by taking the well-known Alloy 4043, reducing the silicon, and adding 0.10% to 0.30% magnesium, thus ensuring its ability to respond to postweld heat treatment. This is a premium filler alloy that is priced for its specialized characteristics and would not normally be used unless postweld heat treating was being performed. Since you stated that postweld heat treatment is not to be used, I would see no reason to use this alloy.

4.7.2.2 Filler Alloy ER4043

While the 4043 filler alloy, a 5% silicon alloy, is often used to weld 6061 base metals, it is not commonly used when shear strength of the component is a predominant consideration. The 4043 filler alloy is a silicon-based filler alloy that is often used to take advantage of the element's capability of promoting fluidity in aluminum. While groove welds can be made using this filler alloy that can characteristically pass minimum transverse tensile test requirements, this filler metal has considerably lower shear strength when compared to the 5xxx series filler alloys.

4.7.2.3 Filler Alloy ER4047

Like the 4043 filler alloy, 4047 is a silicon-based alloy, but has a much higher level of silicon, approximately 12%. The extra silicon within the alloy provides exceptional fluidity. This alloy, which is also registered as a brazing alloy, is most often used for leak-tight joints in thin-wall applications. The 4047 filler alloy has a very narrow freezing range and, consequently, is very resistant to solidification cracking. The 4043 and 4047 filler alloys have very similar mechanical characteristics, with 4047 having slightly higher tensile strength. Both 4043 and 4047 have lower ductility and lower shear strength properties than the 5xxx series filler alloys. They also possess lower column strength when compared to the 5xxx series filler alloys and, consequently, require extra care during feeding to minimize feedability problems.

4.7.2.4 Filler Alloy ER5554

The 5554 filler metal was designed to provide the improved strength and ductility characteristics of a magnesium-based filler metal that was also suitable for elevated-temperature applications. It contains 2.4% to 3.0% magnesium, thereby providing an alloy that is not susceptible to stress corrosion cracking, but has improved shear strength and improved ductility when compared to the 4xxx series filler metals. In addition to the improved mechanical properties of 5554 on the completed weld, we see an increase in the column strength of the wire. This characteristic can distinctly improve the wire's feedability. The 5554 filler metal will typically produce a weld that is not quite as cosmetically appealing as the 4xxx series filler metals and has a slightly greater potential for producing "smut" (a black deposit of metal oxides that is not harmful to the weld).

4.7.3 Conclusion

1. Filler alloy 4643 was designed for its postweld heat treatment capabilities and is therefore not particularly suited for your application.
2. Filler alloys 4043 and 4047 have considerably lower shear strength values when compared to 5554.
3. Filler alloys 4043 and 4047 wires have considerably lower tensile (column) strengths and require more care when feeding, when compared to 5554.
4. Filler alloy 4047 may provide some advantages over 4043—enhanced fluidity, the possibility of faster welding speeds, and lower heat input. This filler alloy may be a consideration for thinner components and produces excellent leak-tight joints.
5. Filler alloy 5554 will typically provide welds of higher strength, but with lower cosmetic appeal when compared to the 4xxx series filler alloys.

Table 4.1—Minimum Shear Strength Values for Aluminum Filler Alloys

Filler Alloy	Shear Strength (ksi)
1100	7.5
2319	16.0
4043	11.5
4047	13
4643	13.5
5183	21.0
5356	17.0
5554	17.0
5556	20.0
5654	12.0

Note: These minimum shear strength values are divided by a safety factor when used to design the size of welds for aluminum structures.

4.8 Filler Alloy Selection Chart

The choice of a filler alloy for aluminum welding is based on the operating conditions of the welded component and consideration of the variables that can affect the operating condition of the weld. The following filler alloy selection chart (Figure 4.4) compares the performance of each filler alloy against these variables.

1. **W—Ease of Welding.** This is the relative freedom from weld cracking and is based on the probability of creating a chemistry in the weld that would be susceptible to solidification cracking.
2. **S—Strength of Welded Joint.** This is an evaluation based on a comparison of fillet weld shear strength. Any rating indicates that the filler alloy is capable of providing the minimum transverse tensile strength as described in AWS D1.2, *Structural Welding Code—Aluminum*.
3. **D—Ductility.** This is based on the free bend elongation of the weld.
4. **C—Corrosion Resistance.** This is based on continuous or alternative immersion in fresh or salt water.
5. **T—Sustained Temperatures.** This is based on the filler alloys suitability for use in applications of sustained temperatures above 150°F [65.5°C].
6. **M—Color Match.** This is based on the filler alloys ability to provide a good color match, when compared to the base alloy, after the weldment has been anodized.

Base Alloys	Filler Alloys	1060 1070 1080 1350						1100						2014 2036						2219						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	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	B	B	A	A	A	A	B	B	A	A	A	A	B	B	A	A	A	A	A	A	A	A	A	A
	4145	A	A	B	A	A	A	A	A	B	A	A	A	A	B	C	B	A	A	A	B	C	B	A	A	A	A	B	A	A	A	A	A	B	A	A	A	A	A	B	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	B	B	A	A	A	A	B	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	B	A	A	A	A
	4145	A	A	B	B	A		A	A	B	B	A		A	A	B	A	A		A	A	B	A	A		A	A	B	B	A																			
	A356.0																																																
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		A	B	C	A	A		A	D	C	B	A		A	B	C	B	A		B	D	C	B	A	
	4145													A	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	B	A	B	A		A	B	A	B	A		A	A	A	B	A		A
	5356	B	A	A	A		A	B	A	A	A		A													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	B	A	B	A		A	B	A	B	A		A	A	A	B	A		A
	5654																															C	C	A	A		B	C	A	A	A		A	B	C	A	A		A
6061 6070	4043/4047	A	A	C	A	A		A	A	C	A	A		B	B	A	A	A		B	B	A	A	A		A	B	C	A	A		A	D	C	A	A		A	B	C	A	A		A	D	C	A	A	
	4145	A	A	D	B	A		A	A	D	B	A		A	A	B	A	A		A	A	B	A	A		A	A	D	B	A		B	C	D	B	A		A	B	D	B	A							
	4643 (1)																																																
	5183	B	A	B			A	B	A	B			A													B	A	B			A	B	A	B			A	B	A	B			A	B	A	B	C		B
	5356	B	A	A			A	B	A	A			A													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			A	B	A	B			A	B	A	B	C		B
	5654																																											C	C	A	B		A
6005, 6063, 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		A	B	C	A	A		A	D	C	A	A		A	B	C	A	A		A	D	C	A	A	
	4145	A	A	D	B	A		A	A	D	B	A		A	A	B	A	A		A	A	B	A	A		A	A	D	B	A		B	C	D	B	A		A	B	D	B	A							
	4643 (1)																																																
	5183	B	A	B			A	B	A	B			A													B	A	B			A	B	A	B			A	B	A	B			A	B	A	B	C		B
	5356	B	A	A			A	B	A	A			A													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			A	B	A	B			A	B	A	B	C		B
	5654																																											C	C	A	B		A
5454	5183	B	A	B	B		A	B	A	B	B		A													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	A	A	B		A													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	A	A	A	A	A													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	B	A	B	B		A	B	A	B	B		A	A	A	B	B		A
	5654																																											B	C	A	B		B
511.0, 512.0, 513.0, 514.0, 535.0, 5154, 5254	5183	B	A	B	B		A	B	A	B	B		A													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	A	A	B		A													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	A	A	A		A													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	B	A	B	B		A	B	A	B	B		A	A	A	B	B		B
	5654	C	A	A	A		B	C	A	A	A		B													C	A	A	A		B	C	C	A	A		B	C	A	A	A		B	B	C	A	A		A
5086, 5056	5183	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
	5356	A	A	A	A		A	A	A	A	A		A													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	A	A	B	A		A	A	A	B	A		A
	5654																																											B	C	A	A		B
5083, 5456	5183	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
	5356	A	A	A	A		A	A	A	A	A		A													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	A	A	B	A		A	A	A	B	A		A
	5654																																											B	C	A	A		B
5052, 5652	4043/4047	A	B	C	A	A		A	B	C	A	A														A	B	C	A	A		A	B	C	A	A		A	B	C	A	A		A	D	C	B	A	
	5183	B	A	B			A	B	A	B			A													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	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	B	A	B			A	B	A	B			A	A	A	B	C		B
	5654																																											B	C	A	B		A
5005, 5050	1100	C	B	A	A	A	A	C	B	A	A	A	A													C	C	A	A	A	A							B		A	A	A	A	1100					
	4043/4047	A	A	C	A	A		A	A	C	A	A														A	B	C	A	A		A	B	C	A	A		A	B	D	A	A		4043/4047					
	4145	B	A	D	B	A		B	A	D	B	A														B	B	D	B	A														4145					
	5183	C	A	B			B	C	A	B			B													C	A	B	C		B	B	A	B			A	B	A	C			B	5183					
	5356	C	A	B			B	C	A	B			B													C	A	B	C		B	B	A	A			A	B	A	B			B	5356					
	5556	C	A	B			B	C	A	B			B													C	A	B	C		B	B	A	B			A	B	A	C			B	5556					
3004	1100	D	B	A	A	A	A	D	B	A	A	A	A													C	C	A	A	A	A							1100											
	4043/4047	A	A	C	A	A		A	A	C	A	A														A	B	C	A	A		A	B	D	A	A		4043/4047											
	4145	B	A	D	B	A		B	A	D	B	A														B	B	D	B	A								4145											
	5183	C	A	B			B	C	A	B			B													C		B	C		A	B	A	C	C		A	5183											
	5356	C	A	B			B	C	A	B			B													C	A	B	C		A	B	B	B	C		A	5356											
	5554																															C	C	A	B	A	A	5554											
	5556	C	A	B			B	C	A	B			B													C		B	C		A	B	A	C	C		A	5556											
3003 ALCLAD 3003	1100	B	B	A	A	A	A	B	B	A	A	A	A													B	B	A	A	A	A	1100																	
	4043/4047	A	A	B	A	A		A	A	B	A	A		B	A	A	A	A		B	A	A	A	A		A	A	B	A	A		4043/4047																	
	4145	A	A	C	B	A		A	A	C	B	A		A	A	B	A	A		A	A	B	A	A		A	A	C	B	A		4145																	
2219	2319													B	A	A	A	A	A	A	A	A	A	A	A	2319																							
	4043/4047	B	A	A	A	A		B	A	A	A	A		B	C	B	C	A		B	C	B	C	A		4043/4047																							
	4145	A	A	B	A	A		A	A	B	A	A		A	B	C	B	A		A	B	C	B	A		4145																							
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																													
	4145	A	A	B	A	A		A	A	B	A	A		A	B	C	B	A		4145																													
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																																			
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Figure 4.4—Aluminum Filler Alloy Chart

5083 5456						5086 5056						511.0 512.0 513.0 514.0 535.0 5154 5254						5454						6005 6063 6101 6151 6201 6351 6951						6061 6070						7005 7121 7039 7046 7146 710.0 711.0						413.0 443.0 444.0 356.0 A356.0 A357.0 359.0						319.0 333.0 354.0 355.0 C355.0 380.0						
W	S	D	C	T	M	W	S	D	C	T	M	W	S	D	C	T	M	W	S	D	C	T	M	W	S	D	C	T	M	W	S	D	C	T	M	W	S	D	C	T	M	W	S	D	C	T	M	W	S	D	C	T	M	
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																								A	A	B	A	A	A	A	A	B	A	A	A	A	A	B	A	A	A	A	A	B	A	A	A	A	B	B	B	A	A	4145
																								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
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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
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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
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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
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A	B	A	A		A	A	B	A	A		A	A	B	A	B		A																																					5356
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B	C	A	A		B	B	C	A	A		B	B	C	A	A		A																																					5654
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**Figure 4.4 (Continued)—
Aluminum Filler Alloy Chart**

Symbol	Characteristic
W	**Ease of welding** (relative freedom from weld cracking)
S	**Strength of welded joint** (as-welded condition). (Rating applies particularly to fillet welds. All rods and electrodes rated will develop presently specified minimum strengths for butt welds.
D	**Ductility** (Rating is based upon the free bend elongation of the weld)
C	**Corrosion resistance** in continuous or alternative immersion in fresh or salt water
T	Recommended for service at **sustained temperatures** above 150°F (65.5°C)
M	**Color match** after anodizing

A, **B**, **C**, and **D** are relative ratings in decreasing order of merit. The ratings have relative meaning only within a given block.

How to Use

1. Select base alloys to be joined (one from the side blue column, the other from the top blue row).
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.

Note: Combinations having no rating are not usually recommended. Ratings do not apply to these alloys when heat treated after welding.

(1) 4643 is a heat-treatable filler alloy and gives higher strength in 6xxx series weldments after postweld solution heat treatment and aging.

(2) An "A" rating for alloy 5083 to 5083 and 5083 to 5456. No rating for alloy 5456 to 5456.

4047 can be used in lieu of 4043. Alloy 4047 provides increased fluidity for welding leak-tight joints, minimizes solidification cracking, and has a slightly higher fillet weld shear strength.

Chapter 5

Welding Discontinuities and Weld Testing

5.1 How to Avoid Cracking in Aluminum Alloys

5.1.1 Introduction

The majority of aluminum base alloys can be successfully arc welded without cracking related problems, however, using the most appropriate filler alloy and conducting the welding operation with an appropriately developed and tested welding procedure is significant to success. To appreciate the potential for problems associated with cracking, it is necessary to understand the many different aluminum alloys and their various characteristics. Having this advance knowledge will help avoid cracking situations.

5.1.2 The Primary Cracking Mechanism in Aluminum Welds

There are a number of cracking mechanisms associated with the welding of metallic alloys. One of the most notorious is hydrogen cracking, also referred to as cold cracking. Hydrogen cracking is often a major concern when welding carbon steels and high-strength, low-alloy steels. However, when welding aluminum alloys hydrogen cracking cannot occur.

Hot cracking is the cause of almost all cracking in aluminum weldments. Hot cracking is a high-temperature cracking mechanism and is mainly a function of how metal alloy systems solidify. This cracking mechanism is also known as hot shortness, hot fissuring, solidification cracking, and liquation cracking.

There are three areas that can significantly influence the probability for hot cracking in an aluminum welded structure. They are susceptible base alloy chemistry, selection and use of the most appropriate filler alloy and choosing the most appropriate joint design.

Aluminum crack sensitivity curves are a helpful tool for understanding why aluminum welds crack and how the choice of filler alloy and joint design can influence crack sensitivity. The diagram shows the effects of four different alloy additions—Silicon (Si), Copper (Cu), Magnesium (Mg), and Magnesium Silicide (Mg_2Si)—on the crack sensitivity of aluminum. The crack sensitivity curves (Figure 5.1) reveal that with the addition of small amounts of alloying elements, the crack sensitivity becomes more severe, reaches a maximum, and then falls off to relatively low levels. After studying the crack sensitivity curves, it is easy to recognize that most of the aluminum base alloys considered unweldable autogenously (without filler alloy addition) have chemistries at or near the peaks of crack sensitivity. Additionally, the Figure 5.1 shows alloys that display low cracking characteristics have chemistries well away from the crack sensitivity peaks.

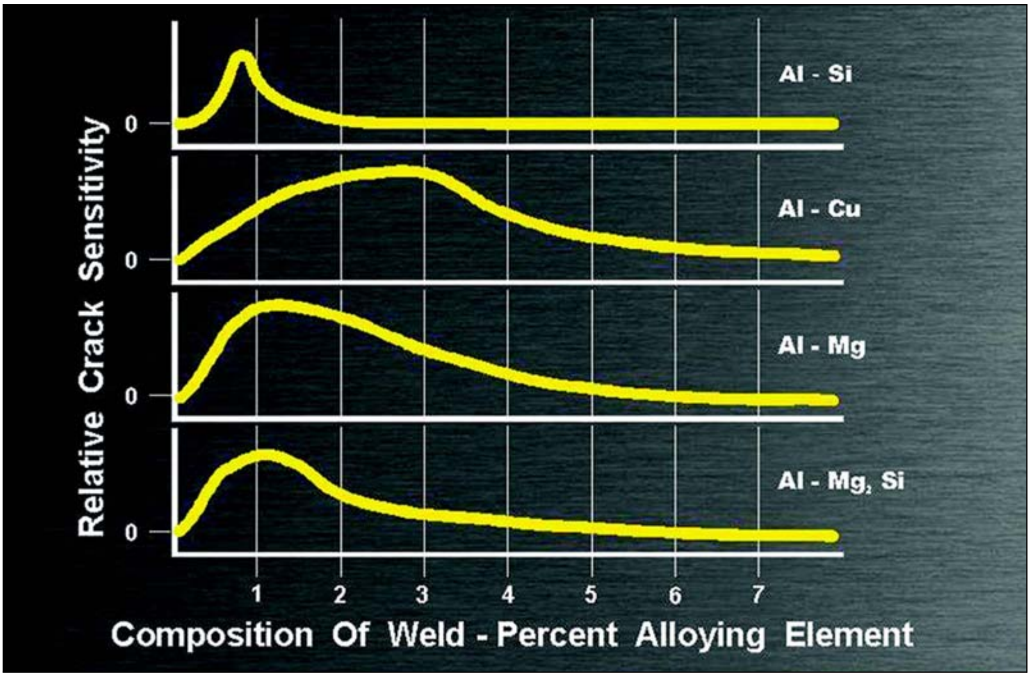


Figure 5.1—The Effects of Four Different Alloy Additions on the Crack Sensitivity of Aluminum

Based on these facts, it is clear that crack sensitivity of an aluminum base alloy is primarily dependent on its chemistry. Utilizing the same principals, it can be concluded that the crack sensitivity of an aluminum weld, which is generally comprised of both base alloy and filler alloy, is also dependent on its chemistry.

With the knowledge of the importance of chemistry on crack sensitivity of an aluminum weld, two fundamental principals apply that can reduce the incidence for hot cracking. First, when welding base alloys that have low crack sensitivity, always use a filler alloy of similar chemistry. Second, when welding base alloys that have high crack sensitivity, use a filler alloy with a different chemistry than that of the base alloy to create a weld metal chemistry that has low crack sensitivity. When considering the welding of the more commonly used 5xxx series (Al-Mg) and the 6xxx series (Al-Mg-Si) aluminum base alloys, these principals are clearly illustrated.

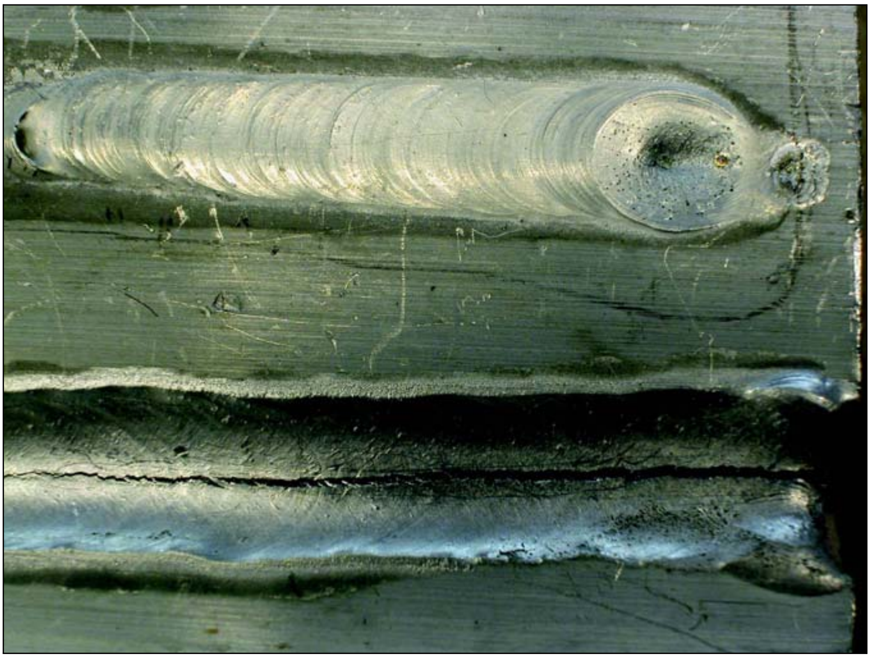
5.1.2.1 The 5xxx Series Alloys (Al-Mg)

The majority of the 5xxx base alloys, which contain around 5% Mg, show low crack sensitivity. Often welded autogenously (without filler alloy), these alloys are easy to weld with a filler alloy that has slightly more Mg than the base alloy. This can provide a weld with excellent crack resistance and a solidification temperature a little lower than the base alloy. These alloys should not be welded with a 4xxx series filler alloy as exercise amounts of magnesium silicide can form in the weld and produce a joint with undesirable mechanical properties.

There are base alloys within this group, such as 5052, that have a Mg content that falls very close to the crack sensitivity peak. In the case of the 5052 base alloy with around 2.5% Mg, definitely avoid autogenous welding. The Mg base alloys with below 2.5% Mg, such as 5052 can be welded with both the 4xxx filler alloys, such as 4043 or 4047 and the 5xxx filler alloys such as 5356. When welding base alloys with below 2.5% Mg it is necessary to change the chemistry of the solidifying weld from the high crack peak level of the base alloy. We alter the chemistry of the weld by selecting a filler alloy with a much higher content of Mg, such as 5356 (5.0% Mg) or with the addition of silicon in the case of 4043.

5.1.2.2 The 6xxx Series Alloys (Al-Mg-Si)

The aluminum/magnesium/silicon base alloys (6xxx series) are of a chemistry that makes them crack sensitive because the majority of these alloys contain approximately 1.0% Magnesium Silicide (Mg_2Si), which falls close to the peak of the solidification crack sensitivity curve. The Mg_2Si content of these materials is the primary reason there are no 6xxx series filler alloys. Using a 6xxx series filler alloy or autogenously welding would invariably produce cracking problems in the weld (see Figure 5.2). During arc welding, the cracking tendency of these alloys is adjusted to acceptable levels by the dilution of the base material with excess magnesium (by use of the 5xxx series Al-Mg filler alloys) or excess silicon (by use of the 4xxx series Al-Si filler alloys).



Notes:

1. The top weld was deposited with no filler alloy, and then subjected to liquid penetrant testing. The testing method revealed many fine linear indications (cracks) within the surface of the weld.
2. The lower weld was also deposited without filler alloy, and excessive heat input during welding resulting in a much more obvious cracking situation.

Figure 5.2—Hot Cracking in 6xxx Series Alloys

Particular care is necessary when TIG (GTAW) welding on thin sections of this type of material. It is often possible to produce a weld, particularly on outside corner joints, without adding filler material by melting both edges of the base material together. However, in the majority of arc welding applications with this base material, the addition of filler material is required to create consistent crack free welds. One possible exception would be counteracting the cracking mechanism by maintaining a compressive force on the parts during the welding operation. This requires specialized fabrication techniques and considerations. For this reason, the method is seldom used.

The most appropriate and successful method used to prevent cracking in the 6xxx series base materials is to ensure adequate filler alloy is added during the welding operation.

Other considerations when welding this group of alloys (6xxx) are the effect of joint design on base alloy and filler alloy dilution as well as the weld profile relating to susceptibility to cracking. Square groove welds in this material are extremely vulnerable to cracking because very little filler alloy mixes with the base material during welding. It is frequently necessary to evaluate the use of a v-groove weld preparation, which will introduce more filler alloy to the weld metal mixture and lower the crack sensitivity. In addition, concave fillet welds that have reduced throat thickness and concave root passes in butt welds may have a tendency to crack (see Figure 5.3).

Note: The reduction in throat thickness at the termination and for a portion of the fillet weld has allowed the stresses developed during welding to fracture the weld.

Figure 5.3—Cracking in Fillet Weld Terminations

There are a few other potential problems with solidification cracking when welding and cutting the 6xxx series alloys, two others in particular that we should be aware.

If we apply excessive amounts of heat together with deep weld penetration to a relatively thin material, we can create a situation where partial melting can actually occur that is away from the weld pool. As noted earlier, this "chemistry" is almost certain to crack upon solidification because of the lack of adequate filler metal. Figure 5.4 shows a 6061-T6 tube with a longitudinal crack in the base metal that is on the opposite side from the weld.

The susceptibility of the 6xxx series alloys to solidification cracking is recognized by AWS D1.2, *Structural Welding Code—Aluminum*, which requires that 18 in [3 mm] of material shall be removed from plasma arc cut edges by machining when the cut edge is to be incorporated into the immediate weld area. The heat of the plasma cutting melts this area, and cracking develops upon solidification. Figure 5.5 shows the edge of a plasma cut 6xxx series plate with solidification cracking.

5.1.3 Further Considerations

The crack sensitivity curves provide an excellent guide to the probability of hot cracking, however, there are other issues to consider to understand cracking in aluminum alloys. One of these issues is the effect of alloying elements other than the principal alloying elements addressed in the crack sensitivity curves. Most certainly, some alu-

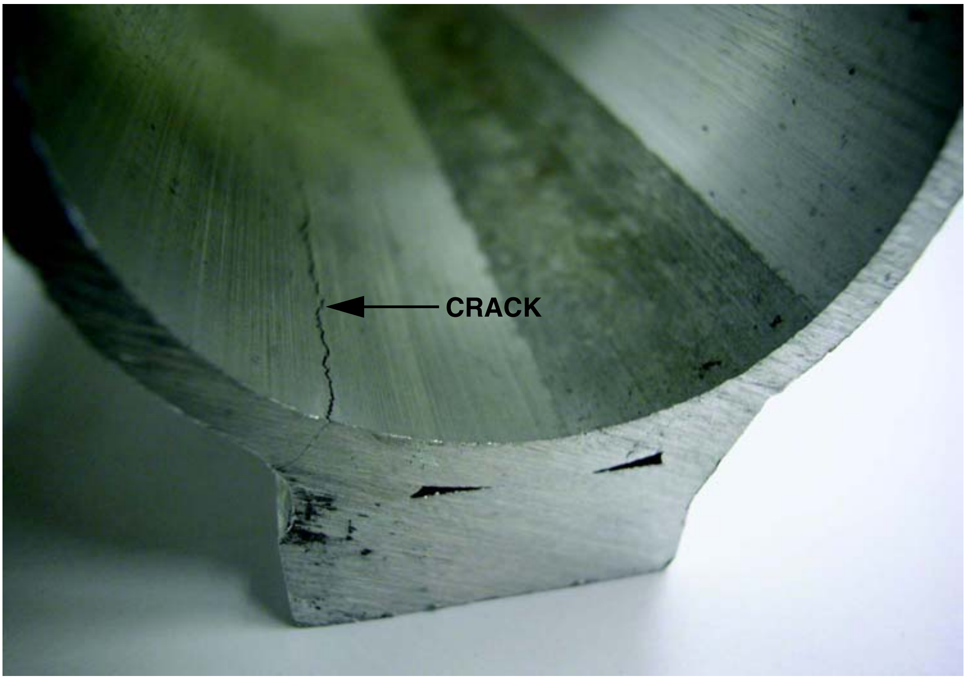
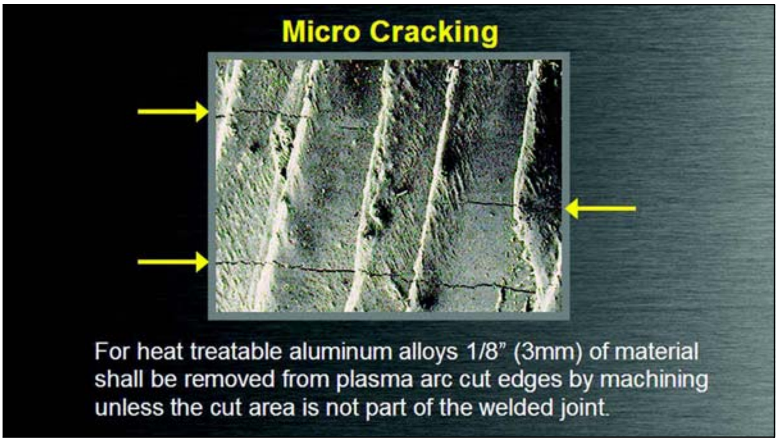


Figure 5.4—A Longitudinal Crack Can be Seen in the Inside of this Pipe on the Opposite Side of the Fillet Weld



Micro Cracking

For heat treatable aluminum alloys 1/8” (3mm) of material shall be removed from plasma arc cut edges by machining unless the cut area is not part of the welded joint.

Figure 5.5—Microcracking Can Develop on the Edge of a 6xxx Series Plate During Plasma Cutting

minum base alloys can be difficult to weld and lead to cracking problems, especially without complete understanding of their properties and/or if inappropriately handled. In fact, some aluminum base alloys are unsuitable for arc welding, and for this reason they are usually joined mechanically by riveting or bolting. These aluminum alloys can be difficult to arc weld without encountering problems during and/or after welding. These problems are usually associated with cracking, most often, hot cracking and on occasion, stress corrosion cracking (SCC).

The aluminum alloys that fall into this difficult-to-weld category can be divided into different groups. Always be aware of the small selection of aluminum alloys designed for machinability, not weldability. Such alloys are 2011 and 6262, which contain 0.20–0.6 Bi, 0.20–0.6 Pb and 0.40–0.7 Bi, 0.40–0.7 Pb, respectively. The addition of the elements (Bismuth and Lead) to these materials provides excellent chip formation in these free machining alloys. However, because of the low solidification temperatures of these elements, they can seriously reduce the ability to produce sound welds in these materials. In addition to the free machining alloys referenced above, other aluminum alloys can be quite susceptible to hot cracking if arc welded. These alloys are usually heat-treatable and are most commonly found in the 2xxx series (Al-Cu), and 7xxx series (Al-Zn) groups of materials.

To understand why some of these alloys are unsuitable for arc welding, it is necessary to consider the reasons why some aluminum alloys can be more susceptible to hot cracking.

Hot cracking, or solidification cracking, occurs in aluminum welds when high levels of thermal stress and solidification shrinkage are present while the weld is undergoing various degrees of solidification. The combination of mechanical, thermal, and metallurgical factors will influence the hot cracking sensitivity of any aluminum alloy. By combining various alloying elements, many high-performance, heat-treatable aluminum alloys have been developed to improve the materials’ mechanical properties. In some cases, the combination of the required alloying elements has produced materials with high hot cracking sensitivity.

5.1.3.1 Coherence Range

Hot cracking of aluminum alloy welds is influenced metallurgically by the temperature range of dendrite coherence and the type and amount of liquid available during solidification. Metal has very low strength and practically no ductility when in the "mushy" temperature range between that where coherent interlocking dendrites first form and the solidus. Tensile stresses above this low strength cause failure by tearing or hot cracking. The wider the coherence range the greater the tendency to hot crack because solidification shrinkage strains are proportional to the temperature interval over which solidification occurs.

5.1.3.2 The 2xxx Series Alloys (Al-Cu)

Hot cracking sensitivity increases in the Al-Cu alloys when adding approximately 3% Cu; however, it then decreases to a relatively low level at 4.5% Cu and above. Alloy 2219 with 6.3% Cu shows good resistance to hot cracking because of its relatively narrow coherence range. Alloy 2024 contains approximately 4.5% Cu causing the perception of having relatively low crack sensitivity. However, alloy 2024 also contains a small amount of Magnesium (Mg). The small amount of Mg in this alloy depresses the solidus temperature, but it does not affect the coherence temperature; therefore, the coherence range extends and the hot cracking tendency increases. The problem when welding 2024 is that the heat of the welding operation will allow segregation of the alloying constituents at the grain boundaries, and the presence of Mg, as stated above, will depress the solidus temperature. Because these alloying constituents have lower melting phases, the stress of solidification may cause cracking at the grain boundaries and/or establish the condition within the material conducive to stress corrosion cracking later. High heat input during welding, repeated weld passes, and larger weld sizes can all increase the grain boundary segregation problem (segregation is a time-temperature relationship) and subsequent cracking tendency.

5.1.3.3 The 7xxx Series Alloys (Al-Zn)

The 7xxx series of alloys, when considering weldability, contain two separate groups: the Al-Zn-Mg and the Al-Zn-Mg-Cu types.

5.1.3.4 Al-Zn-Mg Alloys

Al-Zn-MG Alloys such as 7005 will resist hot cracking better and exhibit superior joint performance than the Al-Zn-Mg-Cu alloys such as 7075. The Mg content in this group (Al-Zn-Mg) of alloys would normally increase the cracking sensitivity. However, adding Zr to refine grain size effectively reduces the cracking tendency. This alloy group welds easily with the high magnesium filler alloys such as 5356, which ensures the weld contains sufficient magnesium to prevent cracking. The recommendation of silicon-based filler alloys, such as 4043, for these alloys is not desirable because the excess Si introduced by the filler alloy can result in the formation of excessive amounts of brittle Mg_2Si particles in the weld.

5.1.3.5 Al-Zn-Mg-Cu Alloys

Al-Zn-Mg-Cu Alloys such as 7075 have small amounts of Cu added. The small amounts of Cu, along with the Mg, extend the coherence range and, therefore, increase the crack sensitivity. A similar situation can occur with these materials as with the 2024 type alloys. The stress of solidification may cause cracking at the grain boundaries and/or establish the condition within the material conducive to stress corrosion cracking later.

5.1.4 Be Aware

The problem of higher susceptibility to hot cracking from increasing the coherence range is not only confined to the welding of these more susceptible base alloys, such as 2024 and 7075. Crack sensitivity can be substantially increased when welding incompatible dissimilar base alloys (which are normally easily welded to themselves) and/or through the selection of an incompatible filler alloy. For example, by joining a perfectly weldable 2xxx series base alloy to a perfectly weldable 5xxx series base alloy, or by using a 5xxx series filler alloy to weld a 2xxx series base alloy, or a 2xxx series filler alloy on a 5xxx series base alloy, we can create the same scenario. If we mix high Cu and high Mg during the welding operation, we can extend the coherence range and, therefore, increase the crack sensitivity.

5.1.5 Conclusion

Avoid hot cracking in aluminum alloys by applying one or more of the following appropriate principals:

- Avoid the extremely crack sensitive base materials that are generally accepted as being nonweldable.
- Use a suitable filler alloy selection chart for selecting the most appropriate filler alloy for the specific base alloy, thereby avoiding the critical chemistry ranges (crack sensitivity ranges) in the weld.
- Select a filler alloy with a solidification point close to or below that of the base material.
- Select the most appropriate edge preparation and root gap to permit sufficient filler alloy material addition thus creating a weld metal chemistry outside the critical chemistry range.
- To counteract cracking problems, use reputable filler alloys that have grain refiners added, such as titanium or zirconium.
- Use the highest welding speed possible. The faster the weld is conducted, the faster the cooling rate and the less time the weld is in the hot cracking temperature range.
- Try to use welding and assembly sequences and techniques that minimize restraint, reduce residual stress and produce welds of acceptable profile.
- Apply a compressive force on the welded joint during welding to counteract the cracking mechanism.

5.2 Why am I Experiencing Cracking Problems in 6061 Welds When Using Both the GMAW and GTAW Processes?

I am experiencing a weld cracking problem on our gas tungsten arc welding (GTAW) production line where we weld thinner sections of 6063-T6 sheet material. We are often required to perform outside corner welds where we sometimes use little or no R4043 filler material, depending on joint fit up. Why do you think the welds are cracking? Why do only some of them crack?

I am also having cracking problems with my aluminum groove weld procedures. I am gas metal arc welding (GMAW) a 6061-T6 base material, 3/8 in [10 mm] thick, with a square edge preparation. The welds crack immediately after welding. The cracks are located in the center of the welds and run along the welds' length. I am using ER5356 filler material.

5.2.1 Crack Sensitivity

The above two questions are associated with a form of cracking that may occur when welding some aluminum base alloys. This problem, which is relatively common, is associated with solidification crack sensitivity and is, in turn, directly related to the actual chemistry of the weld pool. To appreciate this problem, we need to understand that the additions of various alloying elements can seriously affect aluminum's crack sensitivity. The specific alloying elements can be identified along with the amount or range at which these elements increase solidification crack sensitivity. This information can be obtained from solidification crack sensitivity curves (Figure 5.1) and used during welding procedure development to prevent undesirable chemistry mixtures in the weld. Consideration should also be given, when evaluating the cause of cracking, to any differences associated with weld size and variations in tensile stresses introduced by shrinkage, joint expansion, or externally applied loads.

5.2.2 Cracking in GTAW Welds and Why the Welds May be Cracking

We should start by considering the crack sensitivity of 6xxx series base material. Aluminum/magnesium/silicon base alloys (6xxx series) are of a chemistry that is crack sensitive because they contain approximately 1.0% magnesium silicide (Mg_2Si), which falls close to the peak of the solidification crack sensitivity curve—Figure 5.1 at the Al-Mg_2Si curve. The Mg_2Si content of these materials is the primary reason no 6xxx series filler metals are made. The cracking tendency of these alloys is lowered to acceptable levels during arc welding by dilution of the weld pool with excess magnesium (by use of 5xxx series Al-Mg filler metals) or excess silicon (by use of 4xxx series Al-Si filler metals). When Gas Tungsten Arc Welding thin materials, it is often possible to produce a weld, particularly on corner joints, by melting both edges of the base material together without adding filler material. In the majority of arc welding applications with this base material, we must add filler material if we want consistently crack-free welds. A possible exception would be counteracting the cracking mechanism by maintaining a compressive force on the parts during the welding operation, which requires specialized fabrication techniques and considerations. This method, however, is seldom used.

I suspect the welds in question that do not crack are those that have had filler material added during welding. My advice for reducing crack sensitivity is for you to ensure filler metal is added to all welds.

5.2.3 Cracking in GMAW Welds and Why the Welds May be Cracking

If we consider the alloying effect of magnesium in aluminum, we see weld crack sensitivity increases sharply with an increased Mg content up to about 1.5% and then decreases with further Mg additions—Figure 5.1 at Al-Mg curve. With this problem, we must consider the effect of joint design on base metal and filler metal dilution. Square groove welds in this material can be particularly susceptible to cracking because very little filler metal is mixed with the base material during welding. If we examine Figure 5.6, we can see the difference in the amount of Mg in each of the joint designs. The square groove showing dilution of 20% of the 5% Mg found in the 5356 filler material plus 80% of the 1% Mg found in the 6061 base alloy provides a total Mg content in the weld of around 1.7%. In comparison, the single-bevel groove weld configuration has 60% of the 5% Mg in the filler metal and 40% of the 1% Mg found in the base metal and provides a much higher Mg content in the weld of around 3.2%.

If we look again at Figure 5.1, we can see at the Al-Mg curve there is considerable difference in crack sensitivity between a weld with 1.7% Mg and one with 3.2% Mg. The 1.7% Mg weld is marginally past peak crack sensitivity and the 3.2% weld is well beyond that point.

My recommendation is to evaluate the use of a V-groove weld preparation, which will introduce more filler metal into the weld metal mixture and lower crack sensitivity.

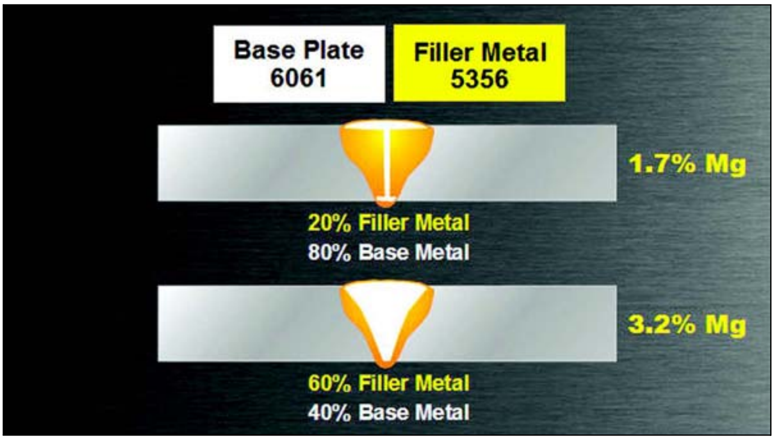


Figure 5.6—Dilution Effect on Weld Composition

5.2.4 Conclusion

The crack sensitivity of aluminum alloys are driven by the chemistry of the alloy being welded. The crack sensitivity of a aluminum weld which is often a mixture of base alloy and filler alloy is also driven by its chemistry. For this reason, we need to appreciate the critical chemistry ranges and design our welding procedures around them to avoid hazardous chemistries in our welds, and consequently reduce the probability for cracking.

5.3 Why is the Tensile Strength Too Low in my 6061 Welds?

? I am having problems passing a gas metal arc welding (GMAW) procedure qualification test for a groove weld with 6061-T6 base material. I am unable to obtain the minimum tensile strength the welding code requires. My guided-bend tests taken from the same weld test sample are passing and there do not appear to be any significant weld discontinuities within the sample. The transverse tension test specimens are failing in the heat-affected zone (HAZ), not the weld. However, the calculated tensile strength is lower than those shown in Table 3.2 of AWS D1.2:2003, *Structural Welding Code—Aluminum*. I am using the ER4043 filler metal and pure argon as my shielding gas.

5.3.1 Why the 6xxx Series Base Alloys Loss Strength After Welding and How This Condition Can be Minimized

This is a frequently asked question. Overheating of the base material during the welding process is the most common reason for a weld made in this base material without major discontinuities not to meet the minimum tensile requirement. To understand why this problem can occur, we must first understand the characteristics of the 6xxx series of base materials.

This is one of the heat-treatable series of aluminum alloys that acquires its strength through a process of thermal treatments. These alloys are often used in the -T6 condition, which indicates they have been solution heat-treated and artificially aged. The -T6 condition is achieved by heating the base material to a temperature of around 990°F [532°C]. This step in the operation is necessary to dissolve the major alloying elements into solution. The heating process is then followed by quenching, usually in water, to trap the alloying elements and produce a supersaturated solution.

In the case of the 6xxx series alloys, the major alloying elements are magnesium and silicon, which combine during the thermal treatment to form magnesium silicide. After solution heat treatment, the material is reheated to a lower temperature (around 320°F [160°C]) and held at temperature for a predetermined time. This second thermal treatment is termed artificial aging and is conducted to precipitate a portion of the elements or compounds back out of the supersaturated solution to enhance the mechanical properties of the material.

The controlled heat treatment conducted on these materials prior to welding to obtain the -T6 condition helps us to understand their response to the arc welding process, which heats the material to the same temperatures in an uncontrolled manner. As purchased, the 6061-T6 base material has a typical tensile strength of 45 ksi [310 MPa] before welding. AWS D1.2 recognizes the metallurgical changes that occur in this base material because of exposure to heat during arc welding and, consequently, requires a minimum tensile strength of 24 ksi [165 MPa]. The minimum tensile strength specified by the code is based on historical testing using a variety of welding procedures. If we consider the typical tensile strength of fully annealed 6061 as being 18 ksi [124 MPa], the importance of controlling the overall heat input during arc welding is clear. There is a direct association between total welding heat input and mechanical properties of the base material adjacent to the weld (the heat-affected zone) after welding. The higher the total heat input, the lower the tensile strength can be expected to fall (see Figure 5.7).

To meet the minimum tensile strength requirements of the code, the welding procedure must be closely controlled to prevent overheating of the base material. First, you must assess the size of the test samples being welded. The code provides minimum dimensions for groove weld test plate size. You must comply with this requirement or, if practical, use a larger test sample than specified. This will provide for superior heat sink and lower the possibility of excessive overheating and prolonged time at temperature within the HAZ. Secondly, comply with the preheating and interpass temperature requirements of the code. D1.2 specifies 250°F [121°C] as the maximum preheat and interpass temperature for this type of material. Also, observe the holding time at temperature requirement, which is not to exceed 15 minutes. If possible, conduct the certification testing without preheating or at lower preheating temperatures and

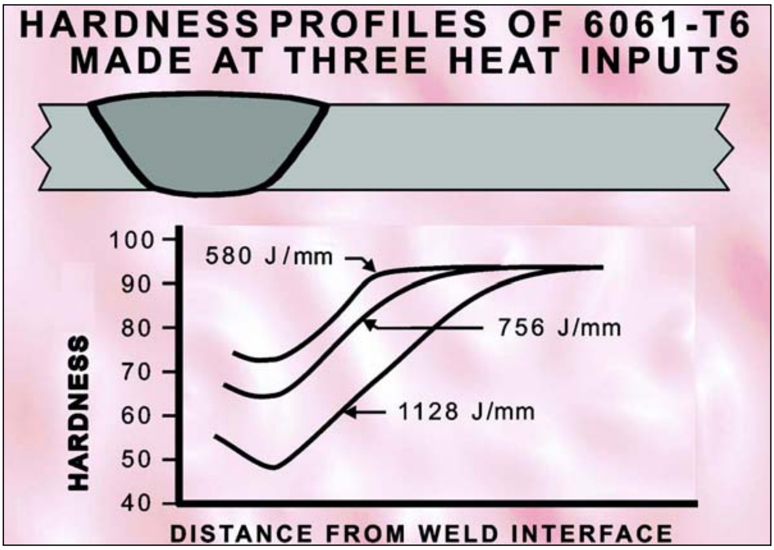


Figure 5.7—Reduction of Strength in the 6xxx Series Alloys After Welding and its Association with Overall Heat Input During Welding

allow the base material to cool to well below the maximum interpass temperature before welding is resumed.

A major contributor to the overall heat input of a weld is travel speed during the welding process. For this reason, it is preferable to select a welding sequence and technique that makes use of faster, stringer-type weld beads as opposed to slower weaving techniques. All of these recommendations apply to welding the 6061-T6 base materials with either a 4xxx or 5xxx series filler metal, regardless of shielding gas type or mixture.

5.3.2 Conclusion

The heat-treatable 6xxx series alloys are susceptible to significant loss in strength when arc welded in the T-6 condition. A certain amount of strength loss is unavoidable regardless of the welding procedure used when arc welding these materials. However, care needs to be taken to prevent excessive amounts of strength reduction by overheating the weldment during the welding operation.

5.4 How Do I Avoid Porosity Problems in Aluminum Welds?

? I am experiencing problems with porosity in my 5086/5356 aluminum welds. The porosity is being detected in groove welds by radiographic inspection and is outside the requirements of our acceptance criteria. What can I do to prevent this porosity problem?

5.4.1 How Does Porosity Occur

Unfortunately, there is seldom a quick answer for resolving problems associated with porosity in aluminum welds. The reason for this is that a number of conditions relating to material, consumables, welding technique, and/or equipment can cause porosity. It is often necessary to address this problem through a process of elimination, evaluating each of the potential problem areas to identify the true cause.

When investigating this type of problem, it is necessary to understand how porosity occurs and how to identify and eliminate these causes.

Porosity is a result of hydrogen gas becoming entrapped within the solidifying aluminum weld pool and leaving voids in the completed weld (see Figure 5.8). Hydrogen is highly soluble in molten aluminum, and for this reason, the potential for excessive amounts of porosity during arc welding of aluminum is considerably high. During the welding operation, it is easy to introduce hydrogen unintentionally through contaminants within the welding area. It is important to thoroughly understand the many sources of these contaminants to detect the cause and take the necessary action to resolve porosity problems.

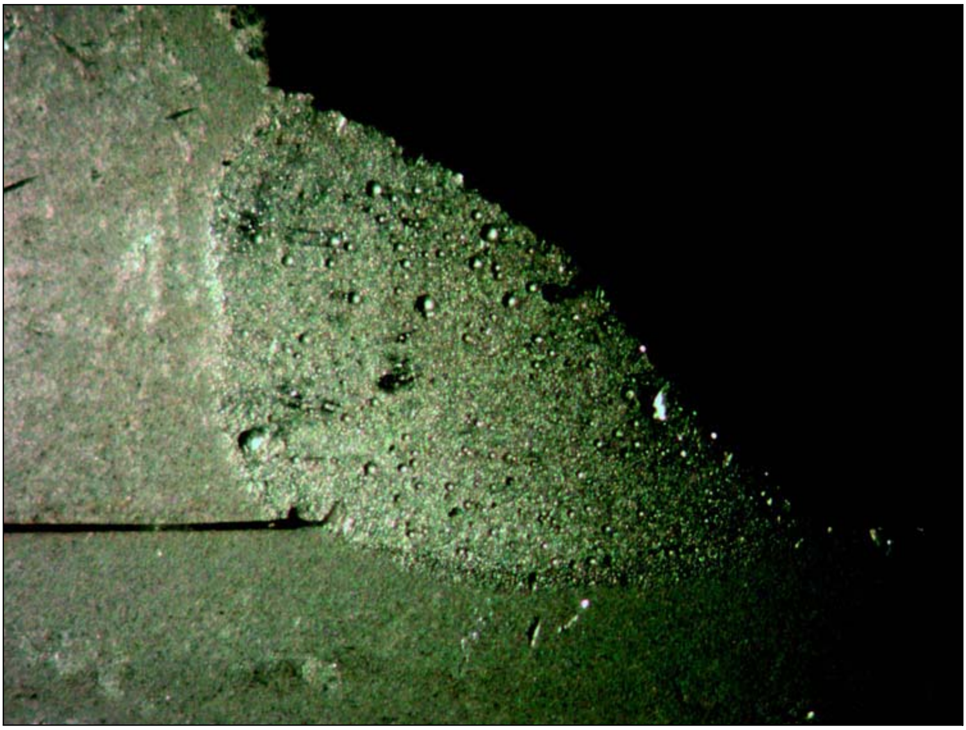


Figure 5.8—Porosity is Seen Here in a Cross Section of a Fillet Weld in Aluminum

5.4.2 Shielding During the Welding Operation

Exposure and contamination of the molten weld metal to the surrounding atmosphere during the welding operation is one consideration when examining a porosity problem. This situation may occur because of inadequate gas shielding during welding.

The following are some examples:

- *Welding in drafty conditions.* Strong drafts due to open doors or fans directed at the area of welding can remove the shielding gas during the welding operation.
- *Excessive spatter buildup inside the gas nozzle when gas metal arc welding.* This condition can restrict gas flow and reduce the efficiency of the shielding gas.
- *Incorrect standoff distance.* This is the distance from the end of the nozzle to the surface of the workpiece, and changes in this distance can produce significant variations in shielding gas efficiency.
- *Establishing and maintaining the correct shielding gas flow rate.* To provide the most efficient gas coverage, the flow rate should be high enough to ensure adequate shielding, but not so high that it causes turbulence in the weld pool during welding.

NOTE: By using argon/helium shielding gas mixtures, a reduction in porosity level is sometimes achievable. The advantage of the helium mixtures is the ability of this gas to provide additional heat during the welding process and, consequently, provide the hydrogen a greater opportunity to escape prior to solidification. The use of helium as an additive, sometimes up to 75%, can help to provide reduced porosity levels; however, the best line of defense against unacceptable porosity levels is to remove the source of (hydrogen) contamination.

5.4.3 Hydrocarbons

Hydrocarbons are sources of hydrogen and porosity, which may be present on the surface of the plate or on the welding wire.

The following are some examples:

- *Contamination of plate surfaces.* A thorough cleaning of plate surfaces that have hydrocarbons on them, such as lubricants, grease, oil, or paint, is necessary to remove contamination prior to welding.
- *Exhaust contaminants on the plate surface from compressed air tools used for weld preparation.* Make sure these tools do not exhaust contaminants, oil, and moisture onto the plate surface.
- *The quality and cleanliness of the aluminum welding wire.* Wire must be clean and free of any residual oil used during the wire manufacturing process. If the quality of the welding wire is inferior, it may be virtually impossible to produce acceptable porosity levels.
- *Anti-spatter compounds.* This type of material, applied to the welding nozzle or plate surface, is not usually recommended for aluminum welding when low levels of porosity are desired.

5.4.4 Moisture

Through a number of sources, moisture (H_2O), which contains hydrogen, can also be a source of contamination to the welding area.

The following are some examples:

- *Water leaks.* This occurs within the welding equipment if using a water-cooled welding system.
- *Inadequately pure shielding gas.* Shielding gas should meet the minimum purity requirements specified by the appropriate welding code or standard. Additionally, contamination of shielding gas may also occur from imperfections within the gas delivery line such as leaking pipes or hoses.
- *Condensation on plate and/or wire.* High humidity and change in temperature (crossing a dew point) can result in condensation on plate and/or wire. When weld-

ing in conditions of high humidity, it is relatively easy to acquire moisture from a rather small fluctuation in temperature (see Table 5.1).

Table 5.1—Dew Point Conditions vs. Relative Humidity

(T Air – T Metal) °F	Relative Humidity %
3.6	87
7.2	75
10.8	66
14.4	57
18.0	50
21.6	44
25.2	38
28.8	34
32.4	30
36.0	26
39.6	23
43.2	21
46.8	18
50.4	16

The temperatures listed in the left column are the required difference between the air temperature and the temperature of the aluminum wire or base plate in order to cross the dew point. As can be seen in the table, as the humidity increases, as shown in the right column, the difference between the air temperature and the aluminum required to produce moisture becomes much smaller. In very high humidity aluminum welding wire that is only slightly cooler than the air temperature can cross a dew point. This can result in the formation of moisture and possibly hydrated aluminum oxide. Manufacturers who perform high quality radiographic standard welding will usually store there welding wire in an area that is heated to slightly above the ambient temperature of the work area. Base plate is typically cleaned immediately prior to welding unfortunately it is not practical to clean the surface of GMAW wire.

- *Hydrated aluminum oxide.* This is another source of moisture and porosity. Aluminum has a protective oxide layer that is relatively thin and naturally forms on any exposed surface. Properly stored aluminum, with an uncontaminated thin oxide layer, can be easily welded with the inert gas (GMAW and GTAW) processes, which break down and remove the oxide during welding. When the aluminum oxide is exposed to moisture, potential problems with porosity arise. The aluminum oxide layer is porous and can absorb moisture, grow in thickness, and become a major problem when attempting to produce welds that are required to be relatively porosity free. This problem can occur on both the base material and welding wire.

5.4.5 Material Preparation Concerns

Other potential contamination problems are associated with material preparation. Cutting or grinding methods, which may deposit contaminants onto the plate surface or subsurface, cutting fluids, grinding disc debris, and saw blade lubricants are all areas of concern. Material preparation methods need to be evaluated as controlled elements of the welding procedure and not changed without revalidation. Certain types of grinding discs, for example, can deposit particles within the aluminum that will react during welding and cause major porosity problems. Additionally, aluminum filler material should be stored in an area that will prevent it from becoming contaminated by hydrocarbons or moisture.

5.4.6 Cleaning Prior to Welding

To achieve low porosity levels for x-ray quality welds, it is important to understand the methods available for the effective removal of hydrocarbons and moisture from the weld area, and to incorporate the appropriate methods into the welding procedure. If these contaminants are present in the weld area during welding, they will produce hydrogen and significantly contribute to porosity problems.

When designing welding procedures intended to produce low levels of porosity, it is important to incorporate degreasing and oxide removal. Typically, you can achieve this through a combination of chemical cleaning and/or the use of solvents to remove hydrocarbons followed by stainless steel wire brushing to remove contaminated aluminum oxide.

5.4.7 Conclusion

Determining the actual cause of porosity within a specific welding operation is not always a straightforward exercise. Without an understanding of the basic principles relating to this problem, it can be an extremely time-consuming and often a frustrating process. You must approach a porosity problem from an organized problem-solving standpoint, and work through the possibilities based on knowledge of the various sources of hydrogen, until the cause is found and eliminated.

The correct cleaning of the aluminum parts prior to welding, and the use of proven procedures, well-maintained equipment, high-quality shielding gas, and high-quality aluminum welding wire that is free from contamination are important in order to achieve low porosity levels.

5.5 Why am I Having Problems Passing Guided-Bend Tests with 6061 Base Alloy and 4043 Filler Alloy?

? I am having problems passing the guided-bend tests for my procedure qualification tests. I am working to AWS D1.2, *Structural Welding Code—Aluminum*. My base material is 6061-T6 and my filler metal is ER4043. I am using the plunger-type guided-bend jig. I am passing the reduced section tension tests on the same test specimen, and there would appear to be no relevant discontinuities in the weld and, therefore, no apparent reason for the bend tests to fail.

5.5.1 What is a Guided-Bend Test and When is it Used?

The guided-bend test has been around for many years and is a common method of testing the integrity of welds made in many different material types. Where properly used, it can be very revealing; however, when testing aluminum, the testing methods used must be thoroughly understood in order for the test results to be meaningful.

The guided-bend test is a relatively quick and, usually, a comparatively economical method of establishing the soundness of a groove weld. This test is designed to help determine whether the weldment tested contains discontinuities such as cracks, incomplete fusion, incomplete joint penetration, or severe porosity. Various types of bend tests are used to evaluate welds.

Guided-bend specimens may be longitudinal or transverse to the weld axis and may be of the root bend, face bend, or side bend type. The type of bend test (root, face, or side) is determined by which surface of the weld sample (root, face, or side) is on the convex (outer) side of the bent specimen and, consequently, subjected to tension load during the testing operation. Probably the most common combination of bend tests used for welder performance and welding procedure test samples are two transverse root bend tests and two transverse face bend tests per test plate.

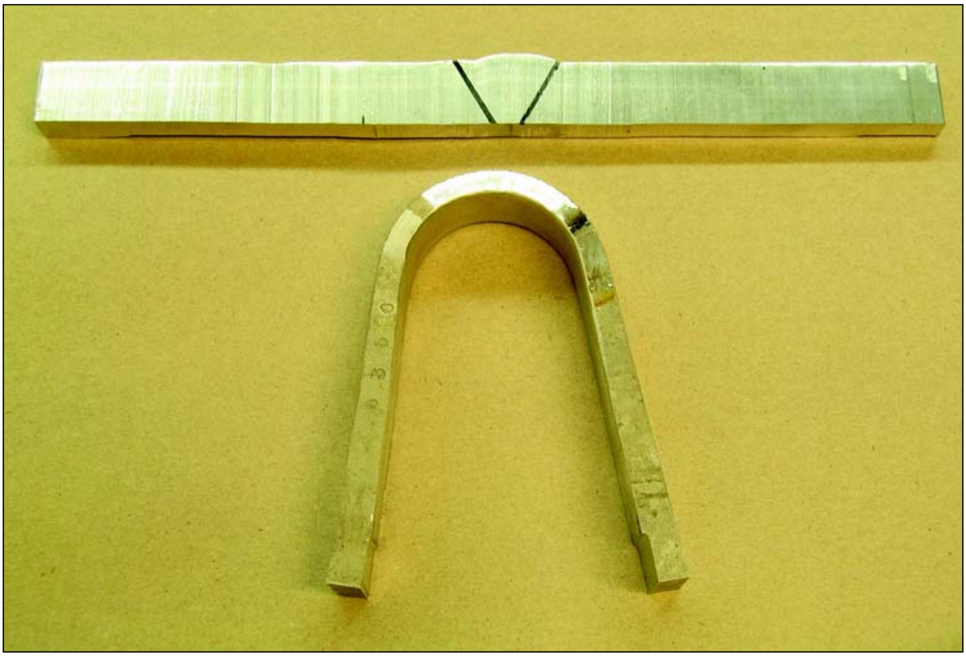
5.5.2 Bend Testing Aluminum is Different than Bend Testing Steel

Most guided-bend testing of steel is conducted with the use of a die and plunger arrangement often referred to as the plunger-type guided-bend test. The plunger-type guided-bend test is not recommended for testing aluminum. The heat-affected zones of welds in aluminum alloys, and particularly in the heat-treatable aluminum alloys, are significantly softer and weaker than the surrounding material. If these welds are bent around a plunger, the bend sample usually bends sharply in the heat-affected zones and kinks and breaks without adequately bending the weld metal, resulting in a test failure. To avoid such meaningless test failures, the wraparound bend test fixture should always be used for testing aluminum (see Figures 5.9, 5.10, and 5.11). This testing method forces the test specimen to bend progressively around a pin or mandrel so that all portions of the weld zone achieve the same radius of curvature and, therefore, the same strain level.

There are a number of other pitfalls to avoid when bend-testing aluminum. We should be concerned about bend test sample preparation prior to bending. A common mistake is to leave the corners of the sample square. Most codes allow up to a 1/8-in [3-mm] radius on the corners of the test specimens. For best results, samples should have a smooth surface, free of sharp notches that may provide stress concentration during the bending operation.

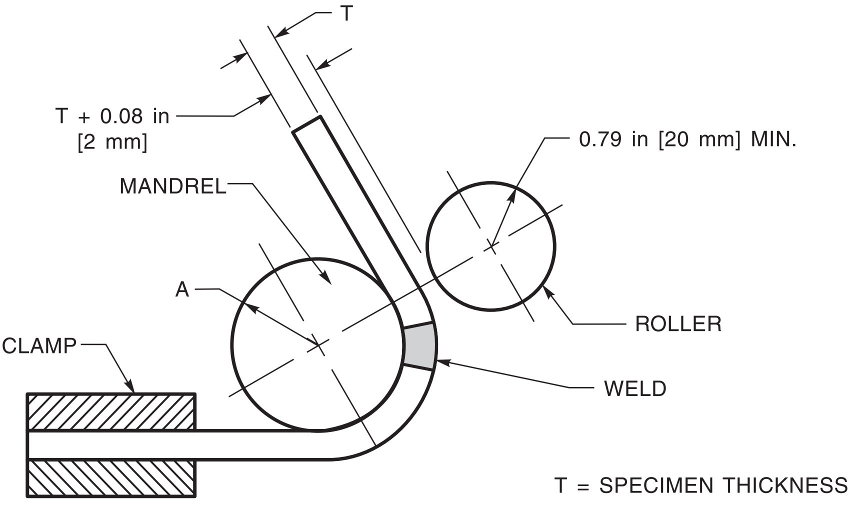
5.5.3 Special Bending Conditions for Aluminum Alloys

We should be aware that most codes, and certainly AWS D1.2, stipulate special bending conditions for various base and filler metals. Test samples of base metals within the 6xxx series (M23) or other base metals welded with the 4xxx series (F23) filler metals are required to be tested under either of two special bending conditions: as-welded or annealed. If testing is to be conducted in the as-welded condition, the



Note: Top sample shows a side bend section prior to full preparation and bending. Lower sample shows a completed side bend specimen.

Figure 5.9—Guided-Bend Test Samples



Note: The “A” dimension shown on the drawing will vary depending on plate thickness and base metal/filler metal being tested.

Figure 5.10—The Mechanism for the Wraparound Bend Test Fixture, the Preferred Method of Bend Testing Aluminum Weldments

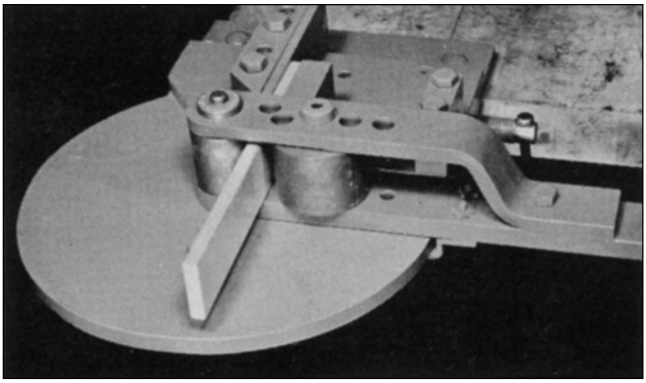


Figure 5.11A—Wraparound Testing Machine with an Aluminum Test Sample Loaded and Ready to be Tested

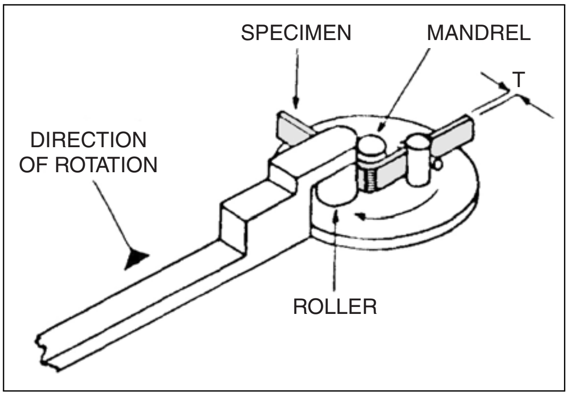


Figure 5.11B—Basic Design of a Wraparound Testing Jig

test specimen is required to be reduced from the standard 3/8-in [10-mm] thickness to 1/8 in [3 mm] prior to bending, and then bent over a diameter of 16-1/2 T. If annealed prior to testing, the standard 3/8-in [10-mm] specimen is required to be bent over a 6-2/3 T diameter.

The specified annealing practice contained in AWS D1.2 is to heat the bend specimens to 775°F [410°C], hold them at this temperature for 2 h to 3 h, then control-cool at 50°F/h [28°C/h] down to 500°F [260°C]. The rate of cooling below 500°F [260°C] is unimportant.

Welds made with the 2219 base material (M24) are required to be annealed and bent over an 8 T diameter. Welds made with 7005 base material (M27) are required to be bend-tested within two weeks of welding. This requirement for 7005 materials is based on the ability of this alloy to gain substantial tensile strength over time, and, consequently, suffer a reduction in ductility through natural aging.

5.5.4 Conclusion

It is obvious that there are many requirements that need to be considered if we expect to obtain the desired results from our guided-bend testing procedures.

It is most important to understand the following:

- The preparation of test samples prior to bend testing is very important.
- There is an optimum method of bend testing aluminum (the wraparound bend test).
- There are major differences between the testing procedures used, which are often dependent on base material and filler metal types being tested.

If test samples are prepared correctly and test procedures specific to the material and filler metal being tested are used, we can go a long way toward assuring that we have no questionable test results.

Chapter 6

Equipment, Welding and Cutting Processes, and Welding Procedures

6.1 The Repair of Aluminum Structures

6.1.1 Introduction

Without a doubt, aluminum is being increasingly used within the welding fabrication industry. We are seeing a major increase in usage within the automotive industry, where the use of aluminum continues to expand. Also within other industries such as furniture, recreation and sporting equipment, shipbuilding, transportation and containers, military and aerospace we see continued developments with aluminum, often as a replacement for steel.

As more components are produced from aluminum, the need for reliable repair work on aluminum weldments is also increasing. Repair work to aluminum structures is conducted extremely successfully on a regular basis; such items as truck bodies and boat hulls repaired after damage from collision or after wear and tear during severe service conditions (see Figure 6.1). This article shall examine some of the more common considerations associated with the repair of aluminum alloys in an attempt to help prevent problems associated with repair work and also to help ensure consistently successful repairs.

6.1.2 Identification of Alloy Type

Probably the most important consideration encountered during the repair operation is the identification of the aluminum base alloy type. If the base material type of the component requiring the repair is not available through a reliable source, it can be difficult to select a suitable welding procedure. There are some guides as to the most probable type of aluminum used in different applications, such as; most extruded aluminum is typically 6xxx series (Al-Mg-Si). Air-conditioning systems and heat exchangers, within the automotive industry, are typically made from 3003, 5052 plate, and 6061 tubing. Car wheels are often made from 5454, which because of its controlled magnesium (less than 3% Mg), is suitable for temperature applications. Ship hulls are often manufactured from 5083 (5% Mg), which is recognized as a marine material. Unfortunately, if the base material type is not known, or unavailable, there is only one reliable way of establishing the exact type of aluminum alloy, and that is through chemical analysis. A small sample of the base material must be sent to a reliable aluminum-testing laboratory, and a chemical analysis must be per-

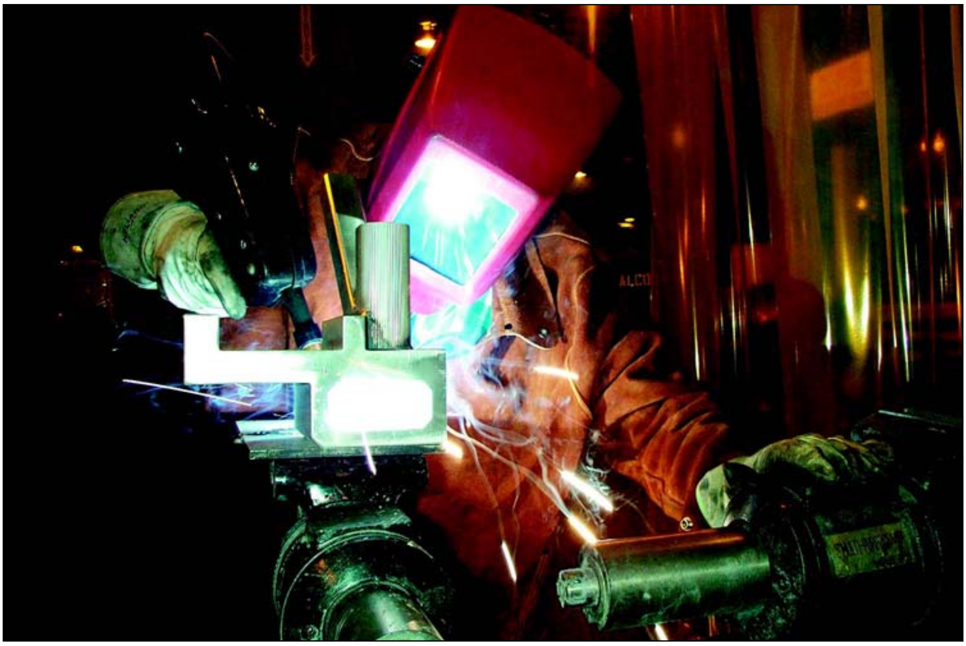


Figure 6.1—GMAW Welding an Aluminum Extrusion Using a Spool Gun

formed. Generally, the chemistry can then be evaluated and a determination as to the most suitable filler alloy and welding procedure can be made. It is very important to be aware that incorrect assumptions as to the chemistry of an aluminum alloy can result in very serious effects on the welding results.

There are 7 major types of aluminum alloys that have a wide range of mechanical properties and, consequently, a wide range of performance and applications. Some have very good weldability, and others are considered to have extremely poor weldability, and are unsuitable, if welded, for structural applications. Some can be welded with one type of filler alloy, and others will produce unacceptable, extremely poor mechanical properties if welded with that same filler alloy. Filler alloy and base alloy chemistry mixture is one of the main considerations relating to welded joint suitability, crack sensitivity, and joint performance. Consequently, without knowing the base material type, you are unable to assess the correct filler to prevent an unsuitable filler alloy, base alloy, mixture.

I must definitely recommend that, if an aluminum component is to be repair welded, and after this, used for any structural application, particularly, if a weld failure, can in any way damage property and/or create injury, do not weld it without understanding its alloy type, and being satisfied that the correct welding procedure is followed.

6.1.3 The Repair of Some High-Performance Aluminum Alloys

Another problem associated with the repair of a small group of aluminum structures is the temptation to repair high performance, typically high replacement price components, made from exotic aluminum alloys. These materials are often found on aircraft, hand gliders, sporting equipment and other types of high-performance, safety-critical equipment and are not usually welded on the original component. There are a small number of high-performance aluminum alloys that are generally recognized as being unweldable. It can be very dangerous to perform welding on these components and then return them to service. Probably the two most commonly found aluminum alloys within this category are 2024, which is an aluminum, copper, magnesium alloy and 7075, an aluminum, zinc, copper, magnesium alloy. Both of these materials can become susceptible to stress corrosion cracking after welding. This phenomenon (stress corrosion cracking) is particularly dangerous because it is generally a type of delayed failure, not detectable immediately after welding, and usually develops at a later date when the component is in service. The completed weld joint can appear to be of excellent quality immediately after welding. X-rays and ultrasonic inspection shortly after welding will typically find no indication of a welding problem. However, changes, which occur within the base material adjacent to the weld during the welding process, can produce a metallurgical condition within these materials that can result in intergranular micro cracking, which may be susceptible to propagation and eventual failure of the welded component.

The probability of failure can be high, and the time to failure is generally unpredictable and dependent on variables such as tensile stress applied to the joint, environmental conditions, and the period of time that the component is subjected to these variables.

It is strongly recommended that great care be taken when considering the repair of components made from these materials. Again, it must be stressed that if there is any possibility of a weld failure becoming the cause of damage or injury to person or property, do not perform repair work by welding on these alloys and then return them to service.

6.1.4 Base Material Strength Reduction After Repair Welding

There are considerations relating to the effect of the heating of the base material during the repair welding process. Aluminum alloys are divided into two groups: the “heat-treatable” and the “nonheat-treatable” alloys. We should consider the differences between these two groups and the effect on each during the repair process. Typically, the nonheat-treatable alloys are used in a strain-hardened condition. This being the method used to improve their mechanical properties, as they do not respond to heat treatment. During the welding process, the heat introduced to the aluminum base will generally return the base material, adjacent to the weld, to its annealed condition. This will typically produce a localized reduction in strength within this area and may or may not be of any design/performance significance.

The heat-treatable alloys are almost always used in one heat-treated form or another. Commonly they are used in the T4 or T6 condition (solution heat-treated and naturally aged or solution heat-treated and artificially aged). Base materials in these heat-treated tempers are in their optimum mechanical condition. The heat introduced to these base materials, during the repair welding process, can change their mechanical properties considerably within the repair area. Unlike the nonheat-treatable alloys, which are annealed and returned to this condition when subjected briefly to a specific temperature, the heat-treatable alloys are affected by time and temperature. The effect from the heating during the welding repair on the heat-treatable alloy is generally a partial anneal and an over-aging effect. Because the amount of reduction in strength is determined largely by overall heat input during the welding process, there are guidelines as to how this reduction can be minimized. Generally, minimum amounts of preheating and low interpass temperatures should be used to control this effect.

However, even with the best-designed welding procedures, considerable loss in tensile strength is always experienced within the heat-affected zone when arc welding these types of materials. Unfortunately, it is usually either cost restrictive or, more often, impractical to perform postweld solution heat treatment because of the high temperatures required and the distortion associated with the process.

6.1.5 Cleaning and Material Preparation Prior to Welding

Even when welding on new components made from new material we need to consider the cleanliness of the part to be welded. Aluminum has a great attraction for hydrogen and hydrogen's presence in the weld area is often related to the cleanliness of the plate being welded. We need to be extremely aware of the potential problems associated with a used component that may have been subjected to contamination through their exposure to oil, paint, grease, or lubricants. These types of contaminants can provide hydrocarbons that can cause porosity in the weld during the welding operation. The other source of hydrogen which we need to consider is moisture, often introduced through the presence of hydrated aluminum oxide. For these reasons it is important to completely clean the repair area to be welded prior to performing the weld repair. This is typically achieved through the use of a degreasing solvent to remove hydrocarbons followed by stainless steel wire brush to remove any hydrated aluminum oxide. More aggressive chemical cleaning may be required for some applications.

In the cases where it is required to remove existing weld or base material to conduct the repair, we need to consider the methods available to perform this operation and their effect on the finished weld. If we need to remove a crack in the surface of a weld prior to rewelding we must use a method which will not contaminate the base material to be welded. Care should be taken when using grinding discs, some have been found to contaminate the base material by depositing particles into the surface of the aluminum. Routing and chipping with carbide tools is often found to be a successful method of material removal. Care must be exercised if using plasma arc cutting or gouging, particularly on the heat-treatable aluminum alloys. This can produce micro cracking of the material surface after cutting which is typically required to be removed mechanically prior to welding.

6.1.6 Conclusion

There are many considerations associated with the repair of aluminum alloys. Perhaps the most important is to understand that there are many different aluminum alloys that require individual consideration. The majority of the base materials used for general structural applications can be readily repaired using the correct welding procedure. The majority of aluminum structures are designed to be used in the as-welded condition and, therefore, with the correct consideration, repair work of previously welded components can and is conducted satisfactorily.

6.2 Why am I Having Feedability Problems when Gas Metal Arc Welding (GMAW) Aluminum?

I have recently changed from using the gas metal arc welding (GMAW) process on steel to welding aluminum with the same process. I am finding it difficult to feed the aluminum wire through my feeding system. I often experience equipment problems such as fusion of the aluminum welding wire to the contact tip, which requires the breakdown of the feeding system and replacement of the contact tip. These problems are time consuming and costly. Is there any way I can improve this situation? I am using 0.047-in.-diameter ER4043 filler metal.

6.2.1 The Importance of Feedability in GMAW Welding of Aluminum

Feedability—the ability to consistently feed the spooled welding wire without interruption during welding—is probably the most common problem experienced when moving from welding steel to welding aluminum using GMAW. Feedability is a far more significant issue with aluminum than steel, primarily because of the differences in the materials' mechanical properties. Steel welding wire is rigid, can be fed more easily over a greater distance, and can withstand far more mechanical abuse than aluminum wire. Aluminum is softer, more susceptible to being deformed or shaved during the feeding operation, and, consequently, requires far more attention when selecting and setting up a feeding system for gas metal arc welding. Feedability problems can be increased when using smaller diameter wires and softer aluminum alloys, such as 1100 and 4043, rather than harder alloys such as 5356. Feedability problems often express themselves in the form of irregular wire feed or as burnbacks (the fusion of the welding wire to the inside of the contact tip).

6.2.2 How the System Affects Feedability

To prevent excessive problems with feedability, it is important to understand the entire feeding system and its effect on aluminum welding wire (see Figure 6.2). If we start with the spool end of the feeding system, we must first consider the brake settings. Brake setting tension should be backed off to a minimum. Only sufficient brake pressure to prevent the spool from free-wheeling when stopping welding is required. Any pressure over and above this will increase the potential for feeding problems and burnbacks. Electronic braking systems and electronic and mechanical combinations have been developed to provide more sensitivity within the braking system and are particularly useful for improved feeding of aluminum wire.

Inlet and outlet guides, as well as liners, which are typically made from metallic material for steel welding, must be made from a nonmetallic material such as Teflon or nylon to prevent abrasion and shaving of the aluminum wire.

Drive rolls designed specifically for feeding aluminum should be used. These often have U-type contours with edges that are chamfered and not sharp. They should be smooth, aligned, and provide correct drive roll pressure. Drive rolls with sharp edges can shave the soft aluminum wire. These shavings can collect inside the feeding sys-

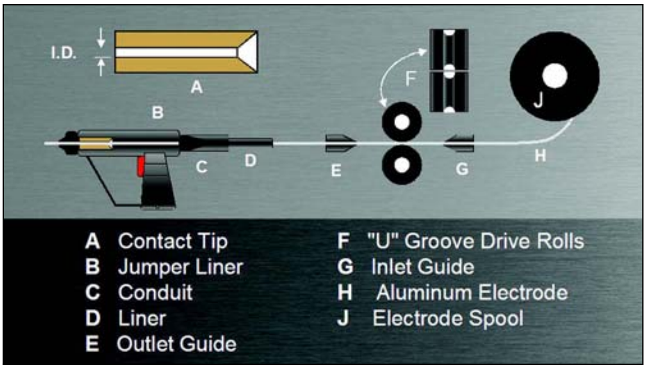


Figure 6.2—Wire Feeding System for Gas Metal Arc Welding of Aluminum

tem and cause burnbacks from blockages within the liner. Excessive drive roll pressure and/or drive roll misalignment can deform the aluminum wire and increase friction drag through the liner and contact tip.

Contact tip dimensions and quality are of great importance. You should only use contact tips made specifically for aluminum wire welding, with smooth internal bores and the absence of sharp burrs on the inlet and outlet ends of the tips. Contact tip bore diameter should be approximately 10 to 15% larger than the electrode diameter.

The quality of the welding wire used for GMAW can influence feedability characteristics. Such characteristics as surface smoothness, wire diameter control, and final treatment of the wire during the spooling operation can assist or detract from the ability to easily deliver the wire through the feeding system. Consistent quality characteristics of the aluminum welding wire should be considered to minimize feedability problems.

6.2.3 Feeding Systems

In terms of aluminum wire feeding, four feeding systems are used: push feeders, pull feeders, push-pull feeders, and spool-on-gun feeding systems. For aluminum welding with the push and the pull feeders, limitations are recognized dependent on application and feeding distance. These systems are generally limited to a practical length of about 12 ft. With push feeders, feeding distance limit is a result of the flexibility of the aluminum wire and its tendency to buckle and bend in the liner; with pull feeders the limit results from a rapid increase in friction drag in the liner, particularly if there are bends in the conduit. Push-pull feeders, were developed to overcome wire feeding problems experienced by the other systems and are the most positive method of feeding aluminum welding wire. Push-pull systems can improve feedability in many applications and are often essential for more critical/specialized operations such as robotic and automated applications to ensure consistent feedability. Spool-on-gun feeding systems are usually designed to use 1-lb spools of wire mounted in the gun. These guns are usually air cooled and are generally limited to smaller wire sizes and light-duty service. Because of their relatively low current rating, they are not perfectly suited to heavy-duty continual production welding, but are often quite effective for tack welding and other light-duty applications. The choice of the most suitable feeding system for each application is based on such factors as the type of welding (light or heavy duty), the electrode size and alloy (large or small diameter/hard or soft filler metal), the need for a long flexible conduit, and the importance of minimizing electrode cost (larger-diameter wire is generally lower priced than smaller diameter).

The demands of welding applications vary extensively, as does the cost of each feeding system. The cost of downtime from feeding problems and replacement parts can also be significant. For these reasons, you should choose the feeding system best suited to your application and set it up to optimize its feeding capability.

6.2.4 Conclusion

Feeding issues with aluminum are probably one of the most common problems experienced within an aluminum GMAW welding environment. It is essential to recognize that far more care is required when designing and setting up a feeding system for aluminum than one for steel. With understanding and the correct equipment, the setup for feeding aluminum wire can be performed very efficiently.

6.3 What Mode of Metal Transfer is the Most Appropriate when Gas Metal Arc Welding Aluminum?

? I am about to move into the welding of aluminum components. I am looking at acquiring some new MIG welding machines and I want to ensure that I select the most appropriate equipment. I will be welding aluminum sheet starting at around 1/8 inch thickness and up to 1/4 inch. In the past I have used short-circuit transfer for welding steel sheet of this thickness but I have been informed that this may not be the best solution for aluminum. Is the selection of metal transfer mode to be used for aluminum any different than that for steel and if so what is the preferred mode of metal transfer to be used when welding aluminum?

We should start with some definitions:

6.3.1 Mode of Metal Transfer

The manner in which molten metal travels from the end of a consumable electrode across the welding arc to the workpiece.

In gas metal arc welding (GMAW), also known as Metal Inert Gas (MIG) welding, the type of metal transfer employed is usually determined by the thickness of the material being welded and the size of the welding electrode being used, and is directly influenced by current setting and shielding gas type employed during welding.

The principle modes of metal transfer are defined as:

6.3.2 Short Circuit Transfer

Metal transfer in which molten metal from a consumable electrode is deposited during repeated short circuits.

This metal transfer which is sometimes known as short arc or dip transfer has been perfected for and is most widely used in the welding of steels and to a much lesser degree is sometimes used for the welding of thin gauge aluminum. This metal transfer is achieved by using low currents and low voltage and small diameter wires. The primary characteristic of this metal transfer is the frequent shorting of the welding wire to the workpiece. This short circuiting often takes place at a rate of around 200 times per second. When produced with the correct equipment this transfer mode can provide a very stable arc of low energy and low heat input. The emphasis here is on the correct equipment, a power source with the correct amount of slope and inductance. All power sources are not created equal when it comes to their ability to produce acceptable arc characteristics for short circuit transfer. When evaluating the suitability of short circuit transfer for use on aluminum we need to recognize the low energy and low heat characteristics of this transfer mode. One of the primary differences between steel and aluminum is their thermal conductivity; the thermal conductivity of aluminum is close to six times greater than that of steel. I am aware of some applications that have successfully used the short circuit transfer for welding aluminum. However, I would be reluctant to recommend this mode of metal transfer without first considering the potential for incomplete fusion when used on aluminum. I believe it is reasonable to say that the short circuit transfer is generally not recommended for GMAW (MIG) welding of aluminum and has in the past been identified as such in technical publications and welding specifications.

6.3.3 Globular Transfer

The transfer of molten metal in large drops from a consumable electrode across the arc.

This transfer mode is not considered for welding aluminum and is most predominantly seen when welding carbon steel with CO_2 shielding gas. This transfer mode is characterized by large amounts of weld spatter and a general lack of arc stability.

6.3.4 Spray Transfer

Metal transfer in which molten metal from a consumable electrode is propelled accurately across the arc in small droplets.

When using argon, or an argon rich shielding gas with the GMAW (MIG) process we can produce the spay transfer mode. When we increase current to beyond the globular-to-spray transition current the metal transfer moves into spray transfer (Table 6.1 shows globular-to-spray transition currents for a selection of aluminum electrode diameters for welding aluminum). The spray transfer is a result of a pinch effect on the molten tip of the consumable welding wire. The pinch effect physically limits the size of the molten ball that can be formed on the end of the welding wire, and therefore only small droplets of metal are transferred rapidly through the welding arc from the wire to the workpiece. The droplets produced in the spray transfer mode are equal to or smaller than the diameter of the wire being used. This transfer mode is characterized by its high heat input, very stable arc, smooth weld bead and very little if any spatter.

Because spray transfer has a very high heat input which can overcome aluminum's high thermal conductivity, the spray transfer mode is recognized as the preferred mode of metal transfer for welding aluminum with the GMAW (MIG) process.

Table 6.1—GMAW Globular-to-Spray Transition Currents

Wire Diameter Inches (mm)	Shielding Gas	Spray Arc Transition Current
0.030 (0.8)	100% Argon	90 Amps ± 5 Amps
0.035 (0.9)	100% Argon	110 Amps ± 5 Amps
0.047 (1.2)	100% Argon	135 Amps ± 5 Amps
0.062 (1.6)	100% Argon	180 Amps ± 5 Amps

6.3.5 Making the Choice

The selection of the most suitable metal transfer for your application is somewhat dependant on the size of the parts being welded and the types of joint design being used. Larger components with well fitted fillet welds may be welded successfully with regular spray transfer. However, smaller parts in the thinner material, with poor fit up particularly in butt welds, may prove challenging to accomplish with this transfer mode without overheating and burning through.

One option which may be worthy of consideration is the pulsed spray transfer.

6.3.6 Pulsed Spray Transfer

An arc welding process variation in which the current is pulsed in order to use the advantages of the spray mode of metal transfer at average current equal to or less than the globular to spray transition current.

This transfer variation is sometimes a suitable compromise between the low heat input short circuit transfer, which is susceptible to fusion problems when used on aluminum and the high heat input spray transfer which may prove to be too hot to handle on some thinner material applications.

Pulsed spray transfer is a modified form of GMAW (MIG) spray transfer welding, which produces a controlled and periodic melting off of droplets which are projected across the arc. This process allows spray transfer welding at average currents which are considerably lower than the current necessary for regular spray transfer welding. The pulsed spray process allows welding of thin sheet which would be melted through by the standard spray transfer. In the pulsed spray process the filler wire is heated by a background current and the end of the wire may start to melt into a drop. When the high current pulse occurs, the drop melts completely and is propelled, by the arc pinch effect, directly from the wire to the weld pool. The pulsed spray transfer mode will typically provide deeper penetration and better root fusion than short circuit transfer and is often the preferred choice for welding thinner material.

With the introduction of solid state devices and computers, pulse current power supplies are designed so that the pulsing rate can be varied over a wide range, and the width of the pulse can be varied independently of the pulsing rate. The magnitude of the background and pulse current can be adjusted independently of one another providing the opportunity to develop pulse programs that can accommodate many welding applications (Figure 6.3 shows the basic current cycle for pulsed spray transfer). Basic pulsed spray transfer has been around for many years originally developed by Airco in the late nineteen fifties. More recently some very imaginative variations of this technology have been developed which involve multiple pulse programs operating together and pulsing within various metal transfer modes. With today's more sophisticated pulsed GMAW (MIG) equipment it is possible to weld very thin aluminum sheet and if required even provide the weld with an appearance close to that produced by the GTAW (TIG) process.

Figure 6.4 shows Pulse/Pulse—The prime advantage of the pulse/pulse process is the ability to more precisely control the heat input. Pulse/pulse is a well established process and has mainly been focused on aluminium welding.

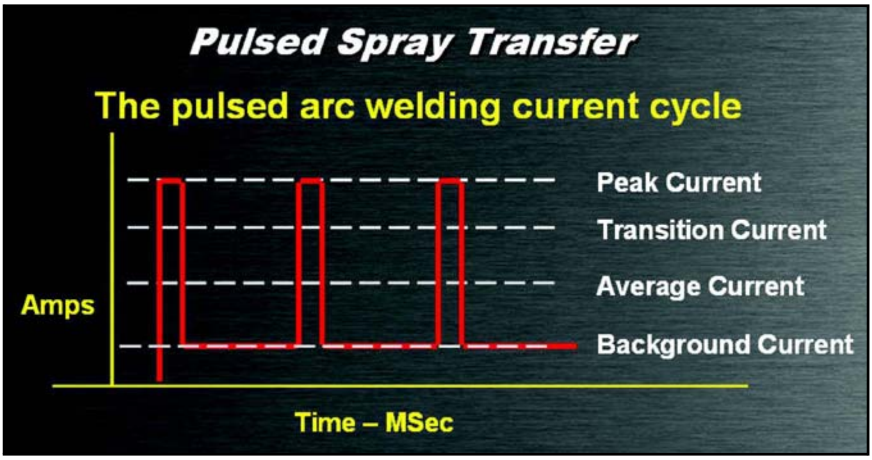


Figure 6.3—Basic Current Cycle For Pulsed Spray Transfer

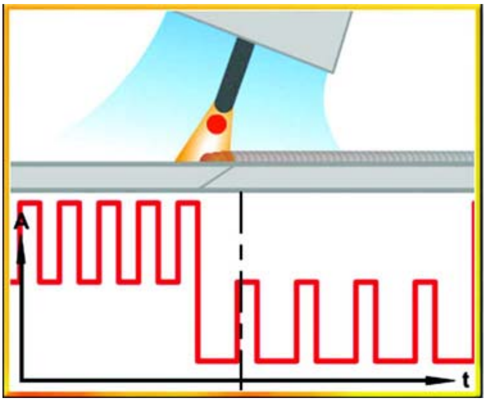


Figure 6.4—Pulse/Pulse. The Prime Advantage of the Pulse/Pulse Process is the Ability to More Precisely Control the Heat Input. Pulse/Pulse is a Well Established Process and has Mainly been Focused on Aluminium Welding.

Figure 6.5 shows Pulse/Short Arc—This process enables full control of the heat input for thin sheet welding and has even been used for the root run on pipes.

Figure 6.6 shows Spray Arc/Pulse—A very efficient process in positional welding of thicker materials and provides additional control over conventional spray transfer.

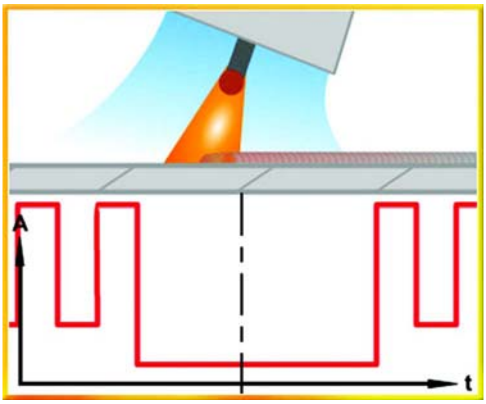


Figure 6.5—Pulse/Short Arc. This Process Enables Full Control of the Heat Input for Thin Sheet Welding and Has Even Been Used for the Root Runs on Pipes.

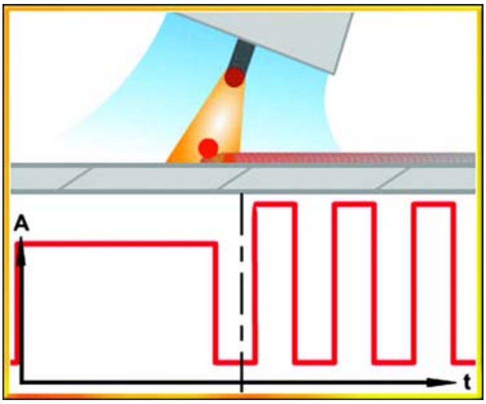


Figure 6.6—Spray Arc/Pulse. A Very Efficient Process in Positional Welding of Thicker Materials and Provides Additional Control Over Conventional Spray Transfer.

6.3.7 Conclusion

The development of welding procedures for welding aluminum and in particular the selection of the most suitable mode of metal transfer is different than when welding steel. Typically for aluminum we will avoid the use of short circuiting transfer which because of is low heat input may introduce weld quality problems such as incomplete fusion. Wherever possible we make use of the much higher heat input and therefore much more appropriate spray transfer mode. One method of overcoming the problem of welding very thin aluminum with the GMAW process is to make use of one of the various types of pulse transfer that are now available and widely used. This transfer mode is sometimes seen as a compromise between short circuiting and conventional spray transfer.

6.4 Is Open Root Welding of Aluminum Pipe Different from Open Root Welding of Steel Pipe?

I am a pipe welder and have worked on many projects over the years including petrochemical and power generation. I have worked with many types of materials including carbon steel, stainless steel, and chrome molybdenum low alloy steels. There is one group of materials that I have not yet worked with and they are the aluminum alloys. I would like to know more about the open root joint welding procedures used for aluminum pipe. Is this type of welding of aluminum pipe any different from the welding of pipes made of steel and can you recommend a source of reference on this subject?

6.4.1 Open Root Joint Welding of Steel Pipes

The all important root bead or root run in steel pipe is often welded with one of three welding processes, the gas tungsten arc welding process (GTAW), the gas metal arc welding process (GMAW), and the shielded metal arc welding process (SMAW). A typical weld joint used for welding steel pipe is a single-v-groove weld with an open root using a feathered edge or land that is welded from one side only. With the correct welding procedure the root run in this type of joint in steel may be completed using any of these three welding processes. The GTAW process is frequently used with or without a consumable insert to produce excellent root profiles in steel pipes. The GMAW process in the short-circuit transfer mode, or using pulsed arc characteristics, is sometimes used for root runs in open root joint welds made in steel pipe. With the correct procedure this process can produce very good results. The SMAW process is used extensively for completing root runs in open root joints when welding various grades of steel pipe. With SMAW the E6010, E7010-P1, and E8010-P1 deep penetration cellulosic type electrodes are often used to produce excellent root runs in the vertical up and vertical down positions when employed by a skilled pipe welder.

6.4.2 Open Root Joint Welding of Aluminum Pipes

A significant difference between welding aluminum alloys and steel is that the root runs of open root joints in aluminum pipes are almost always performed by using the gas tungsten arc welding process (GTAW) (see Figure 6.7).

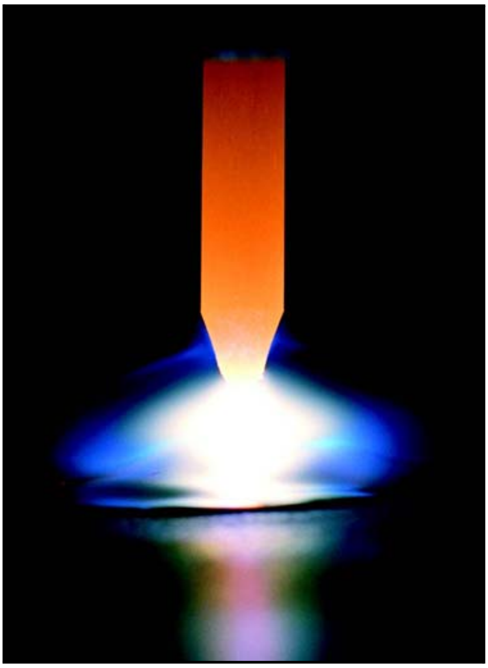


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Figure 6.7—Open Root Joint Welding of Aluminum Pipe is Predominantly Performed by the GTAW Process, Using AC Current to Produce an Arc Between a Tungsten Electrode and the Aluminum Plate and Protecting the Molten Aluminum with Pure Argon Shielded Gas

The gas metal arc welding process (GMAW) in most instances will fail to provide the consistent control necessary for performing root runs in open root joint welding of aluminum pipe. The problem that occurs, is inadequate control over heat input and penetration for such a sensitive and demanding joint configuration in a material with such high thermal conductivity. The GMAW process is more appropriately suited for welding heavier walled aluminum pipe and used after the GTAW root run to deposit subsequent weld beads to fill and cap the weld. In this way, one may take advantage of the GMAW processes' high deposition rate and travel speed without concern for inconsistent root profiles.

The shielded metal arc welding process (SMAW), which is rarely ever used for aluminum welding, would never be used for this type of weld joint.

As stated above the root runs of open root joints in aluminum pipe are most often successfully achieved by using the GTAW process. A typical procedure for gas tungsten arc welding of aluminum would make use of AC current, unlike GTAW welding of steel that conventionally uses DCEN, which, if used on aluminum, can result in poor weld quality. With AC welding we take advantage of the positive half cycle of the current for aluminum oxide film removal and the negative half cycle for electrode cooling. The cathodic cleaning of the positive half cycle that helps to disperse the aluminum oxide film during welding is a very important feature of this method of welding. Without this cleaning action during the welding process such discontinuities as lack of fusion and oxide entrapment in the completed weld would be difficult to avoid. This type of procedure would typically use pure argon shielding gas and pure or Zirconiated tungsten and there would be no requirement for a purging gas to be used during welding as is sometime required for the welding of some steel alloys. The use of a consumable insert or EB insert, as it is sometimes known, is not a viable option when welding aluminum. By definition, an open root joint is an unwelded joint without backing or consumable insert. However, the consumable insert which I mentioned earlier is widely used for pipe welding of steel and is often seen as a convenient method of acquiring excellent root profiles in welded pipes. For those pipe welders who have used consumable inserts there will be a great appreciation for the quality of root runs that can be achieved by simply fusing the pre-fitted insert using the GTAW process with little or no additions of filler metal during the root run. Unfortunately, the consumable insert is generally accepted as being unsuitable for aluminum pipe welding. The reason for this is that the surface areas of the insert that are hidden beneath the joint preparation are inaccessible to the welding arc during the welding process. Consequently, the cathodic cleaning action of the arc, which is the principal method of removing the aluminum oxide and impurities during welding, is unable to adequately clean the entire joint during the welding process. This can result in unacceptable discontinuities in the completed weld.

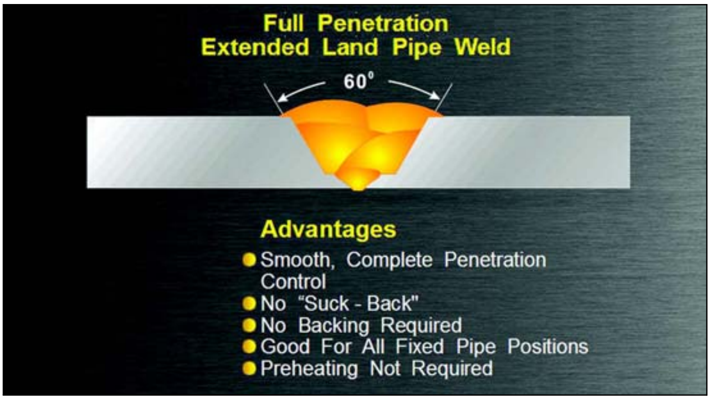
6.4.3 Type of Weld Preparation

Aluminum pipes are welded with backing rings; both temporary and permanent backing rings are used. Permanent backing usually have as a requirement that they must be made from the same aluminum alloy number group as the pipe material being welded, and temporary backing may be made from stainless steel, anodized aluminum or grooved ceramic material.

When welding aluminum pipe without backing and using an open root joint, the joint preparation becomes extremely important for various reasons. One joint preparation that is used to assist the open root welding for aluminum pipe is the extended land preparation (see Figure 6.8). This joint preparation is designed to provide a relativity thin section at the root of the joint that can be used to more easily control root penetration. Care must be taken to add sufficient filler alloy when performing the root run as aluminum piping is often manufactured from alloys that are unsuitable for autogenous welding and without adequate addition of suitable filler alloy the root run will invariably crack.

6.4.4 Reference Material for Welding Aluminum Pipe

There may be a number of publications available that address this subject in some form or another, however, the one that comes to mind for me is the American Welding Society publication *AWS D10.7 Guide for the Gas Shielded Arc Welding of Aluminum and Aluminum Alloy Pipe*. This publication was developed as a guide to facilitate the



Full Penetration
Extended Land Pipe Weld

Advantages

- Smooth, Complete Penetration Control
- No "Suck - Back"
- No Backing Required
- Good For All Fixed Pipe Positions
- Preheating Not Required

Figure 6.8—Extended Land Pipe Weld with the Advantages Listed for This Type of Weld Preparation when Used for Aluminum Pipe Joints

selection and specification of welding processes and procedures for aluminum and aluminum alloy pipe. This recommended practice has been prepared by the Subcommittee on Aluminum Piping of the AWS Committee on Piping and Tubing, and is intended to provide information needed to minimize or avoid difficulties in the welding of such pipe. The data given in this document is presented as initial guides to operating conditions. The first edition of this document, *AWS D10.7-60*, was written to present the advances made in Aluminum Pipe welding during and subsequent to WWII. The second edition of this document was *AWS D10.7-86* which updated *AWS D10.7-60*. The *AWS D10.7M/D10.7:2000*, third edition, changed the document from a 'Recommended Practice' to a 'Guide' and updated the processes and procedures. The most significant change in the *AWS D10.7M/D10.7:2008*, fourth edition was the inclusion of a comprehensive guide for the selection of filler metal. In addition to the new filler alloy selection chart and associated information, the current standard introduces the reader to the properties of aluminum that are important to successful welding operation. Precise welding procedure specifications, including joint designs, are provided with a discussion of welding technique and heat treatment considerations that are unique to welding aluminum alloys.

6.4.5 Conclusion

The procedures that are used for open root joint welding of aluminum alloy pipes are different from those used for welding steel pipe. The selection of the welding process for this type of welding in aluminum is much more restricting and typically the GTAW process is the only process practical. The preferred welding joint preparation for aluminum is different than steel because of the materials high thermal conductivity and the inability to consistently penetrate the root. Consequently the production of high quality root runs in aluminum pipe is challenging and requires a considerable amount of training and skill on the part of the welder.

6.5 What Shielding Gas Should be Used when Arc Welding Aluminum?

What shielding gas should I use when arc welding aluminum? Some people tell me that I should use argon, and others say that helium is the best. I use the Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW) process. Can I use the same gas for each process?

6.5.1 The Two Commonly Used Shielding Gases for Arc Welding Aluminum

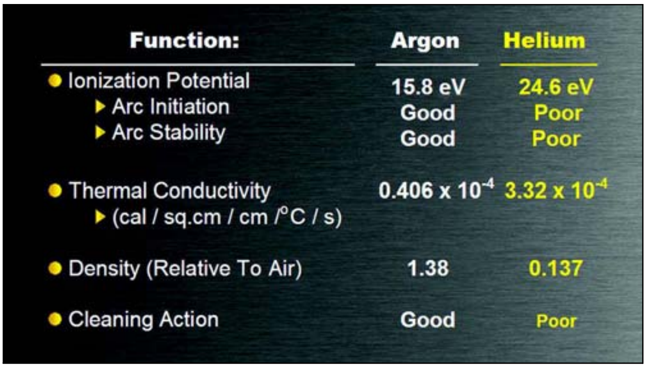
There are two shielding gases commonly used for arc welding aluminum, and these are argon and helium. These gases are used as pure argon, pure helium, and various mixtures of both argon and helium.

Excellent welds are often produced using pure argon as a shielding gas. Pure argon is the most popular shielding gas and is often used for both gas metal arc and gas tungsten arc welding of aluminum. Mixtures of argon and helium are probably the next common, and pure helium is generally only used for some specialized GTAW applications.

When considering a shielding gas for welding aluminum, we need to consider the differences between argon and argon helium mixtures. To understand the effect of these gases on the welding operation, we can examine the properties of each gas in Figure 6.9.

6.5.2 Shielding Gas for Gas Metal Arc Welding

For GMAW the additions of helium range from around 25% helium up to 75% helium in argon. By adjusting the composition of the shielding gas, we can influence the dis-



Function:	Argon	Helium
Ionization Potential	15.8 eV	24.6 eV
Arc Initiation	Good	Poor
Arc Stability	Good	Poor
Thermal Conductivity (cal / sq.cm / cm /°C / s)	0.406×10^{-4}	3.32×10^{-4}
Density (Relative To Air)	1.38	0.137
Cleaning Action	Good	Poor

Figure 6.9—Ionization Potential and the Thermal Conductivity of Helium Shielding Gas is Much Higher than that of Argon Producing Greater Heat when Welding with Additions of Helium in the Shielding Gas

tribution of heat to the weld. This, in turn, can influence the shape of the weld metal cross section and the speed of welding. The increase in welding speed can be substantial, and as labor costs make up a considerable amount of our overall welding costs, this can relate to a potential for significant savings. The weld metal cross section can also be of some consequence in certain applications. Typical cross sections for argon and helium are shown in Figure 6.10.

Tests have shown that the relatively narrow cross section of the pure argon shielded weld has a higher potential for gas entrapment and, consequently, can contain more porosity. The higher heat and broader penetration pattern of the helium/argon mixtures will generally help to minimize gas entrapment and lower porosity levels in the completed weld.

For a given arc length, the addition of helium to pure argon will increase the arc voltage by 2 V or 3 V. With the GMAW process, the maximum effect of the broader penetration shape is reached at around 75% helium and 25% argon. The broader penetration shape and lower porosity levels from these gas mixtures are particularly useful when welding double-sided groove welds in heavy plate. The ability of the weld bead profile to provide a wider target during back chipping can help to reduce the possibility of incomplete joint penetration that can be associated with this type of welded joint.

Pure argon shielding gas will typically produce a completed weld with a brighter, shinier surface appearance. A weld made with a helium/argon mixture would usually require postweld wire brushing to obtain a similar surface appearance. Because of aluminum's high thermal conductivity, incomplete fusion can be a likely discontinuity. Helium shielding gas mixtures can help to prevent incomplete fusion and incomplete penetration because of the extra heat potential of these gases.

6.5.3 Shielding Gas for Gas Tungsten Arc Welding

When considering the shielding gas for gas tungsten arc welding with alternating current (AC), pure argon is the most popular gas used. Pure argon will provide good arc

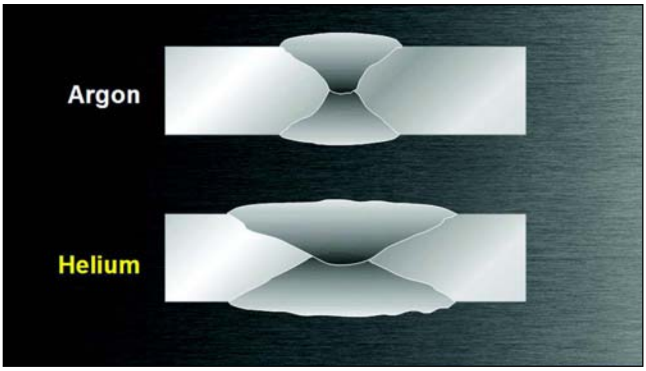


Figure 6.10—Cross Section of GMAW Welds Made with Pure Argon and 75% Helium 25% Argon

stability, improved cleaning action, and better arc starting characteristics when AC-GTAW welding aluminum.

Helium/argon mixtures are sometimes used for their higher heat characteristics. Gas mixtures, usually 25% helium and 75% argon are sometimes used and can help to increase travel speeds with AC-gas tungsten arc welding. Mixtures of more than 25% helium for AC-gas tungsten arc welding are used, but not often, as they can tend to produce instability, under certain circumstances, in the AC arc.

Pure helium or high percentages of helium (He–90%, Ar–10%) shielding gas are used primarily for gas tungsten arc machine welding with direct current electrode negative (DCEN). Often designed as seam welders, the combination of GTAW–DCEN and the high heat input from the gas used can provide fast welding speeds and outstanding penetration. This configuration is sometimes used to produce full penetration butt welds, welded from one side only, onto temporary baking with no V-groove preparation, just a square edged plate.

6.5.4 Conclusion

In answer to your questions, there are a number of choices available for gases and gas mixtures that can be used to weld aluminum. The choice is usually based on the specific application. Generally speaking, the high helium content gases are used for GMAW welding on thicker materials and GTAW welding with DCEN. Pure argon can be used for both GMAW and GTAW welding and is the most popular of the shielding gases used for aluminum. The helium content gases are usually more expensive. Helium has a lower density than argon and higher flow rates are used when welding with helium. It is possible to increase welding speeds in some circumstances by using helium and/or helium/argon mixtures. Therefore, the extra cost of the helium mixtures may be offset by your improved productivity. You should try the different gas types and choose the one that best suites your specific application.

6.6 What Should I Know About the Storage and Preparation of Aluminum Base Alloys and Filler Alloys?

? I have worked for many years in the welding fabrication of carbon steel, and I am moving into the welding fabrication of aluminum. I have heard that the storage and preparation for aluminum base alloys and filler alloys are different. What are the differences, and how can they affect the quality of my welding?

6.6.1 Correct Storage and Preparation is Important

I must start by stating that the storage and preparation of all materials that are welded, including carbon steel, is important and can have significant effect on the finished quality of the welding. The basic rules for cleanliness, removal of contaminants from the welding area, and suitable storage and handling of filler material, should be applied rigidly when welding all materials if we are attempting to produce high-quality welding. I will follow the above statement by identifying the fact, that yes, there are differences between these two materials, carbon steel and aluminum, and that some of these differences are reflected in issues relating to storage and preparation.

As we consider the storage and preparation of aluminum base alloys and filler alloys, we can recognize two potential problem areas. First, aluminum oxide, how it forms, reacts under certain conditions, and how it can be removed, and secondly, contamination from hydrocarbons, their source and removal.

6.6.2 Aluminum Oxide

Probably the most important issue to understand about aluminum regarding storage and preparation is the nature and characteristics of its surface oxide film. Aluminum alloys rapidly develop a self-limiting oxide surface film upon exposure to air. This aluminum oxide on the material's surface has a melting point in excess of 3600°F or 2400°F [1982°C or 1316°C] above the melting point of pure aluminum base material. Because of this large difference in melting temperature, the aluminum oxide film can prevent fusion between filler alloy and base alloy and/or flakes of oxide can become entrapped during the welding process, as inclusions within the completed weld.

Aluminum, with an uncontaminated thin oxide layer, can often be easily welded with the inert-gas (GMAW and GTAW) processes, which break down and remove the thin oxide during welding. Potential problems arise when the aluminum oxide has been exposed to moisture. The aluminum oxide layer is porous and can absorb moisture, grow in thickness, and become a major problem when attempting to produce welds of high quality that are required to be relatively porosity free.

For high-quality welds, it is usually necessary to remove the aluminum oxide mechanically just prior to welding. This is often achieved by brushing with a stainless steel wire brush, but can also be achieved by scraping, filing, machining, or grinding. Care must be taken to employ only tools that are clean and free of contaminants such as oil and grease. An alternative to removal of aluminum oxide mechanically is chemical oxide removal. This process includes: immersion in alkaline (caustic) solution, followed by a water rinse, then nitric acid and water rinse. The use of chemical cleaning, however, is becoming less common as the handling and disposal of these chemicals is often seen as a restricting inconvenience.

6.6.3 Hydrocarbons

Another issue relating to storage and preparation is the presence of hydrocarbons on the surface of base material and or filler alloy. Base material is frequently formed, sheared, sawed and machined prior to the welding operation. If a lubricant is used during any of these preweld operations, complete removal of the lubricant prior to welding is essential if high-quality welds are required. Since it is important to remove lubricants before welding, it is advantageous to use the minimum amount in preweld operations. Sawing and machining of aluminum can often be performed dry. Hydrocarbons, if present, can be removed by a number of methods; wiping with solvents such as acetone or alcohol, detergent spray degreasing, steam degreasing, or wiping with a mild alkaline solution. Solvent cleaners are possibly the most popular method used to remove oil and grease. Most hydrocarbon solvents are highly volatile and evaporate quickly, but the water-based cleaners must be thoroughly wiped away or heat dried. A hydrocarbon solvent suitable for preweld cleaning must dissolve oil and grease readily, evaporate quickly and not leave a residue. Care must be taken, not only in the selection of the correct solvent, but, also in its use. Adequate ventilation is essential, and the manufacturers' recommendations should be followed carefully. It is very important to remember that flammable chemicals are very dangerous in the presence of welding arcs.

It should be recognized that if material has been subjected to contamination from hydrocarbons, those contaminations will need to be removed before wire brushing the part to remove aluminum oxide. Wire brushing on an oily or greasy surface tends to smear the contaminants in to the surface and, in addition, the wire brush becomes contaminated and unsuitable for its intended purpose.

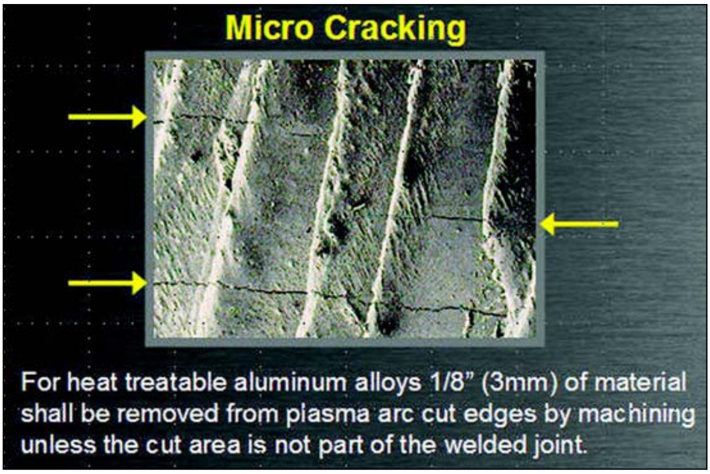
The amount of preweld cleaning required is largely dependent on how much care is taken to keep the material clean and dry in storage and in subsequent handling operations during fabrication and before welding. Some manufacturers have been able to control their handling operations adequately enough so that only wire brushing the joint area is required prior to welding.

6.6.4 Storage of Filler Wire

Both spooled GMAW and straight length GTAW welding wire should be stored correctly. The most common problem is the exposure of wire to moisture. This can occur quite easily if the wire is subjected to abrupt changes in temperature at high humidity. Acquiring wire from a cool atmosphere and immediately unpacking it in a warm, humid atmosphere will subject the wire to condensation from crossing the dew point. This moisture will produce hydrated aluminum oxide on the surface of the wire and, consequently, will result in poor weld quality containing porosity. It is favorable to maintain filler wire in a heated area with a uniform temperature. For example a light bulb inside a storage cabinet can produce adequate heat to prevent condensation on the aluminum filler alloy.

6.6.5 Metalworking Methods and Considerations when Plasma Arc Cutting

Considerations when cutting and beveling are different for aluminum than for steel. Probably the most common method of thermally cutting steel, oxyfuel gas cutting, is not suitable for cutting aluminum. Plasma arc cutting is perhaps the most common method used for cutting aluminum. It is important to recognize that plasma arc cutting can affect the quality of the cut edge on some of the aluminum alloys. The partial melting of the grain boundaries can result in micro cracking in the cut edge (see Figure 6.11). The 2xxx, 6xxx, and 7xxx series (heat-treatable) alloys are particularly prone to this type of cracking, whereas the 1xxx, 3xxx, and 5xxx series (nonheat-treatable) alloys are not. The cracking tendency increases with metal thickness because thick metal imposes greater restraint on the solidifying metal. Some welding standards require that both the roughness and the cracking zone be removed by machining the plasma cut edge to a depth of 1/8 in [3.2 mm] before incorporating the edge into a welded joint.



For heat treatable aluminum alloys 1/8" (3mm) of material shall be removed from plasma arc cut edges by machining unless the cut area is not part of the welded joint.

Figure 6.11—Micro Cracking at the Edge of an Aluminum Plate After Plasma Cutting

Other methods of cutting aluminum are becoming popular. Laser cutting can produce very high-quality cut edges, and abrasive water jet cutting is also capable of producing excellent results. Another cutting method for aluminum includes sawing. Circular saws may be either portable or floor mounted, and band saws are used extensively for preparing weld samples and cutting smaller parts. Tooth shapes have been developed by saw blade manufacturers that perform very well on aluminum. Blades recommended for aluminum have more rake and clearance than those for steel. Most gouging is performed on aluminum with mechanical tools. Straight line back gouging of groove welds is probably best performed by using a rotary cutter machine designed especially for this purpose. Some fabricators have chosen to adapt a small portable power saw for back gouging, replacing the saw blade with a cutting blade ground to the required shape. Tungsten carbide cutters are standard for all gouging machines.

6.6.6 Smut

While aluminum welds are seldom specified to be finished there is one consequence of welding that is sometimes required to be corrected, and that is the removal of smut (sometimes called soot) that is sometimes deposited on the weld and surrounding metal. Smut is a black deposit on the surface of the aluminum which appears during welding and is more prevalent when gas metal arc welding with the 5xxx series filler alloys. Smut is the result of metal vapor that is produced by the intense heat of the arc, and then condensed on the base metal surface. During the welding process the arc temperature far exceeds the boiling point of both aluminum and magnesium, and thus some of the filler metal passing through the arc is vaporized. Because the base metal even in the heat-affected zones does not reach these extreme temperatures, metal vapor condensation can occur on the metal surface. The smut is a deposit of finely divided metal oxides and is not harmful, although it is unattractive. Smut can be removed quite easily by wiping soon after welding however, if left for several hours; it tends to adhere very tightly to the metal surface and may require wire brushing for removal. Figure 6.12 shows typical smut from a GMAW weld with 5356 filler alloy. Figure 6.13 is an x-ray analysis showing that smut consists of aluminum and magnesium oxides.

Figure 6.12—GMAW Weld with Smut—Smut Can be Removed Quite Easily by Wiping Soon After Welding

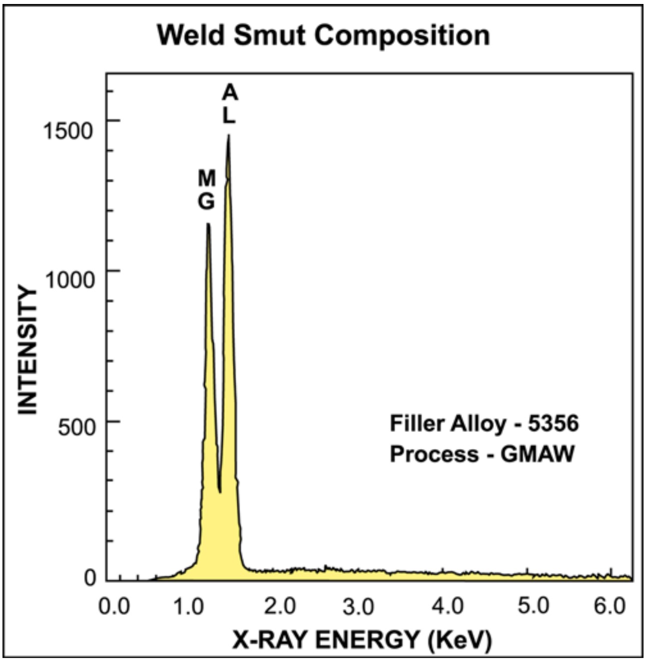


Figure 6.13—Composition of Weld Smut

6.6.7 Conclusion

The storage and preparation of aluminum alloy base material and filler alloy is a very important issue, especially if we are looking for high-quality welds. There are some considerations that are exclusive to aluminum that we need to understand to help us prevent problems associated with the incorrect processing of this material.

6.7 How Can I Minimize Distortion when Welding Aluminum?

In the past I have fabricated some fairly complex steel structures that have, on occasion, presented problems with distortion. I am now considering moving to aluminum as a replacement material for some of these structures. My questions are: What amount of distortion can I expect to see with aluminum, and how can I prevent it?

6.7.1 Considering the Principal Reasons for Distortion

We need to consider the principal reasons for distortion in any arc-welded structure and some of the characteristics of aluminum specifically. Welding distortion can be defined as "the nonuniform expansion and contraction of weld metal and adjacent base metal during the heating and cooling cycle of the welding process." Distortion is a consideration when arc welding all materials and the principals behind this reaction are fundamentally the same.

If we evenly heat a nonrestrained piece of metal in a furnace to a prescribed temperature and then allow it to cool to its original temperature, it will first expand (to a degree based on its coefficient of expansion) and then contract as cooled to its original size. If we apply this kind of uniform heating and cooling to an unrestrained structure, the heating and cooling process should promote no distortion of the structure. Unfortunately, when arc welding, we are usually applying nonuniform localized heating to the structure which we are welding. This heating is limited to the area of the weld and its close vicinity. Also, the heating and cooling is conducted under varying amounts of restraint during the welding process. The part of the welded component outside of the weld area that is not heated, or heated to a much lower temperature, acts as a restraint on the portion that is heated to the higher temperatures and undergoes higher expansion. The nonuniform heating, resulting in nonuniform expansion and contraction, along with weld metal and base metal shrinkage, and the partial restraint from the less affected parts of the structure are the primary cause of thermal distortion problems that occur in welding.

Theoretically, when welding aluminum compared to carbon steels, the effects of some of the main contributing factors for distortion may be somewhat increased. Aluminum has high thermal conductivity; this being a property that may affect distortion and can substantially affect weldability. The thermal conductivity of aluminum is around five times that of low-carbon steel. Aluminum also has high solidification shrinkage, around 6% by volume, and also a high coefficient of thermal expansion. When we arc weld aluminum, we apply high localized heating to the material in and around the weld area. There is a direct relationship between the amount of temperature change and the change in dimension of a material when heated. This change is based on the coefficient of expansion. This is the measure of the linear increase per unit length based on the change in temperature of the material. Aluminum has one of the highest coefficients of expansion ratios, and changes in dimension almost twice that of steel for the same temperature change. However, it is not uncommon to apply higher material thickness to a comparable aluminum structure when compared to steel. This is a design consideration that may be used to provide the necessary rigidity and/or required strength. Because aluminum is approximately 1/3 the weight of steel, we could, in fact, double the original design thickness for our aluminum structure and still have only 2/3 the weight of the original structure made of steel. The significance of such an increase in material thickness would be a substantial reduction in the potential for distortion.

6.7.2 What Methods can we Employ to Reduce Distortion?

The methods used for the control of distortion when welding aluminum are the same as other materials; however dependent on material thickness and structure design, we may need to give greater consideration to the following:

6.7.2.1 Correct Sizes of Welds

Probably the most common cause of excessive distortion is from over welding. To reduce distortion, we should try to keep the heating and shrinkage forces to a minimum. We should design the weldment to contain only the amount of welding necessary to fulfill its service requirements. The correct sizing of fillet welds to match the service requirement of the joint can help to reduce distortion. We should not produce fillet welds that are larger than specified on engineering drawings. We should provide welders with fillet weld gauges so they are able to measure their welds to ensure that they are not producing welds that are much larger than that specified. With butt joints we should control edge preparation, fit-up and excessive weld buildup on the surface to minimize the amount of weld metal deposited and thereby reduce heating and shrinkage.

6.7.2.2 Joint Design

When welding thicker material, a double-V-groove joint requires about half the weld metal of a single-V-groove joint and is an effective method of reducing distortion. Changing to a J-groove or a U-groove preparation can also assist by reducing weld metal requirements in the joint.

6.7.2.3 Intermittent Welds

We may consider the use of intermittent fillet welds, where possible. We can often maintain adequate strength requirements and reduce the volume of welding by 70% by using intermittent fillet welds over continuous welding, if the design allows.

6.7.2.4 Balance Stresses

Balance welding around and position welds near to the neutral axis of the welded structure. The neutral axis is the center of gravity of the cross section of the part. Placing similarly sized welds on either side of this natural centerline can balance one shrinkage force against another. Placing the weld close to the neutral axis of the structure may reduce distortion by providing less leverage for shrinkage stresses to move the structure out of alignment.

6.7.2.5 Fewer Weld Beads

Reduce the number of weld beads, if possible. Few passes with a large electrode are preferable to many passes with a small electrode. The additional applications of heat can cause more angular distortion in multipass single fillet welds and multipass single-V-groove welds.

6.7.2.6 Process Selection

Carefully select the welding process to be used. Use a process that can provide the highest welding speeds and is able to make the weld in the least amount of weld passes. Make use of automated welding, whenever possible, as these techniques are often capable of depositing accurate amounts of weld metal at extremely high speeds. Fortunately, with modern arc welding processes we are often able to use high welding speeds which can help us when fighting distortion.

6.7.2.7 Equal Distribution of Welding Stresses

Use welding sequences or back step welding to minimize distortion. The back step technique allows for the general welding progression to be in one direction but enables us to deposit each smaller section of weld in the opposite direction. This provides us the ability to use prior welds as a locking effect for successive weld deposits. (See Figure 6.14, Back Step Weld Technique.)

6.7.2.8 Other Welding Sequences

Whenever possible, weld from the center outward on a joint or structure, also, alternate sides for successive passes on double-sided multipass welding. An even better method to control distortion is to weld both sides of a double-sided weld simultaneously.

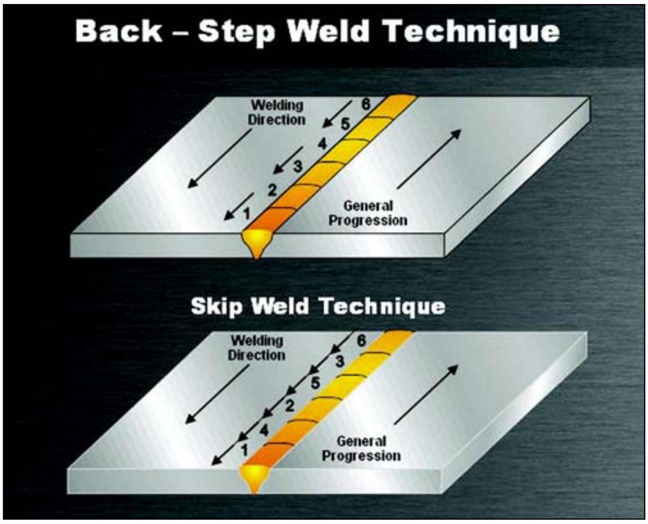


Figure 6.14—The Back Step Welding Technique Helps to More Equally Distribute Weld Stresses Throughout the Component

6.7.2.9 Use the Shrinkage to your Advantage

Preset components so that they will move during welding to the desired shape or position after weld shrinkage. This is a method of using the shrinkage stresses to work for us during the manufacturing process. Through experimentation we can determine the correct amount of offset required to compensate for weld shrinkage. We then need only to control the size of the weld to produce consistently aligned welded components. (See Figure 6.15, Pre-Bend or Bevel Components.)

6.7.2.10 Jigs and Fixtures

Consider the use of restraints such as clamps, jigs, fixtures, and back-to-back assembly. Locking the weldment in place with clamps fixed to a solid base plate to hold the weldment in position and prevent movement during welding is a common method of combating distortion. Another method is to place two weldments back-to-back and clamp them tightly together. The welding is completed on both assemblies and allowed to cool before the clamps are removed. Prebending can be combined with this technique by inserting spacers at suitable positions between the assemblies before clamping and welding. (See Figure 6.16, Back-to-Back Assembly.)

6.7.2.11 Use Extrusions to Reduce the Amount of Welding

Consider the use of aluminum extrusions. Aluminum can be easily acquired in standard and customized extruded configurations. Many manufacturers are taking advantage of extruded aluminum sections to reduce the amount of welding in their fabricated components. Extruded aluminum offers a perfect opportunity to reduce welding (potential for distortion), assist with assembly, and often improve aesthetics.

6.7.3 Conclusion

Weld distortion is caused by localized expansion and contraction of metal as it is heated and cooled during the welding process. Constraint from the unheated sur-

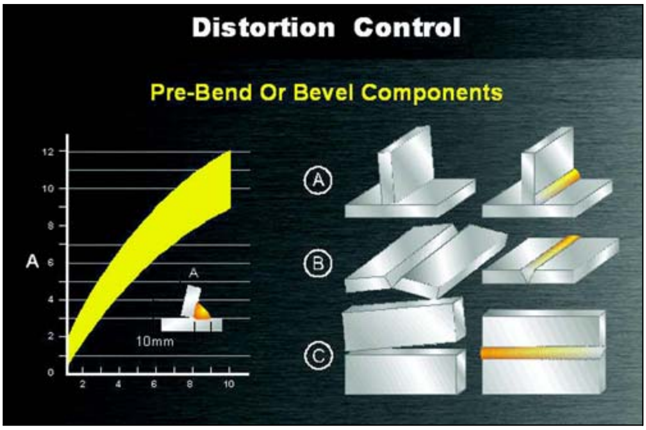


Figure 6.15—Pre-Bend or Bevel Technique Uses the Weld Shrinkage to Move the Component Into the Desired Position After Welding

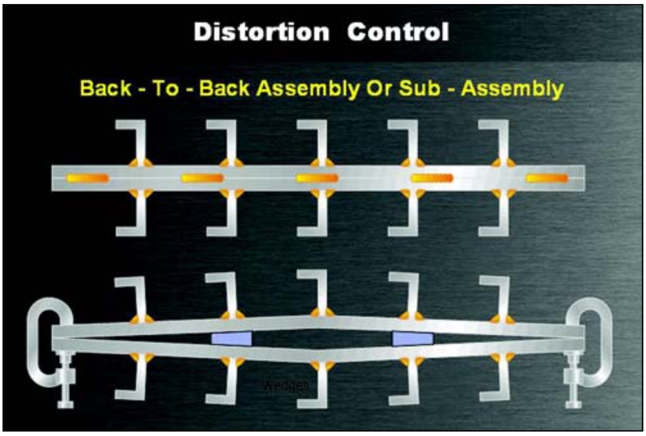
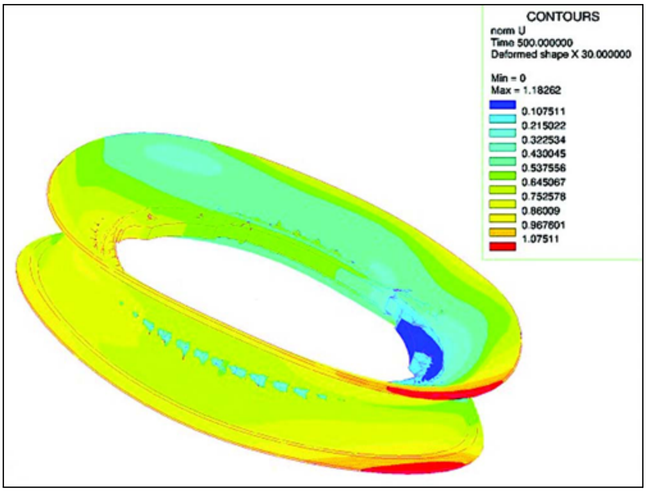


Figure 6.16—Back-to-Back Assembly is One Method of Using Restraint to Prevent Movement During Welding

rounding metal produces permanent changes in the internal tension stresses that are generated. If these stresses are high enough and cannot be adequately resisted by the structure distortion will result. A large number of factors determine what stress levels are developed, their orientation, and whether they will cause unacceptable distortion. These factors include the size and the shape of the welds and where they are located in the structure being welded, the rate of heat input during the welding process, the size and material thickness of the components being welded, the assembly sequence, the welding sequence and others. Ideally to avoid distortion, there should be as little welding as possible in a structure, and especially where thin gauge metal is involved. With aluminum we have some options that are available to us at the design stage that may help to eliminate excessive welding. The use of castings, extrusions, forgings and bent or roll-formed shapes can often help to minimize the amount of welding and thereby reduce distortion.

One method of understanding and planning for distortion prevention is the use of specialized computer software (see Figures 6.17 and 6.18). Computer software has been developed as a tool to understand and predict distortions caused by the welding processes. This software is presented as being able to predict residual stresses and distortions after welding thus allowing welding engineers the opportunity to optimize their process (weld sequence and/or clamping condition).

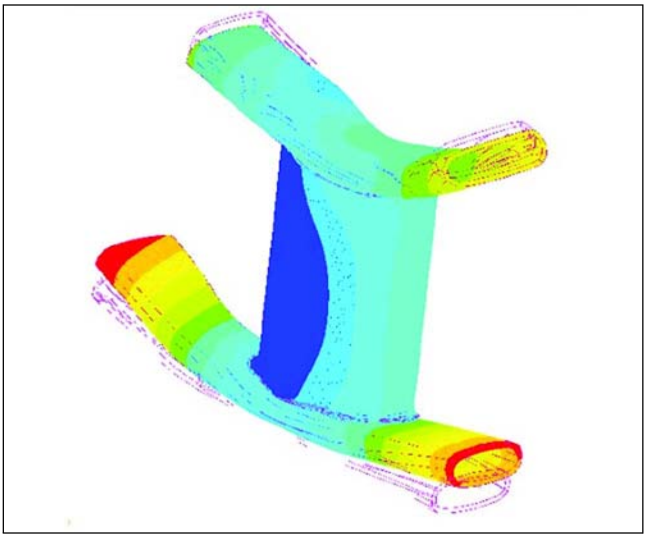
Many complex aluminum structures are welded every day without excessive distortion problems. This is often achieved through the combined effort of designers and manufacturers. The designers need to carefully consider options that are available to help reduce the amount of welding within the structure. The designer also needs to position those necessary welds in areas that promote distortion the very least. The manufacturer needs to develop, employ and control the necessary equipment (welding process, fixturing, etc.) and techniques (welding sequences and balancing methods) to reduce the effects of the welding process that promote distortion.



Note: The various colors indicate the different degrees of distortion throughout the welded structure, dark blue, which shows little if any distortion, to red, which indicates maximum distortion within the structure.

Picture courtesy of SYSWELD, a product of the ESI Group, www.esi-group.com.

Figure 6.17—Distortion of Welded Aluminum Wheel



The purple dotted line indicates the original design dimensions (without distortion). The color dark blue indicates little if any distortion. The pale blue, green, and yellow show varying degrees of distortion to red, which indicates maximum distortion within the structure.

Picture courtesy of SYSWELD, a product of the ESI Group, www.esi-group.com.

Figure 6.18—Predicted Distortion of an Aluminum Suspension Frame

6.8 What is the Friction Stir Welding Process and is it Used for Welding Aluminum?

? I have heard of a welding process called friction stir welding. Apparently it is quite new, and it is a particularly good process for welding aluminum. Can you give me some information on this process and the types of applications for which it is used?

6.8.1 All About the Process

Invented in 1991, the friction stir welding (FSW) process was developed at, and is patented by, The Welding Institute (TWI) in Cambridge, U.K. The first commercially available friction stir welding machines were produced by ESAB Welding and Cutting Products at its equipment manufacturing plant in Laxa, Sweden. The development of this process was a significant change from the conventional rotary motion and linear reciprocating friction welding processes. It provided a great deal of flexibility within the friction welding process group.

The conventional rotary friction welding process requires at least one of the parts being joined to be rotated and has the practical limitation of joining regular-shaped components, preferably circular in cross section and limited in their length. Short tubes or round bars of the same diameter are a good example.

The linear reciprocating process also requires movement of the parts being joined. This process uses a straight-line back and forth motion between the two parts to generate the friction. Regularity of the parts being joined is not as necessary with this process; however, movement of the part during welding is essential.

The obvious limitation of both processes is the joint design and component geometry restrictions. At least one of the parts being joined must have an axis of symmetry and be capable of being rotated or moved about that axis.

Friction stir welding is capable of fabricating either butt or lap joints in a wide range of materials thickness and lengths. During FSW, heat is generated by rubbing a non-consumable tool on the substrate intended for joining and by the deformation produced by passing a tool through the material being joined. The rotating tool creates volumetric heating, so as the tool is progressed, a continuous joint is created. Friction stir welding, like other types of friction welds, is largely solid-state in nature. As a result, friction stir welds are not susceptible to solidification-related defects that may hinder other fusion welding processes.

The FSW process is diagrammed in Figure 6.19. The parts intended for joining are usually arranged in a butt configuration. The rotating tool is then brought into contact with the workpieces. The tool has two basic components: the probe, which protrudes from the lower surface of the tool, and the shoulder, which is relatively large diameter. The length of the probe is typically designed to match closely the thickness of the workpieces.

Welding is initiated by first plunging the rotating probe into the workpieces until the shoulder is in close contact with the component top surface. Friction heat is generated as the rotating shoulder rubs on the top surface under an applied force. Once suffi-

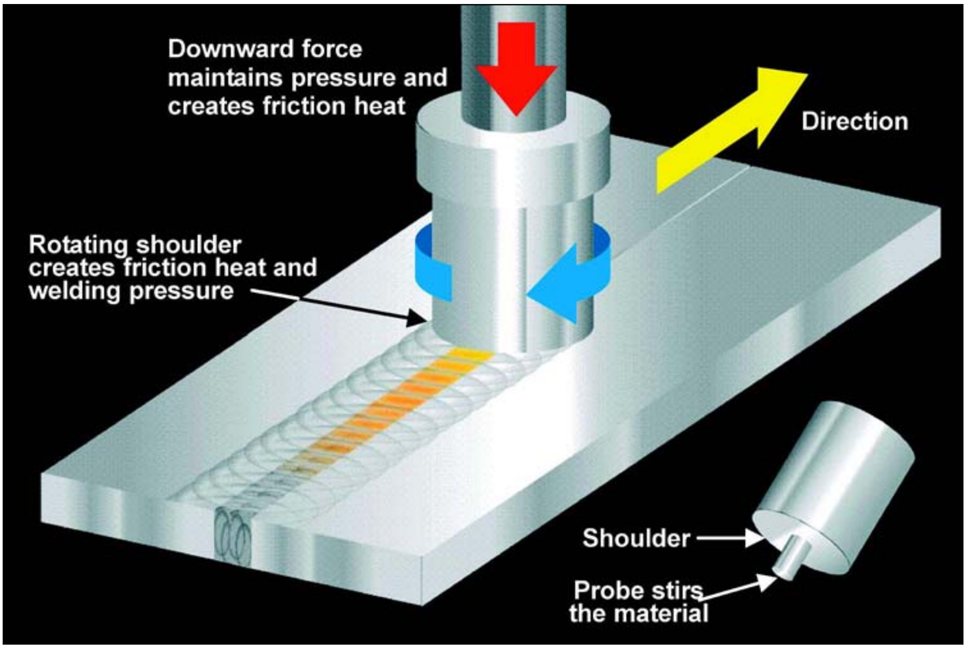


Figure 6.19—The FSW Process

cient heat is generated and conducted into the workpiece, the rotating tool is propelled forward. Material is softened by the heating action of the shoulder, and transported by the probe across the bondline, facilitating the joint.

One limitation of the FSW process is mechanical stability of the tool at operating temperature. During FSW, the tool is responsible for not only heating the substrate material to forging temperatures, but also providing the mechanical action of forging. Therefore, tool material must be capable of sustaining high forging loads and temperatures in contact with the deforming substrate material without either excessive wear or deformation. As a result, the bulk of the FSW applications have involved low forging temperature materials. Of these, the most important class of materials has been aluminum.

A range of virtually all classes of aluminum alloys has been successfully friction stir welded. These include the 1xxx, 2xxx, 3xxx, 4xxx, 5xxx, 6xxx, and 7xxx alloys, as well as the newer Al-Li alloys. Each alloy system is metallurgically distinct. Furthermore, different alloys within the given class may have different forging characteristics. As a result, processing for each alloy may vary. However, high-integrity joints can be obtained in all classes.

6.8.2 Some Applications

Because of the potential of advantages over arc welding in some applications associated with this processes, FSW has received interest from many areas of industry working with aluminum. The advantages include the ability to produce long lengths of welds in aluminum without any melting of the base metal. This provides important metallurgical advantages when compared to conventional arc welding. Melting of the base material does not occur with FSW, and this eliminates the possibility of solidification cracking, which is often a problem when arc welding some aluminum alloys. Other advantages may include the following: low distortion associated with lower heating during the welding process; elimination of porosity problems that are challenging when arc welding aluminum; minimum edge preparation, as butt joints are typically performed with a square-butt preparation; and the absence of welding consumables such as shielding gas or filler metal.

The friction stir welding process is being used and/or evaluated for use within the aerospace, military vehicle, aircraft, automotive, shipbuilding, railway rolling stock industries, and invariably many others.

6.8.3 Conclusion

Friction stir welding is a relatively new welding process that has found use in a number of industries for joining aluminum alloys. It has some advantages over the more traditional welding processes such as GMAW and GTAW, one of which is its ability to successfully weld some of the specialized high-strength heat-treatable aluminum alloys that are generally accepted as being nonweldable by the arc welding methods.

6.9 Can Aluminum be Welded to Steel with the GMAW or GTAW Processes?

? Can I weld aluminum to steel with the GMAW or GTAW processes?

6.9.1 Methods Used to Facilitate the Welding of Aluminum to Steel

While aluminum can be joined to most other metals with relative ease by adhesive bonding or mechanical fastening, special techniques are required if it is to be arc welded to other metals such as steel. Very brittle intermetallic compounds are formed when metals such as steel, copper, magnesium, or titanium are directly arc welded to aluminum. To avoid these brittle compounds, some special techniques have been developed to isolate the other metal from the molten aluminum during the arc welding process. The two most common methods of facilitating arc welding of aluminum to steel are bimetallic transition inserts and coating the dissimilar material prior to welding.

6.9.2 Bimetallic Transition Inserts

Bimetallic transition materials are available commercially in combinations of aluminum to such other materials as steel, stainless steel, and copper. These inserts are best described as sections of material that are comprised of one part aluminum with another material already bonded to the aluminum. The methods used for bonding these dissimilar materials together, and thus forming the bimetallic transition, are usually rolling, explosion welding, friction welding, flash welding, or hot pressure welding—but not arc welding. The arc welding of these steel aluminum transition inserts can be performed by the normal arc welding methods such as GMAW or GTAW. One side of the insert is welded steel to steel and the other aluminum to aluminum. Care should be taken to avoid overheating the inserts during welding, which may cause growth of brittle intermetallic compounds at the steel-aluminum interface of the transition insert. It is good practice to perform the aluminum-to-aluminum weld first. In this way, one can provide a larger heat sink when the steel-to-steel welding is performed and help prevent the steel-aluminum interface from overheating.

The bimetallic transition insert is a popular method of joining aluminum to steel and is often used for producing welded connections of excellent quality within structural applications, such as attaching aluminum deckhouses to steel decks on ships, for tube sheets in heat exchangers that have aluminum tubing with steel or stainless steel tube sheets, and for producing arc welded joints between aluminum and steel pipelines.

6.9.3 Coating the Dissimilar Material Prior to Welding

A coating can be applied to steel to facilitate its arc welding to aluminum. One method is to coat the steel with aluminum. This is sometimes achieved by dip coating (hot dip aluminizing) or brazing the aluminum to the surface of the steel. Once coated, the steel member can be arc welded to the aluminum member, if care is taken to prevent the arc from impinging on the steel. A technique must be used during welding to direct the arc onto the aluminum member and allow the molten aluminum from the weld pool to flow onto the aluminum-coated steel. Another method of joining aluminum to steel involves coating the steel surface with silver solder. The joint is then welded using aluminum filler metal, taking care not to burn through the barrier layer of silver solder. Neither of these coating-type joint methods is typically depended upon for full mechanical strength. They are usually used for sealing purposes only.

6.9.4 Conclusion

The GMAW and GTAW processes can not be used to weld aluminum directly to steel, however there are materials available known as bimetallic transition materials that can assist with the joining of the dissimilar materials. Also, methods that use a coating of aluminum on the steel have been used to assist in this process, however, these types of joints are usually low strength and not used in structural applications.

6.10 What are Bimetallic Inserts and How are they Made by Explosion Welding?

? There is a product on the market called aluminum and steel bimetal plate. This plate has aluminum on one side and steel on the other and assists with the arc welding of aluminum to steel. I understand that it can be manufactured by explosion welding. Can you please provide some information about how this plate is made, what procedures are used when welding it, and in general, how it is used in industry?

6.10.1 Joining Aluminum to Other Metals

The type of plate that you are referring to is, as you said, a bimetal plate, made from two different metals. It is used to assist with the arc welding of aluminum to other metals, such as stainless steel, carbon steel, copper and titanium. This product is available in both plate and pipe, and is essential if you need to use the arc welding process as the principle joining method between components manufactured from these dissimilar materials. While adhesive bonding or mechanical fastening can join aluminum to most other metals relatively easily, arc welding is not a reliable method for joining aluminum to other materials, such as steel. Very brittle intermetallic compounds form when metals such as steel, copper or titanium are directly arc welded to aluminum. To avoid the problems associated with arc welding these dissimilar materials, it is necessary to use special fabrication techniques to isolate the other metal from the molten aluminum during the arc welding process. The most common method of facilitating the joining of an aluminum component to a steel component by arc welding is by using the bimetallic transition insert.

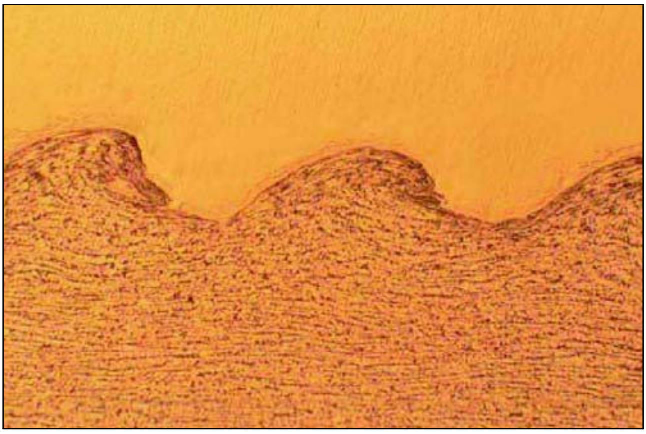
6.10.2 Bimetallic Transition Inserts

Bimetallic transition inserts are available commercially in combinations of aluminum to such other materials as carbon steel, stainless steel, copper, and titanium. These inserts are sections of material that are comprised of one part aluminum with another material already bonded to the aluminum. The methods used for bonding these dissimilar materials together, and thus forming the bimetallic transition, are usually, explosion welding, rolling, friction welding, flash welding, or hot pressure welding.

6.10.3 Explosion Welding of Aluminum to Other Materials

Explosion welding is a common method used for producing bimetallic transition inserts. This solid-state welding process produces a weld by high-velocity impact of the workpieces as a result of detonation. As the name suggests, this welding process uses an explosive force to create the weld. The explosion accelerates one of the materials to a speed at which a metallic bond will form between the two materials when they collide. In a fraction of a second, the weld is produced without the addition of filler metal. This is essentially a low-temperature process in that intense heating and melting of the workpiece does not occur. The faying surfaces, however, are heated to some extent by the energy of the collision, and welding is accomplished through plastic flow of the metal on those surfaces. Welding takes place progressively as the explosion and the force it creates advance from one end of the joint to the other creating the characteristic wavy profile as seen in Figure 6.20. A typical arrangement of the components and setup for explosion welding are shown in the schematic Figure 6.21.

Typically, there are three components used in explosion welding: the backing plate, the cladding plate and the explosive. The backing plate generally remains stationary, the cladding plate is usually positioned parallel to the backing plate and a specified spacing, referred to as the standoff distance, separates the two. The explosion locally bends and accelerates the cladding plate across the standoff distance at a high velocity so that it collides at an angle with and welds to the backing plate. This angular collision and welding front progresses across the joint as the explosion takes place.



Photograph courtesy of Dynamic Materials Corporation, a manufacturer of bimetallic transition components.

Figure 6.20—Microetched Sample of the Characteristic Wavy Profile of an Explosion Welded Joint

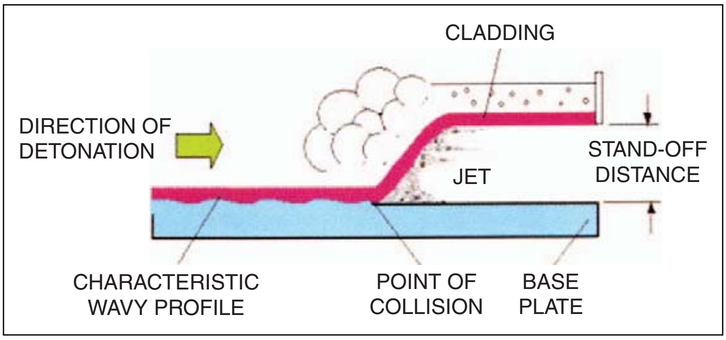


Figure 6.21—Schematic of the Explosion Welding Process

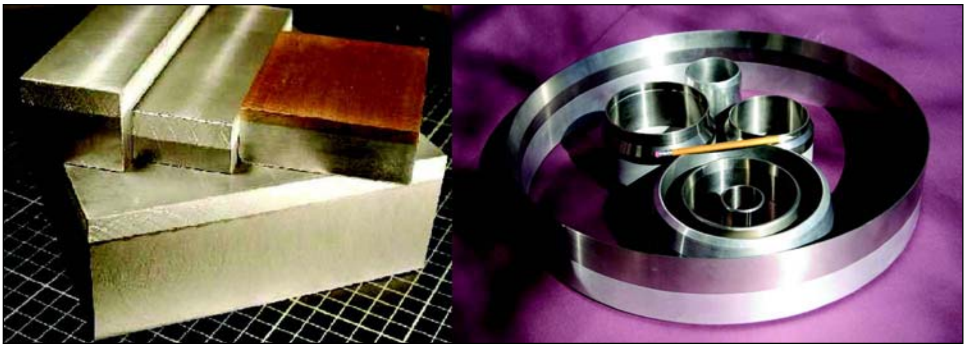
There are three important interrelated variables of the explosion welding process: collision velocity, collision angle, and cladding material velocity. With explosion welding, intense pressure is necessary to make a weld generate at the point of collision. Pressure forces the two surfaces into intimate contact and causes localized plastic flow in the immediate area of the collision point. At the same time, a jet forms at the point of collision, as shown in Figure 6.21. The jet sweeps away the original surface layer on each component, along with any contaminating film that might be present. This exposes clean underlying metal, which is required to make a strong metallurgical bond. Residual pressures within the system are maintained long enough after the collision to avoid release of the intimate contact of the metal components and to complete the weld.

6.10.4 Welding of Bimetallic Transition Inserts

The arc welding of these steel aluminum transition inserts in production can be performed by the normal arc welding methods such as GMAW or GTAW. One side of the insert is welded steel-to-steel and the other aluminum-to-aluminum. Care should be taken to avoid overheating the inserts during welding, which may cause growth of brittle intermetallic compounds at the steel-aluminum interface of the transition insert. It is good practice to perform the aluminum-to-aluminum weld first. Proceeding in this manner can provide a larger heat sink when the steel-to-steel welding is performed, and it also helps to prevent the steel-aluminum interface from overheating. Some manufactures of these bimetallic inserts provide recommended procedures which suggest that care should be taken to avoid heating the steel-aluminum bond zone above 600°F [316°C] during welding. In addition, joint details are recommended for some applications that are designed to minimize the amount of heat directed towards the transition bond.

6.10.5 Principal Applications for Bimetallic Transition Inserts

Bimetallic transition inserts are offered in various thicknesses and are available in strip, plate, and tubular section (see Figure 6.22). The bimetallic transition insert is a popular method of joining aluminum to steel and is often used for producing welded connections of excellent quality within structural applications. One principal use is in the shipbuilding industry, where transition insert joints have become the standard means of welding aluminum superstructures and bulkheads to steel hulls, framing, and decks. This aluminum-to-steel weldability has given naval architects and shipbuilders the freedom to maximize the benefits of materials; the strength and economy of steel, combined with the lightweight and corrosion resistance of aluminum. Structural transition inserts for shipbuilding use are typically composed of 5xxx series aluminum bonded to low carbon-manganese steel. Bimetallic transition inserts are also available for use in other applications like tube sheets in heat exchangers that have aluminum tubing with steel or stainless steel tube sheets as well as for producing arc-welded joints between aluminum and stainless steel pipelines (see Figure 6.23).



Photograph courtesy of Dynamic Materials Corporation, a manufacturer of bimetallic transition components.

Figure 6.22—Transition Joints are Offered in Various Thicknesses and are Available in Strip, Plate, and Tubular Sections

Photograph courtesy of Dynamic Materials Corporation, a manufacturer of bimetallic transition components.

Figure 6.23—Welded Transition Coupling Between Aluminum and Stainless Steel on a Pipeline

6.10.6 Conclusion

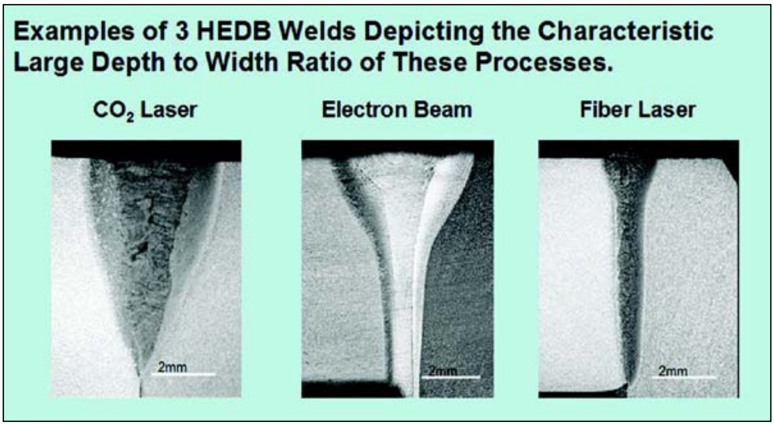
Explosion Welding is often used to weld aluminum to steel; the material produced from this welding method is called Bimetal Plate, and is used in a number of industries to successfully facilitate the arc welding of transitions between aluminum and other materials such as steel.

6.11 Are the Laser Beam and Electron Beam Welding Processes Used for the Welding of Aluminum Alloys?

? I recently heard that aluminum could be welded with the laser welding process and the electron beam welding process. How effective are these processes for welding aluminum, and how do these welding processes work?

6.11.1 Some Advantages of High Energy Density Beam Welding

Laser beam welding (LBW) and Electron beam welding (EBW) are high energy density beam processes. These processes can be very effective for welding aluminum and its alloys and can offer many advantages. Some of their advantages are precise heat input, elevated welding speeds on thin-gauge sheet, deep penetration on thick material, extremely narrow weld bead with parallel fusion boundaries, welds with very high depth-to-width ratios, narrow heat-affected zones, and minimal thermal distortion (some of these characteristics can be seen in Figure 6.24).



Photographs courtesy of IPG Photonics.

Figure 6.24—High Energy Density Beam Welds Showing the Classic Deep and Narrow Penetration of these Processes

One thing to remember, however, is the equipment for these high energy density processes has a capital cost generally much higher than that of the more traditional welding methods.

6.11.2 Laser Beam Welding (LBW)

The word **laser** is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. In the basic process, a laser medium is stimulated such that some of the atoms are raised to a higher energy, *metastable*, state. Each time an electron from these atoms drops back to the ground state, a photon is emitted. As this photon passes by nearby atoms in the metastable state, more photons are released with the same frequency and phase. If the conditions are correct, a chain reaction results, producing waves of high-intensity coherent light. The laser medium is held in a cavity with mirrors at each end. These mirrors reflect the waves back and forth until the buildup of photons is self-sustaining and the laser beam is well collimated. This is called "lasing." One of the mirrors is partially reflective, thus the laser beam is able to exit the cavity and be carried to the workpiece for welding.

6.11.3 Operation

Laser welding operates in two fundamental modes: conduction limited welding, or keyhole welding. The mode in which the laser will operate depends directly on the continuous power density of the laser spot on the workpiece.

1. **Conduction limited welding.** This mode occurs when the continuous power density is relatively low. The laser radiation is absorbed through conduction at the surface of the material and does not substantially penetrate into the material. Consequently, the conduction limited welds tend to exhibit a high width to depth ratio.

2. **Keyhole welding.** When the laser beam focuses to a small enough spot, the energy concentration at the workpiece is so intense that the metal directly under the beam vaporizes, producing a keyhole-shaped effect in the base material. This keyhole enhances energy input to the workpiece by permitting multiple reflections of the beam. This is particularly helpful with laser welding since it enhances coupling of the beam to the aluminum and overcomes the high optical reflectivity inherent to the material. Keyhole welding is capable of producing welds of a high depth-to-width ratio.

6.11.4 Types of Lasers

There are many types of lasers available. Each has their own wavelength and method of generating a laser beam. These different wavelengths are necessary for various applications including industrial, scientific, military, medical, and others. However, only a few types of lasers have the wattage level capacity for "industrial" welding. These lasers would include the CO_2, Nd:YAG, Diode, and Fiber lasers. Aluminum with its high reflectivity and thermal conductivity requires higher power than steel for example.

6.11.4.1 CO_2 Gas Lasers

The most common gas laser for welding aluminum is the CO_2 laser. The laser medium is a small amount of CO_2 gas molecules in a mixture with nitrogen and helium. The gas mixture flows through a discharge tube. The CO_2 gas is excited by an electrical discharge to produce the light. This light has a wavelength of 10.6 microns. Since the surface of aluminum and its alloys is highly reflective, absorption of the large wavelength CO_2 beam can be poor on aluminum. Once a keyhole is established, however, beam power to heat efficiency is approximately 80%. Another consequence of the large wavelength is that mirrors must be used to transport the beam.

6.11.4.2 Nd:YAG Solid-State Lasers

The most common solid-state laser for welding aluminum is the Nd:YAG laser. The laser medium is neodymium (Nd) doped into an yttrium aluminum garnet (YAG) crystal. This crystal is excited by flash lamps or diodes and emits light with a wavelength of 1.06 microns. This small wavelength not only offers good absorptivity on aluminum, but also permits transmission by fiber optic cable. Waves travel back and forth between reflectors to produce a high energy, collimated beam. This beam is focused with lenses, and then launched into a fiber optic cable for transport to the workpiece.

Beam power to heat efficiency is approximately 80% once keyhole is established. Since the beam is carried by fiber optic cable, it is possible to combine beams from two or more lasers in a single optics head to increase power. Combining beams also permits variations in beam configuration, since the beams are not superimposed axially. Inline dual beam laser welding is thought to increase keyhole stability by lengthening the keyhole. Dual beams may also be rotated with respect to the joint line, which improves gap-bridging capability in butt welds. When welding a multi-gauge butt weld, a bias towards the thicker sheet may be used (examples of Nb:YAG laser beam welds can be seen in Figures 6.25 and 6.26). Figure 6.25 illustrates a fillet welded joint in 2014-T4 material. The base is 0.12 in [3 mm] thick and the stringer is 0.14 in [3.5 mm] thick. ER 2319 filler wire was used, and the stringers were welded using a Nd:YAG laser beam, delivered by fiber optics, at a power of about 3.5 kW. The welding speed was 2 m/min. Figure 6.26 shows the microstructure of a similar weld between an aluminum stringer and skin panel.

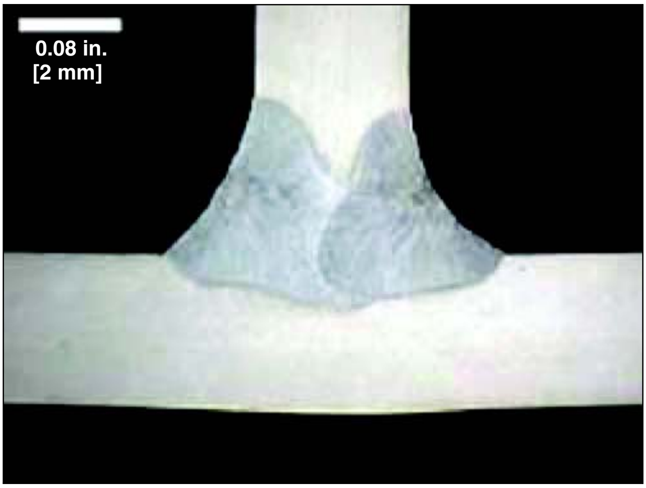


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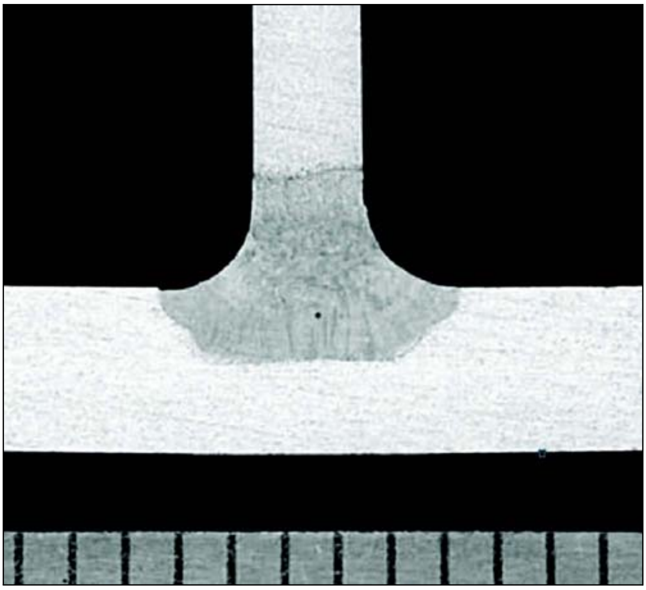
Figure 6.25—Stiffener Manufactured from AA2014 Alloy in the T4 Condition



Note: Scale bar is in mm.

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Figure 6.26—Microstructure of Laser Weld Between Stringer and Skin Panel

6.11.4.3 Direct Diode Lasers

Direct diode lasers are also used for welding aluminum. The laser medium is a multilayer semiconductor diode that is excited by forward biasing. A series of these diodes are stacked to form a linear array that produces a linear beam. The width: length dimensions of this linear beam can be varied by different optical designs. This diffuse beam gives a conduction mode weld, unlike the keyhole weld from CO_2 and Nd:YAG laser.

6.11.4.4 Fiber Lasers

Relatively new to the laser processing field are the fiber lasers. These lasers operate at the same wavelengths as YAG lasers offering several advantages. They are extremely compact, offer wall plug efficiencies greater than 30%, have diode life greater than 100 000 h, and beam quality substantially better than any other material processing laser. In addition, they are available in power levels of 50 kW and higher. They have greatly expanded the market for laser processing with applications including remote welding, high speed deep penetration welding of Aluminum and numerous applications in the Automotive, Aerospace, Nuclear and Ship Building industries. The high-quality beam allows fluence levels, which produce welds only previously possible with electron beam.

6.11.5 Electron Beam Welding (EBW)

This process is capable of producing welds in aluminum plates up to 6 in [152 mm] thick with a depth-to-width ratio of 40-to-1. The electron beam is generated by a triode electron gun, composed of a cathode emitter, grid cup, and anode, which are configured to produce an electrostatic field that accelerates and shapes the electrons into a well-collimated beam.

Heat is generated in the workpiece by impingement of the high-velocity electrons. The key advantage of EBW is the transformation of beam energy into heat, at a constant efficiency of approximately 99%, regardless of material, surface condition, or joint configuration. This is particularly advantageous for aluminum and its alloys, which have high optical reflectivity. The energy concentration from this process on the workpiece is so intense that the metal directly under the beam is vaporized, producing a keyhole.

During electron beam welding, it is necessity to shield against the X-radiation by use of lead, thick steel or concrete enclosures. In addition, since the beam diameters are extremely focused, good fit-up is required for butt joints. The electron beam is diffused by transmission through air; thus, electron beam welding is often performed in a vacuum. It is possible however, with a sacrifice in efficiency, to weld in partial vacuum or atmospheric pressure.

6.11.6 Conclusion

The high density beam processes have some unique characteristics, probably the most significant being their ability to produce very precise weld beads with a deep and narrow penetration profile. These processes tend to be relatively expensive to introduce and are often seen in specialized applications. However, some advantages associated with the high welding speeds are making these processes more attractive to high productivity environments.

6.12 Can Resistance Spot Welding be Used Effectively on Aluminum Alloys?

? I am a welder who has worked with GMAW welding of steel and GMAW welding of aluminum. I have seen resistance spot welding of steel but do not fully understand the process. How does this process work and can it be used for welding aluminum?

6.12.1 About the Process

Resistance Spot Welding (RSW) is one of a group of welding processes that rely on the resistance of metals to the flow of electrical current to produce the heat required for coalescence. The resistance spot welding process produces a localized weld spot between the metals being welded. This is achieved by clamping two, or sometimes more, pieces of material together between two copper electrodes, and then passing a current between the electrodes for a short period of time while the material is subjected to localized pressure (see Figure 6.27). The heat that is generated during this welding process is a result of the electrical resistance of the metal through which the electricity is passed. It is a fusion welding process because melting must occur at the interface between the joint members to cause coalescence, form a cast nugget, and join the members together. Sectioned and polished resistance spot welds can be seen in Figures 6.28 and 6.29. Figure 6.28 shows an aerospace industry weld of very high quality made in a high-strength 2xxx series alloy, and Figure 6.29 shows a commercial quality spot weld in aluminum sheet that has some characteristic discontinuities. The shrinkage cracking within the center of this weld is not uncommon in commercial quality aluminum spot welds particularly in the more crack sensitive 6xxx series materials. These types of discontinuities in the center of the weld nugget will not dramatically reduce the welds strength as the majority of the applied load to this type of joint is at the edges of the nugget. On testing, such a weld would normally fail by tearing out from the thin sheet, leaving a button the same diameter as the weld nugget on the other sheet.

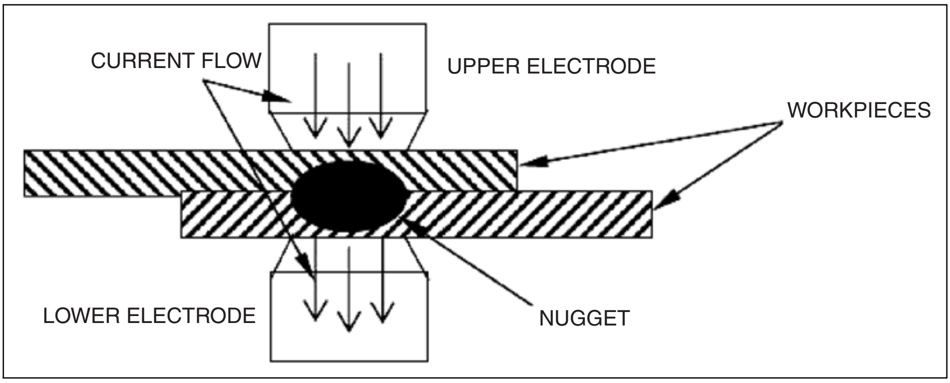

Figure 6.27—Illustration of the Resistance Spot Welding Process

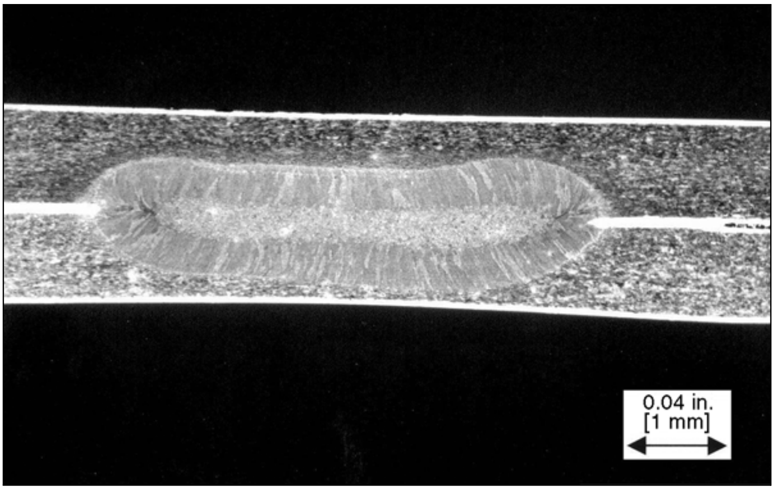

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Figure 6.28—An Aerospace Quality Spot Weld in 0.035 in to 0.039 in [0.9 mm to 1.0 mm] Alclad 2024 Alloy

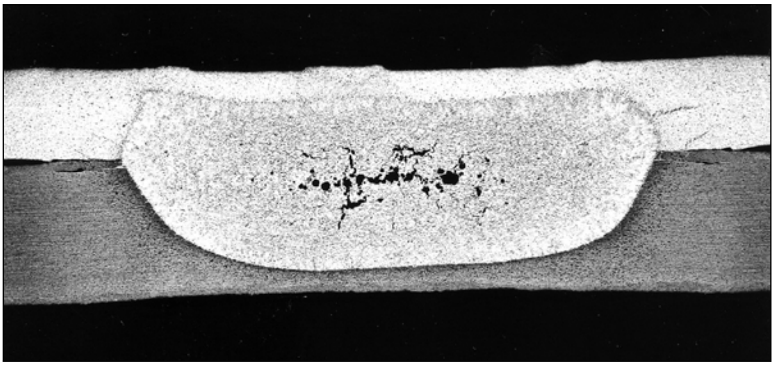

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Figure 6.29—Commercial Quality Spot Weld in 0.08 in [2 mm] 6082 to 0.05 in [1.2 mm] 6016

We can now examine some of the advantages and disadvantages of the resistance spot welding process.

6.12.2 Advantages

- It is an automatic process that requires little operator training.
- It is commonly used for robotic applications.

- The potential for distortion is minimal.
- Welds are typically completed in a very short cycle time (less than one second).
- Welds can be conducted through lubricants, sealers, and structural adhesives.
- Weld location and spacing can be easily adjusted to provide the required joint strength.
- Almost all aluminum alloys are weldable.
- Weld appearance is generally consistent.
- No filler metal is required.

6.12.3 Disadvantages

- It is limited to lap joints.
- It requires access to both sides of the joint.
- The maximum size of a welded assembly is not unlimited.
- The process is not easily made portable.

6.12.4 Differences Between Resistance Spot Welding Aluminum and Steel

Aluminum can be welded very successfully with the resistance spot welding process; however, because of the differences in some of the physical properties of aluminum and steel the procedures used to weld aluminum are somewhat different than those used for steel. The primary differences are listed below.

6.12.4.1 Surface Oxide

When exposed to the atmosphere, aluminum oxidizes rapidly to form its characteristic oxide covering. With prolonged exposure to the atmosphere the aluminum oxide increases in thickness progressively, until the oxidation rate slows down substantially after about 10 days. Controlling the oxide surface on the aluminum is probably the most important single factor in producing consistently good resistant spot welds in aluminum. If the aluminum oxide is relatively thin, has a uniform electrical resistance at all points and is consistent from part to part, then welding procedures can be developed to make consistently high-quality welds.

The condition of the aluminum oxide on the material to be welded may vary greatly due to the length and method of storage and/or the effects of prior fabrication procedures. For best results the aluminum oxide should be removed from all surfaces prior to welding and the weld performed as soon as possible after oxide removal. This is particularly important for aircraft quality welds. About one day is a practical limit for lapsed time between cleaning and welding, to obtain high-quality welds.

6.12.4.2 Coefficient of Thermal Expansion

The coefficient of thermal expansion of aluminum is approximately twice that of steel. Consequently, aluminum alloys undergo greater expansion and contraction when going from a solid to a liquid and back to a solid-state. These increased dimensional changes are greatest in the weld zone and can result in cracking of the nugget if the time interval is very short, or if the welding machine being used is not equipped to accommodate all of the physical characteristics of aluminum. Weld cracking and the stresses built up by metal shrinkage are eliminated or substantially reduced by features found in resistance welders designed for welding aluminum. One of these is a welding head of low inertia and low friction, which permits the head to be moved quickly and with a high degree of control. It has been found that a quick, closely controlled increase in forging pressure, applied when the aluminum in the weld zone is cooling across its plastic range, helps to avert cracks or voids in the weld. Another pertinent feature is the use of current decay, which retards the cooling rate and thus lengthens the time over which the nugget freezes. Current decay makes the controlled application of forging pressure more effective and also relieves the rapid buildup of shrinkage stresses in the weld.

6.12.4.3 Thermal Conductivity

The thermal conductivity of aluminum and its alloys is approximately three times that of steel. Therefore, the rate of heat loss from the weld area is much greater in aluminum than steel. Since the amount of heat loss is also a function of time, it is especially advantageous that welding time be kept short in aluminum welding. Higher welding current and shorter welding time must be used to resistance weld aluminum when compared to steel.

6.12.4.4 Electrical Conductivity

Aluminum and its alloys have a much higher electrical conductivity than steel. Consequently, welding current is typically required to be three times that used for an equivalent gauge in steel. High electrical conductivity can also increase the potential for shunting, which is welding current by-passing or shunting through a previous weld instead of going through the surface contacts where the weld is being made. Care should be taken to compensate for shunting with increased current where necessary.

6.12.4.5 Electrode Wear

The copper that is used for the electrodes in spot welding can become alloyed with the aluminum surface leading to rapid electrode wear and deterioration of weld quality. Consequently, electrode life is generally shorter than when welding galvanized steel. Careful control of electrode condition and good water cooling are essential. The best results are obtained with very frequent light cleaning of the electrode tips to prevent significant buildup of an alloy layer.

6.12.5 Conclusion

The unique properties of aluminum typically require welding procedures and equipment that may have some special features. The equipment will deliver higher currents at lower weld times than for steel. However, once the physical differences of the material and the need for specific equipment are understood, excellent welds can be made by this process.

6.13 What is Stud Welding and Can it be Used Successfully on Aluminum?

? I have been offered a new fabrication contract; it is an aluminum structural job that is predominantly arc welded. However, it would also involve a substantial amount of stud welding. I have welded aluminum with both the GMAW and GTAW processes, so the arc welding is not a problem, but I have never used stud welding. What exactly is this stud welding and can the process be used to weld to aluminum?

6.13.1 Process Description

The arc stud welding process can by described as an arc welding process in which a fastener can be end-joined to a metal workpiece instantaneously (see Figure 6.30). It is a complete fastening system, using a wide variety of fasteners with literally hundreds of uses—each permanently installed by one person, working on one side of the workpiece, in less than one second. Arc stud welding in general can be regarded as a sequential combination of two mechanisms, one mechanical and one electrical.

There are two frequently used types of stud welding; the first is Drawn Arc Stud Welding (DASW) also known as Arc Stud Welding, or Gas-Arc Stud Welding when using a shielding gas like argon, or Short-Arc Stud Welding when the arc time is less than 100 ms. The second type is Capacitor Discharge Stud Welding (CDSW). The source of the electrical energy for CD welding comes from a bank of electrostatic charged capacitors.

Figure 6.30—Aluminum Fastener Stud Welded to Aluminum Plate

6.13.2 Drawn Arc Stud Welding of Aluminum

In the Drawn Arc Stud Welding Process (see Figure 6.31) a fastener and ceramic ferrule are firmly placed against the work surface under spring tension. Triggering the weld gun automatically lifts the fastener from the base metal and initiates a controlled electric arc to melt the end of the fastener and a portion of the base metal. The ceramic ferrule shields the arc, concentrates the heat and contains the molten metal in the weld zone for maximum weld strength and reliability. At the precise moment the end of fastener and the parent metal become fully molten, the fastener is automatically plunged into the work surface. The metal solidifies and a high quality fusion weld is completed. The expendable ferrule is broken away to expose a smooth and complete fillet at the stud base. A ferrule and argon shielding gas must be used together for Drawn Arc aluminum welding. For higher production rates the Gas Arc process is used to welded aluminum studs using gas shielding alone without ceramic ferrules.

6.13.3 Capacitor Discharge Stud Welding of Aluminum

Capacitor Discharge (CD) stud welding is generally used to weld small diameter fasteners to thin base metals. The weld end of the fastener must have a small timing tip specifically designed for the CD welding process. Dimensional consistency of the tips is essential for control the weld time and to give consistently reproducible results. CD studs can be manufactured in a wide variety of shapes.

For welding steel studs the Contact CD process is normally used. In this process the tipped stud stays in contact with the base material until the operator triggers the weld. This allows the instantaneous discharge of current from a bank of DC capacitors. The energy from the capacitors vaporizes the high resistance tip and creates an ionization path for peak current flow and arcing across the areas to be joined.

For welding aluminum the Gap CD process is normally used. Using the Gap CD process the weld is shorter and the amperage is higher. This eliminates the need for gas shielding.

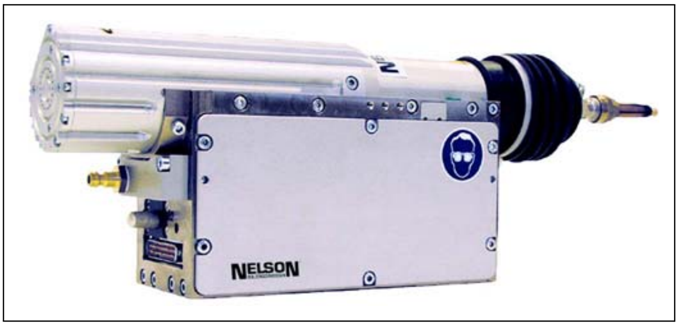


Figure 6.31—Servo Electric Head for Automated or Robotic Drawn Arc Stud Welding

With the initial gap process the stud is retracted manually or pneumatically to hold the stud at a specific height above the base material until the weld is triggered. Using Auto Gap CD guns the stud starts in a position against the base material. When the weld is triggered the gun will go through a sequence where the stud is retracted and released.

The pressure to make the welds is generally less than 20 pound. This reduces the need for rigid fixtures and backside support. In hand held CD guns the source of the pressure is usually a spring. For mounted production guns air pressure is normally used. When the weld current is discharged the pressure applied by the gun fuses the melted end of the stud to the parent metal surface. The welds are completed the two to six milliseconds to create a bond that is stronger than the fastener.

The studs may be loaded or fed into the chucks on the front of the CD guns manually, semi-automatically or the welding process may be fully automated. CD welding has the ability to weld small diameter studs to very thin material. Because the weld cycle is extremely short there is little heat transfer and welds made using CD will not have pronounced distortion, burn-through or reverse side discoloration even on thin material. In addition to welding aluminum CD is also used to weld material with high thermal conductivity such as copper, and copper-zinc alloys. See Figure 6.32.

6.13.4 Stud Welding Aluminum—Process Selection

The basic difference between the Drawn Arc Process and the Capacitor Discharge Process in aluminum is that the typical arc time for Drawn Arc is considerably longer (0.12 second and longer) than for Capacitor Discharge (0.006 second) and the peak current with CD may be ten times of that for Drawn Arc. Because the CD welds are essentially an explosion, the use of shielding gas is not needed. Due to the longer weld time of the Drawn Arc process the use of an inert gas shielding (Argon) is needed when welding aluminum.

The choice of process depends on stud size and material thickness. For larger studs in structural applications the Drawn Arc process is the process of choice. Some stud

Figure 6.32—Hand Held Gun for Capacitor Discharge (CD) Stud Welding

welding equipment manufacturers have suggested that the Capacitor Discharge process has limitations that may make it less reliable than the Drawn Arc process in quality driven applications such as automotive due to the lack of process controllability.

6.13.5 Quality of Stud Welds in Aluminum

If the Drawn Arc process is the method to be used the key to success in stud welding aluminum are clean base material, low amperage, long arc time, long lift, low gas flow rates, good seal of foot and ferrule on base plate to ensure adequate gas shielding and using the correct plunge dampener.

Some considerations are:

- The Ferrule needs to be even with the front of the gas foot, if the ferrule is even with the face of the foot it will assure that there is a good seal against the base martial and prevent the escape of shielding gas needed to give adequate shielding of the molten aluminum during the weld cycle. Both the ferrule and argon gas work together to protect the weld.
- The gas flow rate should be as low as possible but still adequate to prevent oxidation of the aluminum. Inadequate shielding will result in welds that will not pass the 15 degree bend test. Typical argon flow rates are 12 to 18 cubic feet per hour (0.35 to 0.50 cubic meters per hour).
- Base material should be as clean as possible. If chemical etching is not feasible, the aluminum can be mechanically cleaned with rotary burr, or with clean stainless steel wire brushing.
- It is important to note that the lift of arc length settings for aluminum is longer than those used for welding steel studs. The longer effective arc length that is needed for aluminum stud welding is achieved partially by the use of a compound point on the weld base of the stud. The lift setting on the gun still needs to be increased to the settings recommended by the stud welding equipment suppler in order to obtain good weld results.
- Typically reverse polarity is used when stud welding aluminum.
- Avoid the use of excessive weld heat; the best indication of excessive weld heat is when the molten aluminum fuses to the ceramic ferrule. When there is a proper balance of weld time, amperage, arc length, and gas flow the ferrule can be removed from the weld intact with little or no damage to it.
- A final caution is needed regarding the thickness of material that is used for standard aluminum stud welding applications. The base material thickness must be at least 1/2 the stud diameter. This ratio is greater than the 1/3 ratio of material thickness to stud diameter that is used for steel. The extra thickness for aluminum is needed to prevent burning through the base during the longer weld time cycle and to support the load that is applied to the stud.

6.13.6 AWS Code for Stud Welding Aluminum

The AWS D1.2 *Structural Welding Code—Aluminum* has a section specifically designated to the stud welding of aluminum in the 2008 edition this is Section 6 — *Stud Welding*.

This section of the code contains general requirements for arc stud welding and capacitor discharge stud welding of aluminum alloy studs to aluminum alloys and stipulates specific requirements within the following areas:

- The mechanical properties of aluminum alloy studs.
- Workmanship Requirements.
- Preproduction Testing Requirements.
- Procedure Qualification and Performance Qualification Testing.
- Inspection of Stud Welding during production.
- Acceptance Criteria for Bend Tests and Tension Tests.

Note: One area to be aware of is the differences between bend test procedures for aluminum studs compared to the procedures used for steel studs. Bend tests for aluminum studs are typically conducted by bending the stud to an angle of only 15 degrees from the axis of the stud, whereas steel studs are typically required to be bent to 30 degrees.

6.13.7 Conclusion

The stud welding process is a commercially available welding process that is used for attaching studs to the surface of material. This process is suitable for use with aluminum provided the correct workmanship requirements are followed. When the correct process and procedures are used, consistently reliable joints can be made.

Stud welding aluminum is different than stud welding steel and there are some specific considerations when selecting the most appropriate equipment and developing suitable procedures. If you are getting into this welding process on aluminum for the first time I would suggest that you consult the experts who can provide specialized technical support.

Acknowledgment

I would like to thank Nelson Stud Welding, Inc. for providing me technical assistance and permission to reproduce the photographs in this article.

6.14 How does Plasma Arc Cutting of Aluminum Compare with Laser Cutting and Water Jet Cutting?

? I am looking at installing an automated cutting system for aluminum in my welding fabrication shop. I was thinking of using plasma arc cutting however, I have been informed that there may be some advantages of using either laser cutting or water jet cutting. Can you please give me an overview of plasma arc cutting of aluminum and some information about laser and water jet cutting in comparison?

6.14.1 The Most Appropriate Cutting Process

Traditionally plasma arc cutting has been the predominant cutting process for aluminum plate. However, it may now be said that cutting technology is at a point where any size manufacturer may afford and operate state-of-the-art cutting equipment. It is also said, that the newer laser and water jet technologies have some inherent advantages over their older counterpart plasma that may be desirable for some specific applications. What we need to ask is this, just because something is new or different does this necessarily equate to it being better or more efficient? When choosing a cutting process you always have to determine which process will supply you with the optimum solution for your particular application. The selection of the most appropriate cutting process is most definitely application driven.

6.14.2 Overview of Plasma Arc Cutting of Aluminum

Plasma arc cutting is performed with specialized equipment developed for this purpose. The arc is drawn from a tungsten or hafnium electrode using DCEN power. The arc plasma is constricted through a small orifice to produce a concentrated heat source and high gas velocity, which melts, expels metal, and makes the cut. For cutting thin metal there may be a single gas flow to provide both plasma and arc shielding, but for cutting thicker metal, dual gas flows are used. The single flow gases may consist of air or nitrogen. For dual flows the gases may consist of nitrogen, argon, or an argon/hydrogen mixture. The selection of the gas or gases for a plasma arc cutting operation is based on such factors as gas cost, the thickness of metal to be cut, and the quality of cut required. Because air is the cheapest gas, single flow systems using air have been designed for cutting sheet metal gauges. For the medium thickness materials nitrogen is common. For the thickest metal and the best quality cuts, an argon/hydrogen mixture is usually specified for the plasma gas. The manufacturer's recommendations should be followed in selecting the gas or gases for each application.

Plasma arc cutting leaves a heat-affected zone, and some partial melting of grain boundaries. The partial melting of the grain boundaries can result in micro cracking in the cut edges. The 2xxx, 6xxx, and 7xxx series (heat-treatable) alloys are particularly prone to this type of cracking. Most standards for fabricating aluminum require that the plasma cut edge be removed by machining to a depth of around 1/8 inch (3.2 mm) before the edge is incorporated into a weld.

The plasma arc process can also be very effective for gouging aluminum; unlike air carbon arc gouging, the plasma gouging process leaves a clean smooth surface after gouging. The orifice in the gun has to be larger than one for plasma cutting to reduce the plasma jet velocity, and the power source should have a high operating voltage to maintain a long but stable arc. Some expertise is involved in manipulating the gun to achieve effective gouging. A groove depth per pass of not more than about 1/4 inch (6.3 mm) is preferred, but multiple passes are practical. Mechanized gouging is also practical with this process.

Plasma cutting is sometimes performed either on a water table or under water.

When aluminum is plasma arc cut on a water table, molten aluminum dropping into the water can "steal" oxygen from the water and release free hydrogen gas. If the hydrogen gas becomes trapped between the aluminum and the water surface, an explosive mixture can develop and be ignited by the cutting arc. Forced air cross flow should be used between the aluminum and the water to avoid a build up of hydrogen. Similarly, when aluminum is plasma arc cut under water, the molten aluminum reacts with the water to release hydrogen. Dangerous concentrations should be avoided by inserting a perforated piping system in the tank to aerate the water. The situations in the above two examples can be accelerated by use of argon-hydrogen shielding gas mixtures, due to the extra hydrogen being available.

Safety precautions should also be taken when plasma arc cutting aluminum over or within water, when the apparatus being used is one that cuts a variety of metals. Steel dross can build up in the bottom of the tank and if molten aluminum contacts it, a thermite reaction can occur and sustain itself until the bottom of the tank opens up. Frequent removal of the dross and scrap metal from the cutting water tank is recommended.

6.14.3 Comparing Plasma Arc Cutting with Laser and Water Jet Cutting

Plasma Arc Cutting Aluminum *(Typically the lowest capital investment) see Figure 6.33*

Today plasma arc cutting can be divided into conventional plasma and precision plasma.

- ***Conventional plasma arc cutting***

Provides fast high production rates and high cutting speeds if cut face quality is not a major concern.

Figure 6.33—High Speed Conventional Plasma Arc Cutting of Aluminum Sheet

- ***Precision plasma arc cutting***

Provides improved cut quality but lower cutting speeds when compared to conventional plasma. Precision plasma arc cutting speed is comparable to laser, but without the higher laser cut quality. This process is sometimes seen as an economical compromise between laser and conventional plasma.

Laser Cutting Aluminum *(Typically the highest capital investment) see Figure 6.34*

This process cuts by converting an electrical energy source into a light energy beam which is focused by a lens or series of mirrors onto the base surface, heating the material to a molten state. Laser will typically provide good quality cuts at speeds lower than conventional plasma but far greater than abrasive water jet cutting. Cut accuracy is superior to both conventional and precision plasma arc cutting.

Abrasive Water Jet Cutting Aluminum *(Typically higher capital investment than plasma and lower than laser, but retains the highest operating costs of all three) see Figure 6.35*

This process cuts by passing high pressure water through a cutting head orifice, mixing the water with fine garnet abrasive powder in a focusing tube, creating a high velocity jet mixture. The jet mixture forces the abrasive particles through the material, creating a mechanical erosion of the workpiece.

This cutting process has superior cut quality and accuracy when compared to the plasma arc and laser cutting processes. However, its slower cutting speed and higher operating costs can be a hindrance when obtaining and operating this type of machine.

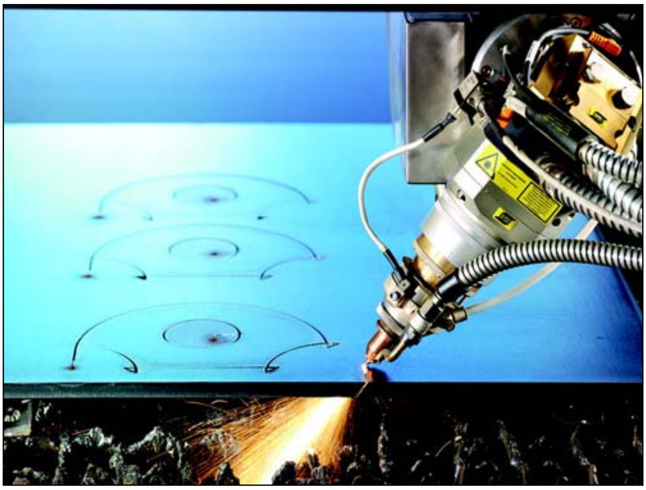


Figure 6.34—Mechanized Laser Cutting of Aluminum Plate

Figure 6.35—Extremely High Quality Precision Cutting of Aluminum with Abrasive Water Jet

6.14.4 Combination Cutting

One should not overlook the possibility of combining more than one of the above cutting processes on the same cutting machine and using them within the same manufactured component. For example, it is often advantageous to implement water jet cutting for some of the area of a component, taking advantage of its extremely high quality and accuracy of cut, but also implementing plasma for its highly superior speed. For instance, a flange or some other mechanically connected component, which requires very high tolerance on one section of the component, may have that section produced with water jet. The larger profiles on the same part that have a lower tolerance requirement can be cut at higher speed by plasma. This is a method used to capitalize on the best characteristics of each of the cutting processes in order to produce the most economical part.

6.14.5 Conclusion

In order to select the most appropriate cutting process there are a number of variables that need to be evaluated, such as: material thickness to be cut, cutting speed, cut accuracy, cut quality, material savings, environmental issues, operation cost, equipment investment cost, and return on investment. The choice of cutting process is usually based on cutting speed and cut quality however; economical and environmental considerations are often equally important. My advice is to work with a reputable cutting equipment supplier who has trained and experienced staff. They will be able to evaluate your particular cutting requirements based on the above variables in order to determine which of these three processes or combination of processes may best meet your specific needs.

Acknowledgment

I would like to thank the aluminum association for allowing me to use some material on plasma arc cutting from their publication "Welding Aluminum Theory and Practice."

Chapter 7

The Common Welding Processes

7.1 Introduction to the GTAW and GMAW Processes

The most commonly used processes for the welding of Aluminum alloys are Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW). For many years, aluminum was generally joined mechanically with rivets and other fastening devices. Improved welding techniques gradually caused a trend toward welded joints. Today, welded aluminum joints are specified in a wide variety of industries.

Oxyfuel gas welding with oxyhydrogen or oxyacetylene was initially used for aluminum welding. This process required the use of fluxes which had to be removed subsequent to welding, since they were a corrosion hazard to the aluminum in the presence of moisture. Furthermore, welding, other than in the flat position, was very difficult. Both factors imposed a severe limitation on welded aluminum structures.

The development of the gas tungsten arc welding process (GTAW) during World War II provided a practical solution to the problems associated with oxyfuel gas welding of aluminum. The corrosion hazard resulting from the flux was eliminated by the inert gas shield and all-position welding techniques were developed. Subsequently, the gas metal arc welding process (GMAW) was developed and provided a substantial reduction in welding time for applications where this process was suitable.

7.2 Gas Tungsten Arc Welding of Aluminum Alloys

7.2.1 Introduction

Gas Tungsten Arc welding (GTAW) sometimes referred to as Tungsten Inert Gas (TIG) welding is an arc welding process that uses a nonconsumable tungsten electrode with either alternating current (AC), direct current electrode positive (DCEP) or direct current electrode negative (DCEN) and inert shielding gas (see Figures 7.1 and 7.2 for a typical GTAW setup). Filler metal may or may not be added as dictated by the joint type and the base alloy being welded. The GTAW process was developed prior to the development of the Gas Metal Arc welding (GMAW) process and for some time was applied to all metal thicknesses and joint types. GTAW is not as effective on many joint types as (GMAW) Gas Metal Arc Welding. It does not penetrate readily into narrow grooves or corners and has difficulty in penetrating to the root of fillet welds. Welding speeds with GTAW are nearly always lower than with GMAW thus, the GMAW process has definite advantages for many production applications. GTAW

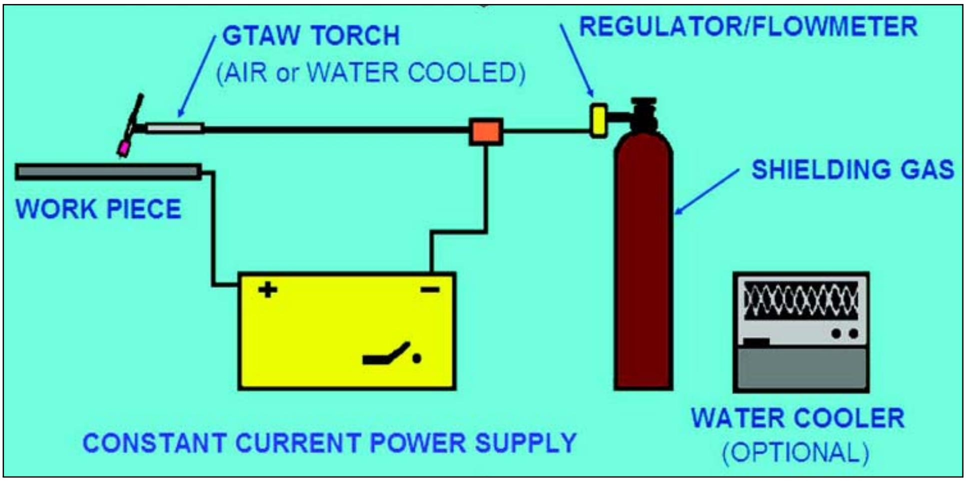


Figure 7.1—Schematic Representation of GTAW Equipment Showing the Different Components

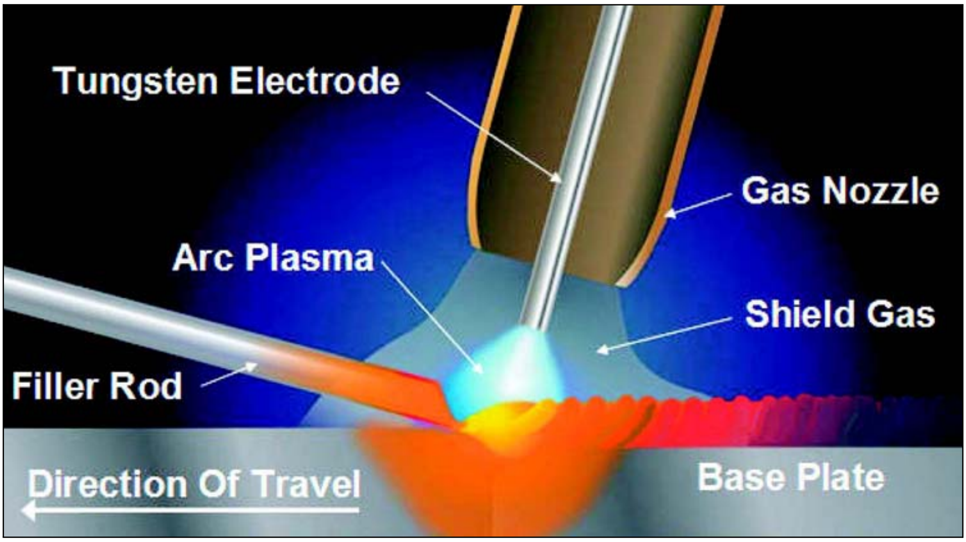


Figure 7.2—GTAW Welding Arc and Surrounding Components

is most commonly used for the welding of thinner gauges of aluminum where visual appearance is most important, it is also used for the precision welding of root runs from one side, usually in full penetration groove welds and for pipe welding. The most important difference between GTAW welding of aluminum, when compared to welding steel, is the need for the breakdown and removal of aluminum oxide during the welding process. For this reason the aluminum alloys are predominately welded with the alternating current (AC) version of this welding process (see Figure 7.3). The

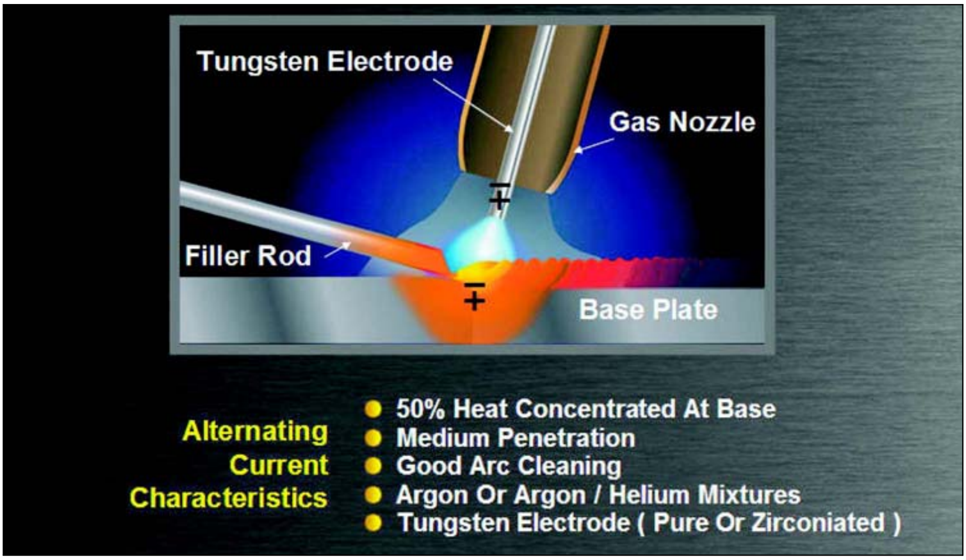
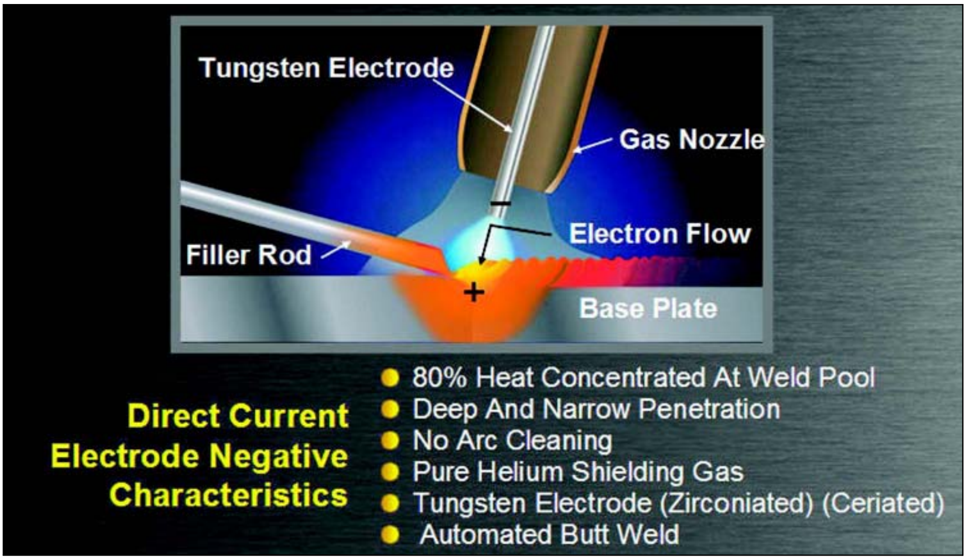


Figure 7.3—Alternating Current GTAW and its Characteristics

direct current versions are sometimes used for special applications. An ideal GTAW welding arc supplies the maximum amount of heat into the base metal and the minimum into the electrode. It also provides good arc cleaning to remove the aluminum oxide in advance of the weld pool. Each of the three modes mentioned above (AC, DCEN and DCEP) lacks one or more of these requirements to some degree. DCEN which is sometimes used for heavier material thickness (up to 1 in [25 mm]) produces an arc that concentrates about 80% of its heat into the weld pool (see Figure 7.4). This results in relatively deep and narrow weld penetration using a small diameter electrode, but it does not provide any arc cleaning to remove aluminum oxides. Alternatively, the DCEP arc gives excellent cleaning action, but only about 20% of its heat is generated at the weld pool, and the remaining 80% at the electrode. With DCEP weld penetration is extremely shallow and a large tungsten electrode must be used to carry the excessive heat generated on that side of the arc. The DCEP GTAW process is not typically used for welding aluminum.

7.2.2 GTAW Welding with Alternating Current (AC)

A balanced wave AC arc gives adequate cleaning action for most applications and divides the arc heat about evenly between electrode and weld pool. As previously mentioned the AC mode of GTAW is by far the most common method of welding aluminum alloys with this process. There are some GTAW power sources for AC welding that allow for adjustment of the balance between polarities (% electrode positive and % electrode negative) this enables the user to choose either enhanced arc cleaning (DCEP) or greater penetrating power (DCEN). Under most circumstances AC GTAW is used predominantly for manual welding whereas DCEN GTAW is manly used for automatic welding.



Direct Current Electrode Negative Characteristics

- 80% Heat Concentrated At Weld Pool
- Deep And Narrow Penetration
- No Arc Cleaning
- Pure Helium Shielding Gas
- Tungsten Electrode (Zirconiated) (Ceriated)
- Automated Butt Weld

Figure 7.4—Direct Current GTAW and its Characteristics

7.2.3 GTAW Welding with Direct Current Electrode Negative (DCEN)

DCEN mode is primarily used for automatic welding of tightly fitted butt joints, in gauges up to 1/4 in [6.4 mm] or sometimes even thicker. Special care is required in preparing the joint surfaces prior to welding because this method of GTAW provides no arc cleaning during the welding process. It is normal to use the pure helium shielding gas with this polarity; this provides a much hotter arc and can produce excellent quality welds with this process. This polarity is most often used for automated seam welding of butt joints.

7.2.4 GTAW Welding with Direct Current Electrode Positive (DCEP)

With the exception of a few applications, such as a method sometimes referred to as TIG Brazing used primarily on thin metal, DCEP has very limited application for aluminum.

7.2.5 GTAW Alternating Current (AC) Equipment

GTAW AC requires the following equipment:

- An AC power source designed for GTAW.
- A shielding gas supply.
- A welding torch.

- A tungsten electrode.
- Aluminum alloy filler metal.

7.2.6 Power Sources

The AC-GTAW process was designed to create a welding arc using the sine wave single-phase power supplied by utilities but with the open circuit voltage limited to 80 V for operator safety. A high-frequency power generator is added to initiate the arc and help stabilize it. This resulted from the need for the arc to extinguish and reignite as the weld polarity is reversed during each cycle with the AC current (120 times per second with 60 Hertz [Hz] power). Because aluminum is a less effective emitter of electrons than tungsten, the electrode-positive half cycle is more difficult to initiate than the electrode negative one. If delays in positive reigniting occur, the arc tends to act as a rectifier in the welding circuit. High-voltage, high-frequency energy is added to the arc, which overcomes this problem under normal circumstances. Under abnormal conditions, such as the arc not remaining in one location long enough to completely remove all traces of oxide from the aluminum surface, it is possible for some electrode positive half cycles to be not only late in initiating but sometimes missing entirely. This makes the arc so unstable that it does not readily accept filler metal into the weld pool, and if the instability is severe enough, there will also be a noticeable loss of cleaning action. This is because arc cleaning occurs during the electrode positive (EP) half cycle. Moreover, an unstable arc tends to act as a rectifier in the welding circuit, which could cause a DC component in the power source transformer to overheat. The more modern welding machines have circuit components to stabilize this instability. The development of GTAW power sources has resulted in machines that provide more stable arcs under adverse conditions. In fact, some of these machines can maintain an AC arc, under normal conditions, without continuous high-frequency stabilization. Welding without continuous high-frequency power is especially beneficial in situations where radio frequency interference cannot be tolerated. These machines are called square wave power sources because their welding current wave form resembles a true square wave.

Another power supply available for GTAW is the inverter. The inverter is not characterized by its voltage current relationship but by its method of attaining a direct current or alternating current output and its very fast response. Inverter power supplies receive the incoming line voltages and “chop” it at a rapid frequency (in the kilohertz [kHz] range), which is converted to a low-frequency AC square wave. Some GTAW inverter square wave power supplies offer enhanced circuitry that provides adjustable AC frequency leading to a more focused arc, one that improves arc control. All this has become possible with the advent of solid-state electronics, and the result is a machine with novel performance features for welding aluminum. Square wave and inverter type machines have other advantages. They tend to cause much less tungsten spitting, a common cause of tungsten inclusions in welds. Wave form and frequency are no longer tied to the wave form and frequency of the incoming power. Also, the positive and negative portions of each cycle do not have to be identical, either in amplitude or in time interval. Some square wave machines allow the welder to select an arc with either more penetrating power or more cleaning action than provided by a balanced arc. However, square wave machines also have some limitations. Without continuous high-frequency power, some tend to give an unstable arc on an etched surface or on weld metal surfaces. To correct for the latter it is common to wire brush between weld passes or to use continuous high frequency and, if necessary, adjust it to maximum power.

7.2.7 Shielding Gas for GTAW Welding

For most AC-GTAW of aluminum, pure argon is the preferred shielding gas, but occasionally additions of helium are added to argon to produce a hotter arc. Argon helium mixtures can be helpful on thick metal or when large weld grooves are to be filled in the flat position. Helium is more expensive than argon and, because of its lower density, greater gas flows are necessary. A mixture of more than 50% helium in argon is seldom used for AC-GTAW, 25% helium in argon is usually the preferred mixture. Consistent purity of the shielding gas is essential. Welding grade gases are supplied to 99.997% purity for argon and 99.995% for helium, and their dew points are –76°F [–60°C] and –71°F [–56°C] or lower, respectively. It is important to remember that this purity must be maintained until the gas reaches the arc. If the gas delivery system has any leaks, the gas will become contaminated. Particular care should be taken to ensure that all connections within the gas line are secure and that they cannot aspirate air into the gas supply. It is recommended that the power source provide a preflow and postflow of shielding gas for periods that can be adjusted to suit the welding conditions. Preflow is designed to purge the gas hoses and the torch before an arc is initiated. Postflow is designed to protect the tungsten electrode and weld crater from the atmosphere until it has cooled enough that it will not be oxidized.

7.2.8 Welding Torches

The thickness of metal to be welded, and therefore the current levels to be used, will determine the torch size needed. For manual welding there are very few applications requiring more than about 400 A. Torches are rated for light, medium and heavy duty service. Only torches for very light duty can be used without water cooling. Most torches can be fitted with either ceramic or metal cups. Because the ceramic cups are much cheaper and quite durable, they have become the most popular. The smaller torches have the benefit of smaller hose and cable assemblies, which makes them easier to manipulate. On the other hand, the larger torches permit the use of larger electrodes (3/16 in to 1/4 in [4.8 mm to 6.4 mm]) and therefore greater welding current. A torch to be used for welding a range of aluminum thicknesses should be capable of accepting at least a 3/16 in [4.8 mm] diameter tungsten electrode. Manufacturer's ratings for torches for GTAW are often based on DCEN welding and, if so, must be down rated for AC welding of aluminum. The rating of a torch for AC welding should be ascertained before purchase. See Figure 7.5 for a typical GTAW torch brake-down and Figure 7.6 for a selection of GTAW torches.

7.2.9 Tungsten Electrodes

Electrodes are commonly available in three types: pure tungsten, zirconiated tungsten and thoriated tungsten. Either pure or zirconiated tungsten electrodes are suitable for AC welding, but the zirconiated have a slightly higher current rating and are somewhat less prone to become contaminated. Table 7.1 gives current ratings for the two common types of tungsten electrodes used for AC welding. Thoriated tungsten electrodes are generally recommended for DC welding. With a conventional AC welding

Figure 7.5—GTAW Torch Components

Figure 7.6—Selection of GTAW Torches

arc they do not melt to form a hemispherical tip but instead tend to produce a number of projections. An arc from these projections is unstable, gives poor cleaning action and may cause tungsten spitting into the weld pool. Thus, thoriated tungsten electrodes are generally not recommended for conventional AC welding. They are recommended for use with some inverter type power supplies for AC or DC welding. Other GTAW electrode types, Ceriated and Lanthanated, are available. Some benefits claimed by the manufacturers over standard tungsten electrodes include longer life,

Table 7.1—Current Ratings for Tungsten Electrodes for AC-GTAW with Argon

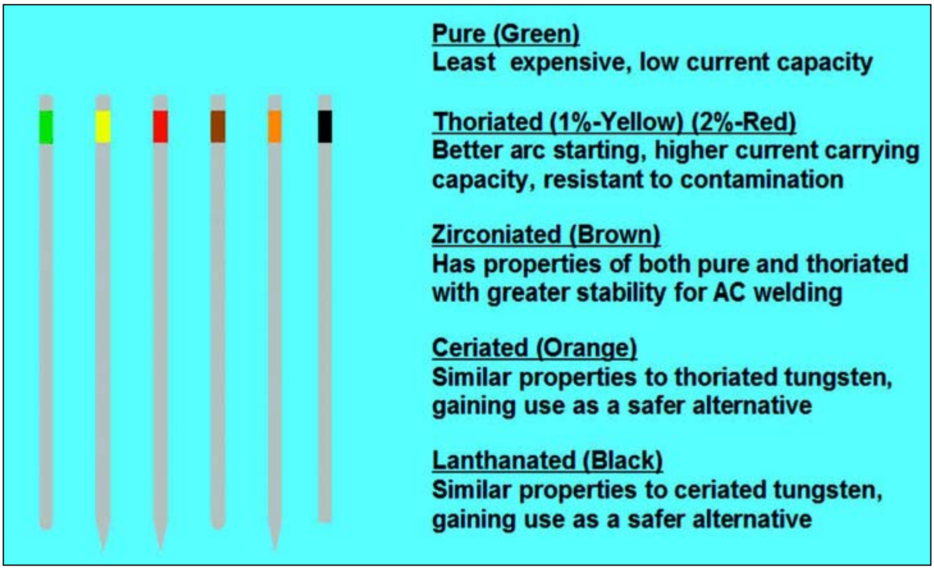
Electrode Diameter		Balanced Wave		Unbalanced Wave	
in	mm	Pure Tungsten	Zirconium Tungsten	Pure Tungsten	Zirconium Tungsten
0.010	0.3	Up to 15	Up to 15	Up to 15	Up to 15
0.020	0.5	10–20	5–20	5–15	5–20
0.040	1.0	20–30	20–60	10–60	15–80
1/16	1.6	30–80	60–120	50–100	70–150
3/32	2.4	60–130	100–180	100–160	140–235
1/8	3.2	100–180	160–250	150–210	225–325
5/32	4.0	160–240	200–320	200–275	300–400
3/16	4.8	190–300	290–390	240–350	400–500
1/4	6.3	250–400	340–525	325–450	500–630

Note: All values are based on argon shielding gas. With other shielding gases, equipment types, or applications, current ranges may vary somewhat.

greater current-carrying capacity, and freedom from the small amount of radioactivity associated with the thoriated tungsten's. Figure 7.7 shows the color coding for tungsten electrodes as stipulated by AWS A5.12, *Specification for Tungsten and Tungsten-Alloy Electrodes for Arc Welding and Cutting*. For satisfactory AC-GTAW, the electrode tip should form into a smooth, stable, molten hemisphere. If the electrode is too large for the current being used, it will not form a full hemisphere and the arc will tend to be misdirected. If the electrode is too small, its end may become overheated and form a ball larger than the electrode, and the arc will be unstable and tend to spit tungsten into the weld pool. Some square wave inverter power supply manufactures recommend that the tungsten be ground to a point for optimum performance when welding AC. Electrodes are normally used in sizes from 0.040 in to 3/16 in [1.016 mm to 4.8 mm]. Although size selection is usually made according to current rating, there are times when a larger than normal electrode is beneficial, such as when welding with the torch in the horizontal position, because a large electrode has less tendency to overheat and to droop. In this case the welder can use the next larger electrode than the one specified and taper grind the tip to the specified size so that it forms the desired hemisphere.

7.2.10 Filler Alloy

GTAW can be performed with or without adding filler alloy. Welding without addition of filler alloy is called autogenous welding. It can be used for edge and corner welds and also for automatic butt welding of light gauge sheet, but it should be limited to alloys that are not prone to hot cracking. Some aluminum base alloys require a filler alloy of a different chemistry to themselves to modify the weld chemistry and prevent solidification cracking. GTAW with filler usually uses filler rod in 36 in [914 mm] lengths, in sizes from 1/16 in to 1/4 in [1.6 mm to 6.4 mm]. Under some circumstances it may be



Pure (Green)
Least expensive, low current capacity

Thoriated (1%-Yellow) (2%-Red)
Better arc starting, higher current carrying capacity, resistant to contamination

Zirconiated (Brown)
Has properties of both pure and thoriated with greater stability for AC welding

Ceriated (Orange)
Similar properties to thoriated tungsten, gaining use as a safer alternative

Lanthanated (Black)
Similar properties to ceriated tungsten, gaining use as a safer alternative

Figure 7.7—Different Types of Tungsten Electrodes and Their Color Coding

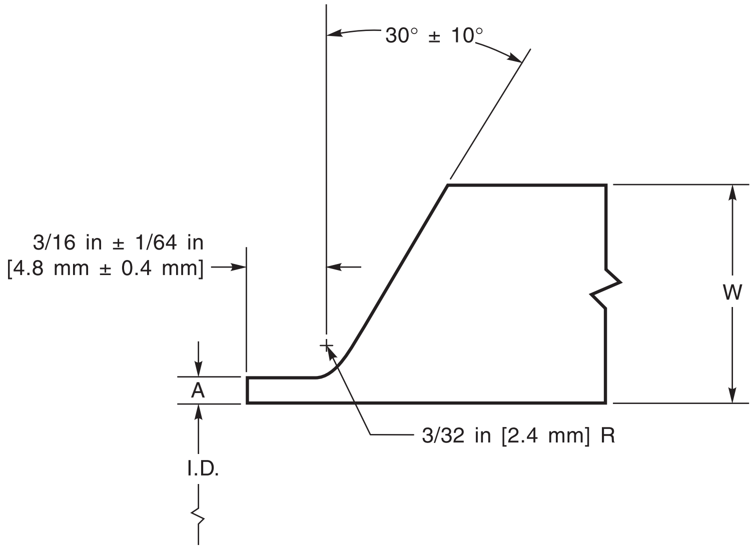
preferable to use spooled filler wire. The latter is used for automatic welding or with manual torches fitted to mechanically feed filler wire to the weld pool. The AWS specification that controls the manufacturing of aluminum filler metal is AWS A5.10, *Specification for Bare Aluminum and Aluminum Alloy Welding Electrodes and Rods*.

7.2.11 Pipe Welding

Manual AC-GTAW has commonly been used for welding aluminum pipe. With the correct joint design, equipment, procedures, and skills, the process is capable of making high-quality pipe welds in all positions. The joint design is the most important variable influencing this technique. With the pipe in the horizontal-fixed position welding must progress through three positions (overhead, vertical, and flat), while maintaining uniform penetration, bead shape, and weld quality. To do this, the effect of gravity on the weld pool must be minimized. This is accomplished by maintaining a consistent root opening or by using a special edge preparation on the pipe ends, often termed the extended land bevel (see Figure 7.8). Figure 7.9 shows a typical weld made with this edge preparation and lists its advantages. Complete instructions for the application of manual AC-GTAW for joining aluminum pipe are given in AWS D10.7, *Guide for the Gas Shielded Arc Welding of Aluminum and Aluminum Alloy Pipe*.

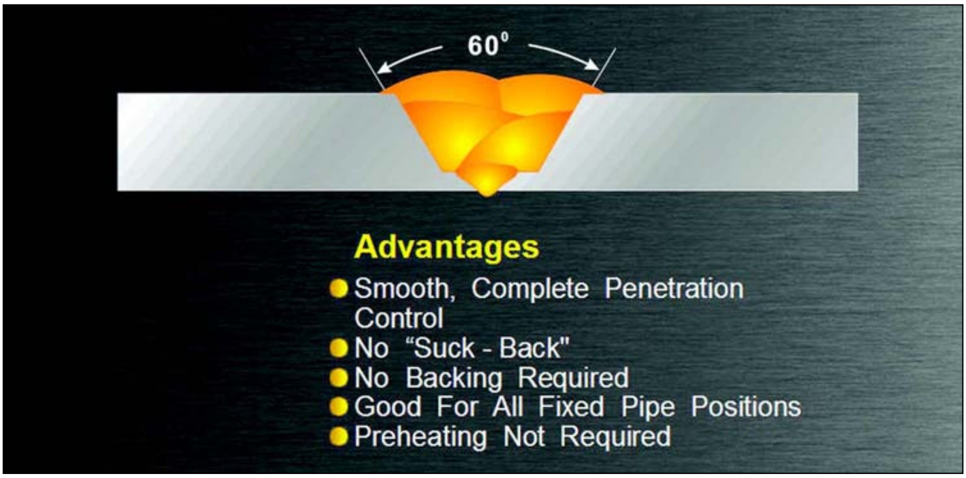
7.2.12 Welding Procedures

Welding procedures are typically developed to document the method used to produce welds. For structural welding of aluminum often welding procedures are developed and tested in accordance with the requirements of AWS D1.2, *Structural Welding Code—Aluminum*. Table 7.2 provides some current characteristics that may be evaluated as a starting point in developing the most appropriate parameters for a welding procedure.



Pipe Size		A		W, max.	
in	mm	in	mm	in	mm
1/8 through 2-1/2	3.2 through 64	1/16 ± 1/64	1.6 ± 0.4	0.276	7.01
3 through 12	76 through 305	3/32 ± 1/64	2.4 ± 0.4	0.500	12.7

Figure 7.8—The Extended-Land Bevel



Advantages

- Smooth, Complete Penetration Control
- No "Suck - Back"
- No Backing Required
- Good For All Fixed Pipe Positions
- Preheating Not Required

Figure 7.9—Advantages of Welds Made with the Extended-Land Bevel

Table 7.2—Typical AC-GTAW Procedures for Fillet and Lap Welding Aluminum

Aluminum Thickness in [mm]	Weld Position[1]	Preheat[2] °F [°C]	Weld Passes[3]	Diameter in [mm]			Argon Flow cfh [L/min]	AC A	Arc Travel Speed ipm [mm/sec]	Approximate Filler Rod Consumption[3] lb/100 ft [kg/100 m]
				Filler	Tungsten Electrode	Gas Cup Inside				
1/16 [1.6]	F, H, V	None	1	3/32 [2.4]	1/16–3/32 [1.6–2.4]	3/8 [9.5]	16 [8]	70–100	8–10 [3.4–4.2]	0.5 [0.74]
	O	None	1	3/32 [2.4]	1/16–3/32 [1.6–2.4]	3/8 [9.5]	20 [9]	65–90	8–10 [3.4–4.2]	0.5 [0.74]
3/32 [2.4]	F	None	1	3/32–1/8 [2.4–3.2]	1/8–5/32 [3.2–4.0]	3/8 [9.5]	18 [8]	110–145	8–10 [3.4–4.2]	0.75 [1.2]
	H, V	None	1	3/32 [2.4]	3/32–1/8 [2.4–3.2]	3/8 [9.5]	18 [8]	90–125	8–10 [3.4–4.2]	0.75 [1.2]
	O	None	1	3/32 [2.4]	3/32–1/8 [2.4–3.2]	3/8 [9.5]	20 [9]	110–135	8–10 [3.4–4.2]	0.75 [1.2]
1/8 [3.2]	F	None	1	1/8 [3.2]	1/8–5/32 [3.2–4.0]	7/16 [11.2]	20 [9]	135–175	10–12 [4.2–5.1]	1 [1.5]
	H, V	None	1	1/8 [3.2]	3/32–1/8 [2.4–3.2]	3/8 [9.5]	20 [9]	115–145	8–10 [3.4–4.2]	1 [1.5]
	O	None	1	1/8 [3.2]	3/32–1/8 [2.4–3.2]	7/16 [11.2]	25 [12]	125–155	8–10 [3.4–4.2]	1 [1.5]
3/16 [4.8]	F	None	1	5/32 [4.0]	5/32–3/16 [4.0–4.8]	1/2 [12.7]	25 [12]	190–245	8–10 [3.4–4.2]	2.5 [3.7]
	H, V	None	1	5/32 [4.0]	5/32–3/16 [4.0–4.8]	1/2 [12.7]	25 [12]	175–210	8–10 [3.4–4.2]	2.5 [3.7]
	O	None	1	5/32 [4.0]	5/32–3/16 [4.0–4.8]	1/2 [12.7]	30 [14]	185–225	8–10 [3.4–4.2]	2.5 [3.7]
1/4 [6.3]	F	None	1	3/16 [4.8]	3/16–1/4 [4.8–6.3]	1/2 [12.7]	30 [14]	240–295	8–10 [3.4–4.2]	4.5 [6.7]
	H, V	None	1	3/16 [4.8]	3/16 [4.8]	1/2 [12.7]	30 [14]	220–265	8–10 [3.4–4.2]	4.5 [6.7]
	O	None	1	3/16 [4.8]	3/16 [4.8]	1/2 [12.7]	35 [16]	230–275	8–10 [3.4–4.2]	4.5 [6.7]
3/8 [9.5]	F	Optional Up to 350°F [177°C] Maximum	2	3/16 [4.8]	1/4 [6.3]	5/8 [16.0]	35 [16]	325–375	8–10 [3.4–4.2]	9.5 [14.2]
	H		2	3/16 [4.8]	3/16–1/4 [4.8–6.3]	5/8 [16.0]	35 [16]	280–315	8–10 [3.4–4.2]	9.5 [14.2]
	V		3	3/16 [4.8]	3/16–1/4 [4.8–6.3]	5/8 [16.0]	35 [16]	270–300	8–10 [3.4–4.2]	9.5 [14.2]
	O		3	3/16 [4.8]	3/16–1/4 [4.8–6.3]	5/8 [16.0]	40 [19]	290–335	8–10 [3.4–4.2]	9.5 [14.2]

[1] F = Flat; H = Horizontal; V = Vertical; O = Overhead.

[2] Preheating at excessive temperatures or for extended periods of time will reduce weld strength. This is particularly true for alloys in heat-treated tempers.

[3] Number of weld passes and electrode consumption given for weld on one side only.

7.2.13 Conclusion

The GTAW process is not the fastest way to weld aluminum; however, it is often the most appropriate method of welding to achieve high-quality welds on particularly intricate applications. The process is sometimes mechanized, but when used manually a very high level of skill is required on the part of the welder to produce high-quality welds.

7.3 Gas Metal Arc Welding of Aluminum Alloys

7.3.1 Introduction

Gas Metal Arc Welding (GMAW) sometimes referred to as MIG (Metal Inert Gas) welding is an arc welding process that uses an aluminum or aluminum alloy wire as combined electrode and filler metal in a direct current, electrode positive (DCEP) arc, and an inert shielding gas (see Figure 7.10). Because filler metal is added automatically and continuously, autogenous welding is not possible. The welding current, arc length and electrode wire speed are controlled by the welding machine and, once adjusted for a welding procedure, do not require readjustment. Thus, for this process "manual" welding is termed "semiautomatic" welding. The GMAW process is also very adaptable to automatic welding. In either the semiautomatic or automatic modes, the process is capable of welding very thin metal up to unlimited thickness.

7.3.2 The GMAW Process

The GMAW process has the similar advantages over the earlier welding processes the same as gas tungsten arc welding (GTAW) does (e.g., no need for flux, little spatter,

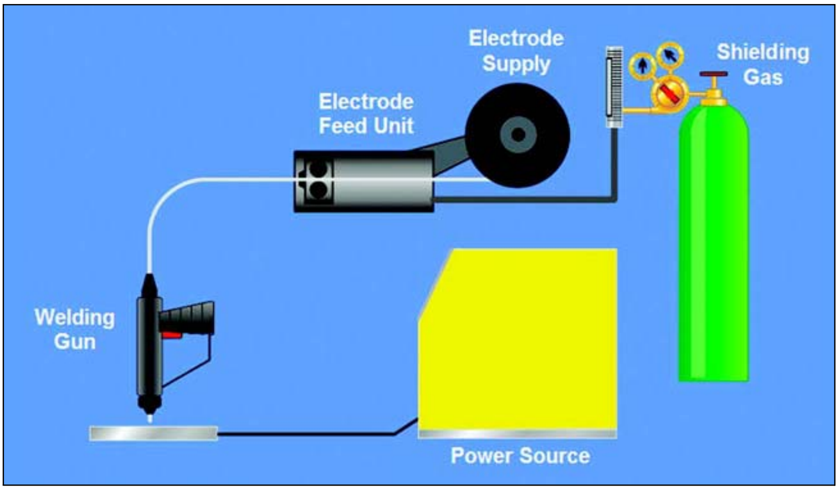
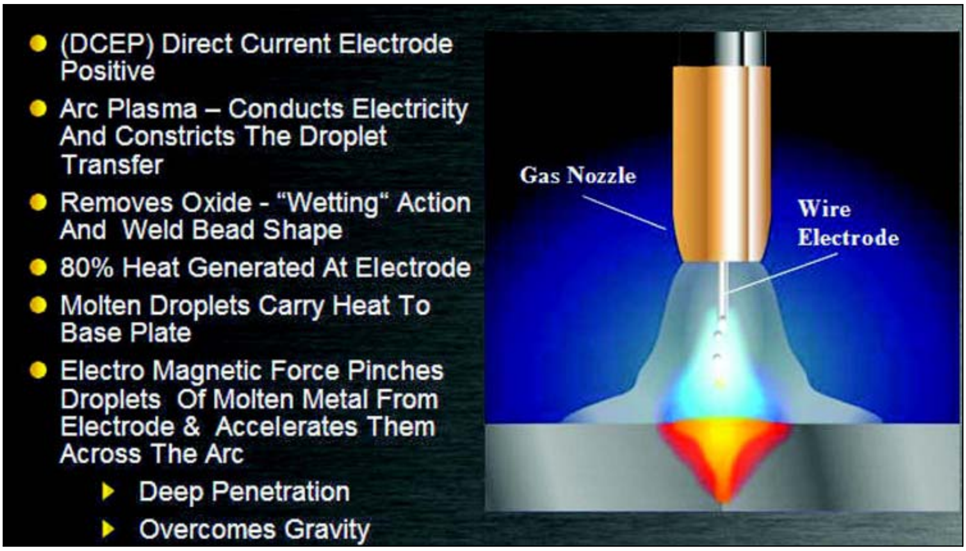


Figure 7.10—Schematic Representation of the GMAW Process

ability to weld in all positions, and an arc that removes the oxide film to allow coalescence of joint edges and filler). However, it has some additional advantages in that much higher welding speeds, greater depths of penetration, and narrower heat-affected zones are possible with GMAW than with GTAW. The GMAW arc is a very efficient and concentrated heat source in comparison with other welding arcs. Added to the above advantages, semiautomatic GMAW requires only one hand compared with manual GTAW, in which the welder has to coordinate both hands to achieve the desired results. Consequently, this process generally requires a lower skill level and less training to master when compared to the GTAW process.

The GMAW process almost always uses direct current, electrode positive (DCEP) power; direct current electrode negative (DCEN) does not have any practical application for welding aluminum. Some specialized GMAW power supplies are capable of supplying alternating current (AC), offering advantages in specific applications. With DCEP the arc removes the aluminum oxide film to permit coalescence of joint edges and filler metal. In removing the oxide from the face of the joint, it also permits the weld metal to “wet” to this surface and to form a more desirable weld profile. With DCEP polarity most of the arc heat (about 80%) is generated at the electrode. When using the correct current settings molten filler metal is transferred across the arc to the weld pool in a spray of superheated droplets. This mode of heat transfer and weld deposition, termed spray transfer, has the advantage of concentrating the welding heat for high thermal efficiency and narrow heat-affected zones. The spray transfer mode is produced by a magnetic force, generated by the welding current, which pinches off droplets of molten metal and accelerates them to high speeds across the arc. The inertia of this metal, as it reaches the weld pool, gives the spray transfer gas metal arc it’s characteristically deep penetrating ability, and the positive metal transfer under magnetic force overcomes gravity and makes it possible to weld in all positions (see Figure 7.11).



- (DCEP) Direct Current Electrode Positive
- Arc Plasma – Conducts Electricity And Constricts The Droplet Transfer
- Removes Oxide - “Wetting“ Action And Weld Bead Shape
- 80% Heat Generated At Electrode
- Molten Droplets Carry Heat To Base Plate
- Electro Magnetic Force Pinches Droplets Of Molten Metal From Electrode & Accelerates Them Across The Arc
  - Deep Penetration
  - Overcomes Gravity

Figure 7.11—GMAW Spray Transfer

The short circuiting and globular modes of metal transfer, which use lower amperage and voltage values, and are commonly used for steel welding, are not recommended for GMAW welding of aluminum alloys. It has been found that particularly the short circuiting transfer mode, used predominantly for thin sections of steel, will generally not produce the necessary heat required for welding aluminum and can result in incomplete fusion and other welding discontinuities. GMAW requires that the electrode wire feed rate balance the burn-off rate in the arc. If more filler is supplied than is being melted, the arc gets progressively shorter and finally stubs out into the weld pool. If less filler is being supplied than is being melted, the arc gets progressively longer and finally reaches the point of melting back to the contact tip causing a "burnback." In either case the result is that the welding operation shuts down. Two approaches are possible to synchronize wire feed and burn-off. One is to vary the wire speed to suit the current and the other is to vary the current to suit the wire speed. Although feeders have been designed to apply arc voltage to the feed motor to achieve the first of these approaches, it is not commonly used for aluminum welding. The second approach (to vary the current to compensate for wire speed fluctuations) has been the driving force behind most of the power source modifications since the GMAW process emerged.

7.3.3 Equipment

The following equipment and consumables are used for the process:

- A DC power source designed for GMAW
- An electrode feeder and gun combination
- A shielding gas supply with pressure regulator and flowmeter
- Aluminum or aluminum alloy electrode wire

7.3.4 Power Sources

Gas metal arc welding of aluminum requires a suitable and stable arc, one which provides the following:

- Adequately cleans the base metal in and around the weld pool
- Deposits a uniform weld bead without under cutting
- Gives uniform penetration
- Is easily and consistently initiated

The characteristics of an arc are largely determined by the power source relationship between voltage and current. The GMAW arc requires direct current power with suitable static and dynamic voltage current relationships to enable the arc to best perform its welding task. It also needs a balance between electrode wire feed rate and burn-off rate. Some important factors to be considered are:

- Electrode wire speed uniformity
- Joint geometry
- Weld pool dynamics
- Arc initiation

The earliest power sources for GMAW had steeply sloping voltage current characteristics, and were called "droopers" or "constant current" machines. The terms "drooper" and "constant current" refer to the shape of the curve that is drawn if the voltage current relationship is plotted. The principal advantage of the drooper power source is that the current stays essentially constant even when the arc voltage is being changed by either electrode speed fluctuations or joint variations. Constant current generally results in more uniform penetration. Later developments led to the introduction of machines with quite flat characteristic slopes, which were termed either "constant voltage" or "constant potential" machines. The principal advantage of the constant voltage (CV) power source is that the arc length is essentially constant. It is also easier to initiate the arc. It is generally believed to reduce the occurrence of burn-backs.

The main disadvantage of constant voltage machines is that any variation in electrode to work distance causes a change in welding current. In older transformer controlled power supplies this variation could be quite pronounced. However, modern CV power supplies control the arc much more rigidly so that current variations are much less. In the 1980s, a power source type called an "inverter" emerged. It was not characterized by its voltage current relationship but by its method of attaining a direct current output and its very fast response to arc variations. Instead of transforming voltage at line frequency (normally 60 Hz) and then rectifying to direct current, this power source type rectifies first and then "chops" to a high frequency (in the kHz range) for voltage transformation to welding voltage. It then rectifies the power to provide the direct current for welding. Most modem inverter power supplies are software programmable. All this has become possible with the advent of solid-state electronics, and the result is a machine with novel performance features for welding aluminum. Voltage current relationships for inverter power sources vary from model to model, and with some machines even vary during welding, to obtain optimum welding conditions. The very fast dynamic response with these machines enables them to produce stable arcs even under adverse conditions. These machines provide a "stiff arc" that makes it easier to penetrate to the root of joints and especially into deep grooves and other difficult to weld joint geometries. These machines are small, in many cases light enough to be portable, and are also very energy efficient.

7.3.5 Pulsed GMAW

Pulsed GMAW is a variation of the GMAW process. It maintains an arc at low current and then superimposes periodic pulses of high current to separate and transfer the droplets of molten metal from the electrode to the weld pool. This results in a low average current, but the metal transfer occurs at high current, which is necessary for spray transfer and for a stable arc. Figure 7.12 shows typical voltage and current characteristics for a pulsed gas metal arc weld. The low average current allows welding of thinner base metal with a given electrode size. This has a special advantage for very thin metal where previously it was only possible to use GMAW with very small electrodes. Small diameter electrode wires are difficult to feed and also to maintain in alignment with the joint. Pulsed welding allows for an increase of at least one electrode wire size over conventional GMAW. There are additional advantages for pulsed GMAW on aluminum. The arc can be less penetrating than with conventional GMAW; which is helpful on very thin base metals. It also permits slower welding speeds, which can be an advantage on complex joints where extra time may be needed for torch manipulation. Somewhat better control of weld bead shape, especially of the

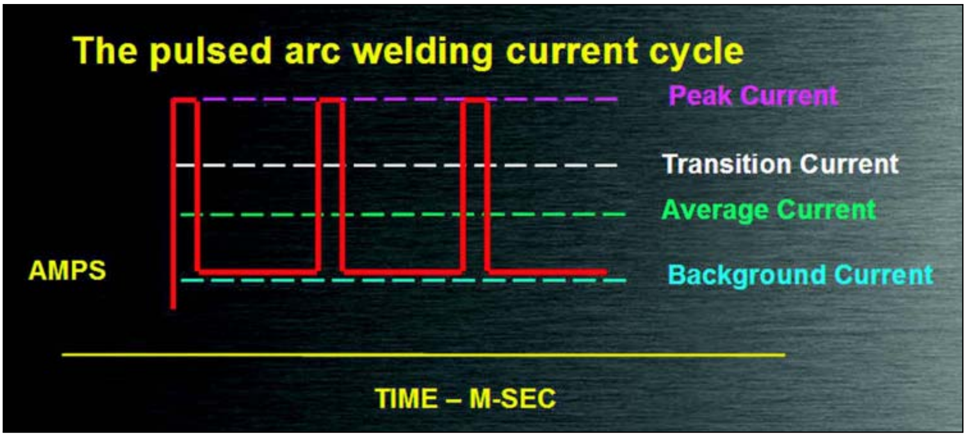


Figure 7.12—Typical Variation in Current for Pulsed Gas Metal Arc Welding

reinforcement, is possible. Pulsed GMAW is rarely applied to weld material over 1/4 in [6.4 mm] in thickness. Pulsed GMAW requires a special power source to supply the two different current levels, as well as circuitry to switch between them. The first such power source was developed during the 1960s. In the late 1970s, following the advances in solid-state electronics, a new generation of pulsed GMAW machines emerged. More recently inverter type power sources have been developed having arc pulsing options; these have some unique welding capabilities. Pulsed GMAW machines may have fixed-frequency pulsing, variable frequency pulsing controlled by electrode wire speed (termed synergic pulsing), variable frequency pulsing controlled by arc voltage or variable pulse width pulsing also controlled by arc voltage systems.

7.3.6 Electrode Feeder and Gun

The common GMAW machine has a feeder and gun designed to work together as a unit, although some feeders and guns can be adapted to other similar units. This combination of feeder and gun has a number of necessary functions:

- To drive electrode wire from a spool to the gun so that it arrives at the arc at a uniform and controlled speed.
- To transfer welding current to the electrode wire.
- To guide the electrode wire so that the welder can direct where the weld bead will form.
- To deliver shielding gas to the arc area so as to blanket the arc and the weld pool.
- To provide cooling for the power cable and the gun.
- To provide control circuitry so that the welder can initiate and interrupt welding power, electrode wire feed, shielding gas, and cooling water as desired.

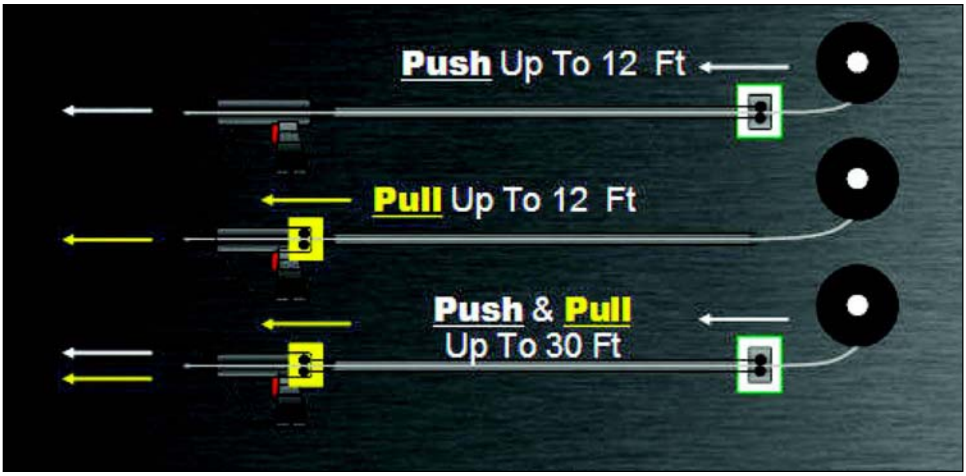


Figure 7.13—The Different Types of Feeding Systems for Aluminum Welding

In terms of electrode wire feed, there are three main systems: push feeders, pull feeders and push pull feeders (see Figure 7.13). For aluminum, push and pull feeders are limited to a practical length of flexible conduit of about 12 ft [3.5 m]. With the push feeder this limit results from the flexibility of aluminum electrode and its tendency to buckle and bind in the conduit, and with the pull feeder from the length of a flexible drive shaft or a rapid increase in friction in the liner if there are bends in the conduit. Push feeders are generally limited to welding with 3/64 in [1.2 mm], or larger, electrode. Pull feeders were used at one time for 1/16 in [1.6 mm] electrode, and smaller, but they are not commonly available today. Push-pull feeders were developed to overcome the electrode feeding problems experienced by the other systems. They can have conduits over 30 ft [9 m] long if they minimize friction in the flexible conduit by providing light tension in the electrode. The "spool on gun" GMAW is the other system available to aluminum fabricators; the guns are air cooled and generally suited for light duty service. They are usually rated for 200 A at 60% duty cycle and use 1 lb [0.4 kg] spools of electrode in sizes 3/64 in [1.2 mm], and smaller. Because of their low current rating, they are not truly suitable for continuous production welding but can be quite effective for tack welding and other lighter duty operations.

Choice of the most suitable system for each application is based on such factors as the type of welding, the need for a long flexible conduit and the importance of minimizing electrode cost. The electrode size and alloy are also a factor in determining the optimum wire feed system for the application. The larger the diameter of the electrode, the easier it is to feed, and the 5xxx and 2xxx alloy electrodes are stronger and somewhat easier to feed than the 1xxx and 4xxx alloys. The demands of welding operations vary widely and, for that reason, various GMAW systems are in use. However, robotic GMAW is so demanding of the feeding systems that push-pull is becoming the standard for it. A GMAW system combines a spool of electrode wire, a drive motor (or motors), drive rolls, and the necessary circuitry to initiate and interrupt welding power, wire feed, shielding gas and cooling water. The wire speed control may be on the feeder or on the gun. U-groove wire feed rolls are preferred; knurled and V-groove rolls may distort or break the wire surface, releasing flakes of aluminum oxide, which eventually collect in constricted areas of the system (such as the contact tip or liner) and cause arcing and wire stoppages. Feeders for automatic welding are usually simple, close coupled systems such as would be used on a seam welder. However, the weight limitations on robots mean that close coupled units are not practical for most robotic applications. This is why push-pull feeding systems are commonly used for robotic welding. Most feeding systems for aluminum GMAW are of the constant wire speed type. There are machines available that use arc voltage to regulate the wire speed as an aid to maintaining a constant arc length, but they were developed for welding other metals and have not proven very effective on aluminum.

7.3.7 Shielding Gas

The shielding gases used with the GMAW process when welding aluminum alloys are generally argon or mixtures of argon and helium. Other gases such as oxygen, nitrogen, carbon dioxide or hydrogen, even in trace amounts, in the shielding gas cause dirty and porous welds, and are thus not recommended. The shielding gas not only protects the arc and the weld pool from the surrounding air, but also helps to determine the arc characteristics. This results from the ionizing potential of the particular gas. GMAW arcs in argon tend to give narrow fusion at the limit of penetration, while those in helium give a much wider fusion shape at this location (see Figure 7.14). The wider shape has the advantage that it allows more tolerance for misalignment between the arc and the joint, and helps to avoid inadequate penetration and lack of fusion. Mixes of the two gases give intermediate weld shapes. Argon is used for most semiautomatic and some automatic welding, because it gives good penetration, clean welds and is cheaper than helium. Argon helium gas mixes are useful for semi-

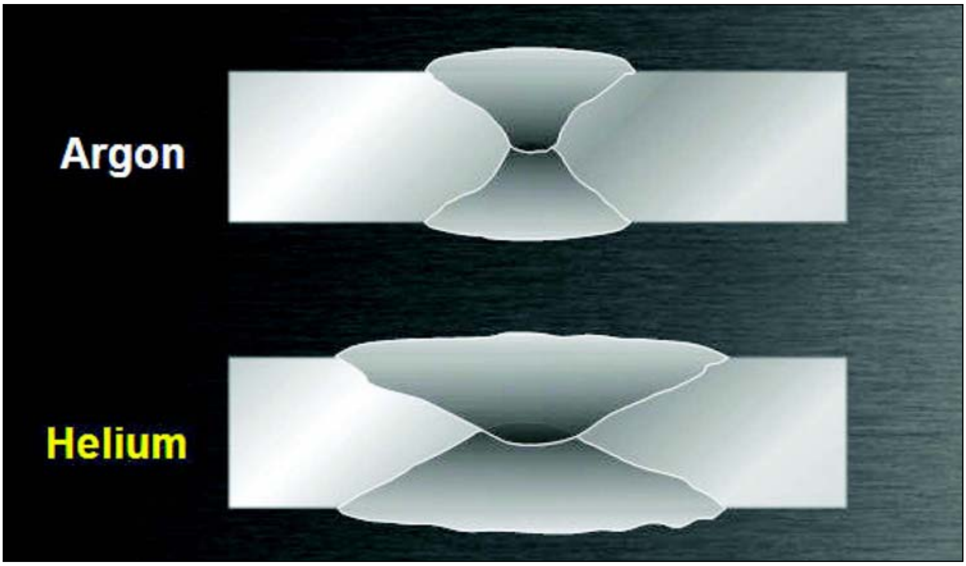


Figure 7.14—The Characteristics of the Two Primary Shielding Gases Used for GMAW Aluminum Welding

automatic welding of the thicker metal gauges, or where a hotter arc is needed. They are also used for most automatic welding of aluminum base metal thicker than about 1/2 in [12.7 mm], and especially on butt joints where maximum penetration is required. Helium percentages from 50% to 75% are preferred; they produce sound welds over a wider range of current and voltage combinations than pure argon shielding. One mix (25% argon and 75% helium) is commonly available from gas suppliers. The consistent purity of the shielding gas is essential. Welding grade gases are supplied to 99.997% purity for argon and 99.995% for helium, and their dew points are –76°F [–60°C] and –71°F [–57°C] or below, respectively. It is important to remember that this purity must be maintained in delivering the gas to the arc. If the delivery system or the welding equipment has any leaks, the gas can become contaminated.

7.3.8 Electrode Wire

The electrode wire is a critical component in the GMAW process, because it not only acts as the anode in the arc, but also provides the weld filler metal. As the anode, it must be centered in the gas nozzle at all times and its rubbing action inside the contact tip must transfer the required welding current consistently. As filler metal, it must not add hydrogen forming compounds to the weld pool. Because relatively small wire sizes are used the surface area of filler added to the weld pool is much higher than for GTAW. Thus, the surface cleanliness of GMAW electrode is very important if weld porosity is to be avoided. The surface must also be free from kinks and waves to permit uniform feeding at all speeds. All GMAW electrodes should, as a minimum, meet the requirements of AWS A5.10, *Specification for Bare Aluminum and Aluminum Alloy Welding Electrodes and Rods*. It sets high-quality standards for manufacture and packaging. Correct protection of the electrode during storage and use is also important. As soon as a spool is removed from its carton and plastic enclosure, it is in danger of becoming contaminated by the shop atmosphere, and so some precautions are in order. Some wire feeders have a closed compartment for the wire spool that is beneficial and should be used as designed. If the feeder has no cover for the spool, it is good practice to return the spool to its package whenever it is not in use. Alternatively, the entire feeder can be covered with a plastic sheet. Additional precautions may be necessary if there is any possibility of moisture forming on the electrode surface. This can occur if the electrode is stored in an unheated area, and then brought into a heated shop and opened before it can reach ambient temperature. Electrodes should be stored in a dry, heated area where the relative humidity is less than 35%. This is especially important for the 5xxx series electrode alloys. During periods of very high relative humidity in the ambient atmosphere, even normal daily temperature variations can affect the quality of GMAW electrode. To protect the electrode under these conditions, some GMAW feeders have been fitted with resistance heaters in the electrode spool compartment to raise the temperature just enough to maintain a low relative humidity and to prevent condensation on the wire surface.

7.3.9 Welding Procedure Development

Developing a qualified welding procedure requires establishing the optimum setting for each parameter, and the maximum permissible variation from these settings. The sequence of steps in the development process usually approximates the following:

- Metal thickness and alloy, filler (electrode) alloy and joint type are usually specified by the designer. He may also specify the joint geometry, backing type and welding position.

- The welding current is principally related to the metal thickness, although the joint type will also have a bearing. The current determines the heat, and thus the penetrating power of the arc. As noted in Table 7.4, the current levels for semiautomatic spray GMAW range from about 70 A to 400 A. The lower limit can be reduced by pulsed GMAW; which permits the use of average currents down to 30 A or less. The upper limit for semiautomatic welding is brought about mainly from the individual welder's ability to tolerate the intense arc heat. Automatic GMAW overcomes this restriction, and procedures using currents as high as 900 A have been reported.

- The choice of shielding gas is mainly related to metal thickness, because argon is better for most metal thicknesses, but argon helium mixtures can be beneficial for very thick metal. Gas flow is mainly a function of the welding current, but it is also influenced by other factors such as welding position, joint type, nozzle size, and environmental conditions such as air drafts in the welding area.

- The arc length has an effect on weld penetration. Within the normal usable range, shorter arcs tend to give deeper penetration and narrower weld beads. They are usually preferred for root passes on groove welds and for fillet welds. Longer arcs are somewhat less penetrating, and tend to give wider weld beads. The arc length is usually increased before making filling and capping passes.

- The number of passes to complete a weld is mainly a function of the metal thickness, joint type and joint fit up, but welding position can also have an effect. Small multiple passes are often necessary when welding in positions other than the flat position, and especially in the horizontal and overhead positions. Welders may have a personal preference for greater or fewer passes. Multiple pass welds using interpass cooling can improve the strength of heat-treatable alloy welds. Fewer, but larger, passes mean lower welding speeds, which is sometimes helpful. Also using fewer passes tends to reduce distortion.

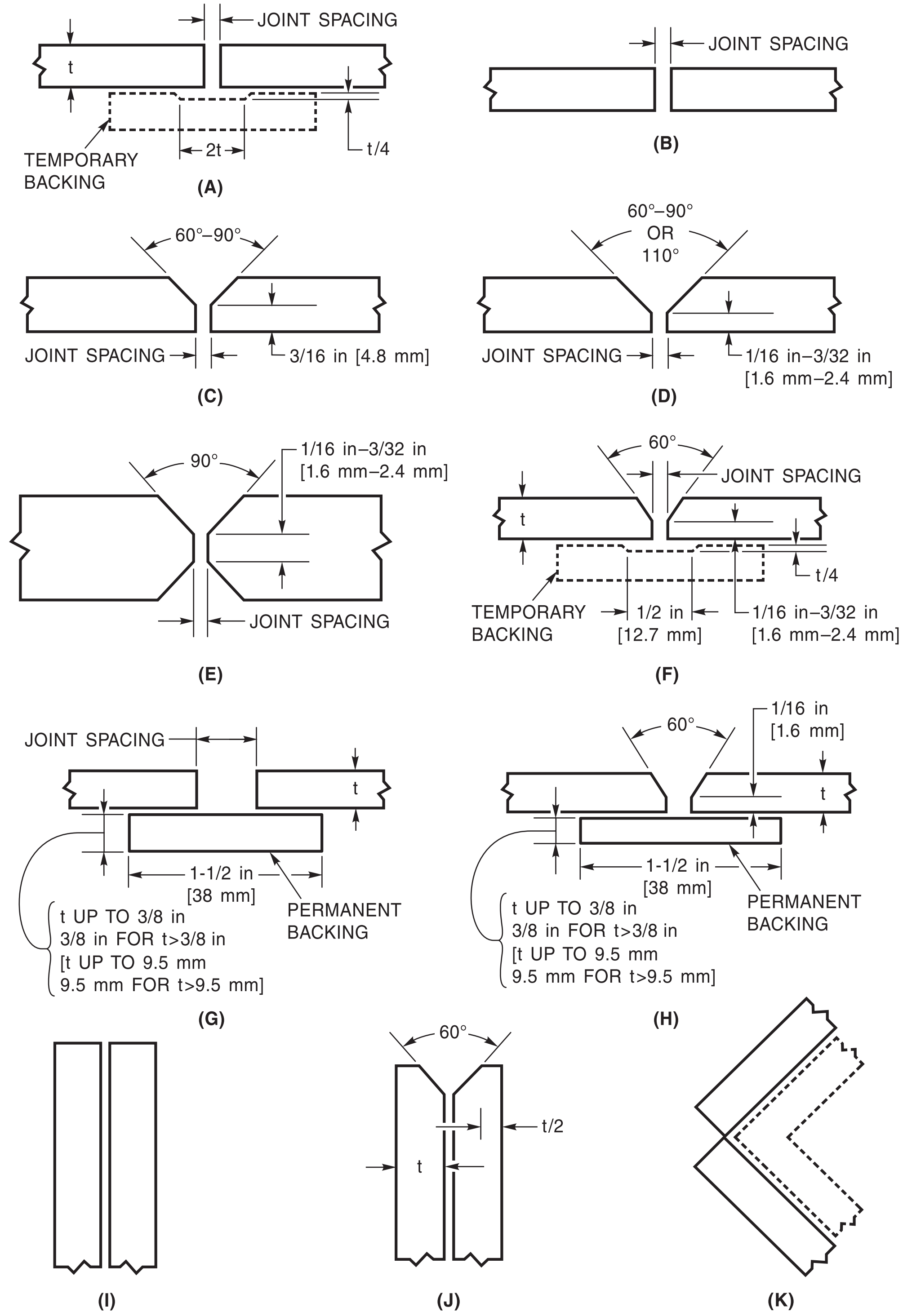
- The welding speed for semiautomatic GMAW is to some degree at the discretion of the welder. Speeds in the range of 12 ipm to 30 ipm [5.1 mm/sec to 12.7 mm/sec] are most common. Automatic GMAW has been reported at speeds as high as 100 ipm [42.3 mm/sec].

- The gun angle is influenced mainly by welding speed (the higher the speed, the greater the angle from the vertical), to ensure adequate gas shielding of the arc and weld pool. Angles from 5° to 15° are normal for semiautomatic welding, but they may reach 30° or more at the high speeds possible with automatic welding.

7.3.10 Conclusion

The GMAW process is recognized as being the most affordable welding process for the majority of high productivity applications that involve regular structural welding. The large majority of heavy fabrication industries make use of this process flexibility, high productivity, and ease of operation. Provided care is taken with the equipment selection and setup, this welding process can be, and is, used successfully on many aluminum welding projects.

Tables 7.3 and 7.4 provide guidelines for the evaluation of parameter during welding procedure development.



Note: Dimensions for Joint Spacing are shown in Table 7.4.

Figure 7.15—Typical Joint Geometries for Arc Welding of Aluminum

Table 7.3—Typical Semiautomatic GMAW Procedures for Fillet and Lap Welding Aluminum

Metal Thickness[1] in [mm]	Weld Position[2]	Weld Passes[3]	Electrode Diameter in [mm]	DC, (EP)[4] A	Arc Voltage[4] V	Argon Gas Flow cfh [L/min]	Arc Travel Speed ipm/pass [mm/sec]	Approximate Electrode Consumption[3] lb/100 ft [kg/100 m]
3/32 [2.4]	F, H, V, O	1	0.030 [0.8]	100–130	18–22	30 [14]	24–30 [10–13]	0.75 [21.2]
1/8 [3.2]	F	1	0.030–3/64 [0.8–1.2]	125–150	20–24	30 [14]	24–30 [10–13]	1 [1.5]
	H, V	1	0.030 [0.8]	110–130	19–23	30 [14]	24–30 [10–13]	1 [1.5]
	O	1	0.030–3/64 [0.8–1.2]	115–140	20–24	40 [19]	24–30 [10–13]	1 [1.5]
3/16 [4.8]	F	1	3/64 [1.2]	180–210	22–26	30 [14]	24–30 [10–13]	2.3 [3.5]
	H, V	1	0.030–3/64 [0.8–1.2]	130–175	21–25	35 [16]	24–30 [10–13]	2.3 [3.5]
	O	1	0.030–3/64 [0.8–1.2]	130–190	22–26	45 [21]	24–30 [10–13]	2.3 [3.5]
1/4 [6.3]	F	1	3/64–1/16 [1.2–1.6]	170–240	24–28	40 [19]	24–30 [10–13]	4 [6]
	H, V	1	3/64 [1.2]	170–210	23–27	45 [21]	24–30 [10–13]	4 [6]
	O	1	3/64–1/16 [1.2–1.6]	190–220	24–28	60 [28]	24–30 [10–13]	4 [6]
3/8 [9.5]	F	1	1/16 [1.6]	240–300	26–29	50 [23]	18–25 [8–10]	9 [13.4]
	H, V	3	1/16 [1.6]	190–240	24–27	60 [28]	24–30 [10–13]	9 [13.4]
	O	3	1/16 [1.6]	200–240	25–28	85 [40]	24–30 [10–13]	9 [13.4]
3/4 [19.0]	F	4	3/32 [2.4]	360–380	26–30	60 [28]	18–25 [8–10]	36 [54]
	H, V	4–6	1/16 [1.6]	260–310	25–29	70 [33]	24–30 [10–13]	36 [54]
	O	10	1/16 [1.6]	275–310	25–29	85 [40]	24–30 [10–13]	36 [54]

[1] Metal thickness of 3/4 in [19.0 mm] or greater for fillet welds sometimes employs a double vee bevel of 50° or greater included vee with 3/32 in to 1/8 in [2.4 mm to 3.2 mm] land thickness on the abutting member.

[2] F = Flat; H = Horizontal; V = Vertical; O = Overhead.

[3] Number of weld passes and electrode consumption given for weld on one side only.

[4] For 5xxx series electrodes use a welding current in the high side of the range given and an arc voltage in the lower portion of the range. 1xxx, 2xxx, and 4xxx series electrodes would use the lower currents and higher arc voltages.

Table 7.4—Typical Semiautomatic GMAW Procedures for Groove Welding Aluminum

Metal Thickness in [mm]	Weld Position[1]	Edge Preparation[2]	Joint Spacing in [mm]	Weld Passes	Electrode Diameter in [mm]	DC, (EP)[3] A	Arc Voltage[3] V	Argon Gas Flow cfh [L/min]	Arc Travel Speed ipm/pass [mm/sec]	Approx. Electrode Consumption lb/100 ft [kg/100 m]
1/16 [1.6]	F	A	None	1	0.030 [0.8]	70–110	15–20	25 [12]	25–45 [10–19]	1.5 [2.2]
	F	G	3/32 [2.4]	1	0.030 [0.8]	70–110	15–20	25 [12]	25–45 [10–19]	2 [3.0]
3/32 [2.4]	F	A	None	1	0.030–3/64 [0.8–1.2]	90–150	18–22	30 [14]	25–45 [10–19]	1.8 [2.7]
	F, H, V, O	G	1/8 [3.2]	1	0.030 [0.8]	110–130	18–23	30 [14]	24–30 [10–13]	2 [3.0]
1/8 [3.2]	F, H, V	A	0–3/32 [0–2.4]	1	0.030–3/64 [0.8–1.2]	120–150	20–24	30 [14]	24–30 [10–13]	2 [3.0]
	F, H, V, O	G	3/16 [4.8]	1	0.030–3/64 [0.8–1.2]	110–135	19–23	30 [14]	18–28 [6–12]	3 [4.5]
3/16 [4.8]	F, H, V	B	0–1/16 [0–1.6]	1F, 1R	0.030–3/64 [0.8–1.2]	130–175	22–26	35 [16]	24–30 [10–13]	4 [6.0]
	F, H, V	F	0–1/16 [0–1.6]	1	3/64 [1.2]	140–180	23–27	35 [16]	24–30 [10–13]	5 [7.5]
	O	F	0–1/16 [0–1.6]	217	3/64 [1.2]	140–175	23–27	60 [28]	24–30 [10–13]	5 [7.5]
	F, V	H	3/32–3/16 [2.4–4.8]	2	3/64–1/16 [1.2–1.6]	140–185	23–27	35 [16]	24–30 [10–13]	8 [4.0]
	H, O	H	3/16 [4.8]	3	3/64 [1.2]	130–175	23–27	60 [28]	25–35 [10–15]	10 [15.0]
1/4 [6.3]	F	B	0–3/32 [0–2.4]	1F, 1R	3/64–1/16 [1.2–1.6]	175–200	24–28	40 [19]	24–30 [10–13]	6 [9.0]
	F	F	0–3/32 [0–2.4]	2	3/64–1/16 [1.2–1.6]	185–225	24–29	40 [19]	24–30 [10–13]	8 [12.0]
	H, V	F	0–3/32 [0–2.4]	3F, 1R	3/64 [1.2]	165–190	25–29	45 [21]	25–35 [10–15]	10[15.0]
	O	F	0–3/32 [0–2.4]	3F, 1R	3/64–1/16 [1.2–1.6]	180–200	25–29	60 [28]	25–35 [10–15]	10 [15.0]
	F, V	H	1/8–1/4 [3.2–6.3]	2–3	3/64–1/16 [1.2–1.6]	175–225	25–29	40 [19]	24–30 [10–13]	12 [18.0]
	O, H	H	1/4 [6.3]	4–6	3/64–1/16 [1.2–1.6]	170–200	25–29	60 [28]	25–40 [11–17]	12 [18.0]
3/8 [9.5]	F	C–90°	0–3/32 [0–2.4]	1F, 1R	1/16 [1.6]	225–290	26–29	50 [23]	20–30 [8–13]	16 [24.0]
	F	F	0–3/32 [0–2.4]	2F, 1R	1/16 [1.6]	210–275	26–29	50 [23]	24–35 [10–15]	18 [27.0]
	H, V	F	0–3/32 [0–2.4]	3F, 1R	1/16 [1.6]	190–220	26–29	55 [26]	24–30 [10–13]	20 [30.0]
	O	F	0–3/32 [0–2.4]	5F, 1R	1/16 [1.6]	200–250	26–29	80 [38]	25–40 [11–17]	20 [30.0]
	F, V	H	1/4–3/8 [6.3–9.5]	4	1/16 [1.6]	210–290	26–29	50 [23]	24–30 [10–13]	35 [52.5]
	O, H	H	3/8 [9.5]	8–10	1/16 [1.6]	190–260	26–29	80 [38]	25–40 [11–17]	50 [75.0]
3/4 [19.0]	F	C–60°	0–3/32 [0–2.4]	3F, 1R	3/32 [2.4]	340–400	26–31	60 [28]	14–20 [6–8]	50 [75.0]
	F	F	0–1/8 [0–3.2]	4F, 1R	3/32 [2.4]	325–375	26–31	60 [28]	16–20 [7–8]	70 [105.0]
	H, V, O	F	0–1/16 [0–1.6]	8F, 1R	1/16 [1.6]	240–300	26–30	80 [38]	24–30 [10–13]	75 [112.5]
	F	E	0–1/16 [0–1.6]	3F, 3R	1/16 [1.6]	270–330	26–30	60 [28]	16–24 [7–10]	70 [105.0]
	H, V, O	E	0–1/16 [0–1.6]	6F, 6R	1/16 [1.6]	230–280	26–30	80 [38]	16–24 [7–10]	75 [112.5]

[1] F = Flat; H = Horizontal; V = Vertical; O = Overhead.

[2] See joint designs in Figure 7.15.

[3] For 5xxx series electrodes use a welding current in the high side of the range given and an arc voltage in the lower portion of the range. 1xxx, 2xxx, and 4xxx series electrodes would use the lower currents and higher arc voltages.

7.4 Brazing and Soldering of Aluminum Alloys

7.4.1 Brazing

Brazing is a group of joining processes that produce coalescence of materials by heating them to the brazing temperature in the presence of a filler metal having a liquidus above 450°C (840°F) and below the solidus of the base metal. The filler metal is distributed between the closely fitted faying surfaces of the joint by capillary action.

Brazing must meet each of three criteria:

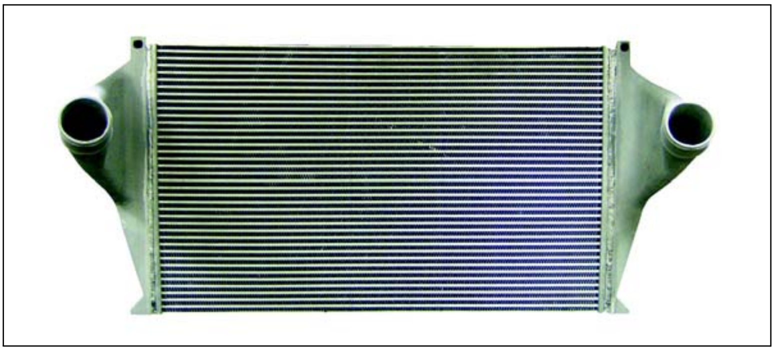
(1) The part must be joined without melting the base metal.

(2) The filler metal must have a liquidus temperature above 450°C (840°F).

(3) The filler metal must wet the base metal surface and be drawn into the joint by capillary action.

A selection of brazed components can be seen in Figures 7.16 through 7.19.

All brazing processes, with the single exception of vacuum brazing, require flux to remove the aluminum oxide and make coalescence possible. Aluminum brazing is capable of making excellent joints in thin gauge products, and is especially useful for very complicated or inaccessible joints that are not readily joined by other methods. It has also been used to join very thick metal. Brazed joints are strong and, because of their ideal shape and smooth blending into base metal surfaces, they have superior fatigue strength over most welds. Brazed joints in heat-treatable alloys can be water quenched from the brazing temperature, which is equivalent to solution heat-treatment, and then naturally or artificially aged to yield higher strengths. One disadvantage of brazing is that the entire assembly must be heated to a temperature approaching the melting point of the base metal.



This picture is courtesy of Active Heavy Duty Cooling.

Figure 7.16—A Controlled Atmosphere Brazed (CAB) Aluminum Core with Cast Aluminum Tanks GMAW (TIG) Welded to the Core. This Heat Exchanger is an Air to Air "Charge Air Cooler" (CAC) Used to Cool Combustion Air from the Turbo Charger on a Diesel Engine.

This picture is courtesy of Active Heavy Duty Cooling.

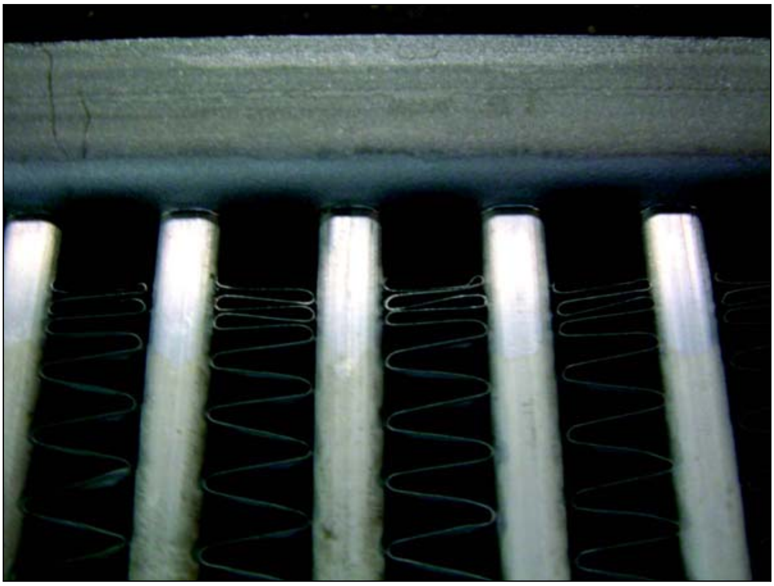
Figure 7.17—A Controlled Atmosphere Brazed (CAB) Aluminum Radiator Core with Mechanically Attached Nylon Tanks. This Heat Exchanger is Used on a Class 8 Truck.

Because the yield strength of aluminum alloys decreases rapidly at elevated temperatures, it is often necessary to provide support for components, which otherwise would distort under their own weight during brazing. Another disadvantage of brazing is the corrosive effect of most flux residues on aluminum. Two approaches can be taken to avoid this problem. One is to use vacuum brazing to eliminate the need for flux. The other is to use a chloride free fluoroxide flux, which contains none of the constituents that are corrosive to aluminum.

7.4.2 Brazeability

Most nonheat-treatable aluminum alloys, and many of the heat-treatable aluminum alloys, can be brazed. In the former group, 1100, 3003, 3004, and 5005 are the alloys that best respond to brazing. In the latter group, 6061, 6063, and 6951 are very commonly brazed. Casting alloys that can be brazed include 710.0, 711.0, 712.0, 356.0, A356.0, 357.0, 359.0, and 443.0. Some alloys are not suitable for brazing; those with low melting points, thus requiring brazing temperatures below those possible with existing filler alloys, include 2011, 2014, 2017, 2024, and 7075 alloys.

A second group of alloys is difficult to flux braze because existing fluxes are not effective in removing their tenacious oxides. These are the 5xxx series alloys having more than 2% magnesium. However, the latter can be vacuum brazed if special care is



This picture is courtesy of Active Heavy Duty Cooling.

Figure 7.18—Close up of a Controlled Atmosphere Brazed (CAB) Brazed "Charge Air Cooler" (CAC) Core Showing Tube to Manifold Joints and Fin to Tube Joints.

taken. Die castings are difficult to braze not only because they do not wet easily with the filler metal, but also because they tend to contain large amounts of gas and contaminants that expand during brazing and cause blistering. Aluminum can be brazed to such other metals as steel, nickel, titanium, beryllium, kovar, monel and inconel. It is not brazed to magnesium because the resulting joint is extremely brittle and not of any practical use. Also brittle intermetallic compounds form in brazes between aluminum and copper, and between aluminum and brass, so that these combinations have little application. However, transition materials can be used to join aluminum to copper and brass by brazing.

7.4.3 Filler Metals

Brazing filler metal comes in several forms: wire, thin sheet (shim stock), cladding on sheet (brazing sheet) or metal powder mixed with the flux. Each of these forms has advantages for particular applications. Brazing sheet is made in a range of thicknesses, with different core alloys and with cladding either on one side or on both sides.

7.4.4 Fluxes

Brazing fluxes are chemicals that, when heated, remove the oxide from aluminum, shield the joint zone from the atmosphere until the braze is completed and promote base metal wetting and filler metal flow. They consist mainly of chlorides and fluo-

This picture is courtesy of Active Heavy Duty Cooling.

Figure 7.19—A High Pressure Oil Cooler Consisting of a Controlled Atmosphere Brazed (CAB) Brazed Aluminum Core with Extruded Aluminum Tanks that are GTAW (TIG) Welded to the Core. This is a Two Pass Oil to Air Heat Exchanger Which Operates at 500 psi.

rides ground to a fine powder and mixed in proportions to produce the desired activity within a temperature range. Traditionally, aluminum brazing has been based on chloride fluxes (fluxes consisting mainly of chlorides). However, more recently fluoride fluxes, i.e., consisting mostly of fluorides, have come into common use, and for some applications have advantages over chloride fluxes.

7.4.5 Chloride Fluxes

Chloride fluxes act by entering through cracks in the oxide, which open up when the aluminum is heated. The flux then penetrates between the metal and the oxide and lifts the oxide to allow filler metal and base metal to coalesce. While this is the basic mechanism, individual flux compositions have been formulated to have special properties for specific requirements. Table 7.5 lists the commonly available chloride fluxes together with their recommended applications. For torch and furnace brazing, the flux powder must be mixed to a thin paste that can be brushed, dipped, roller coated or

Table 7.5—Brazing Combinations with Various Fluxes

Base Metal	Brazing Alloy	Optimum Brazing Range, °F (°C)	Suggested Flux Torch	Furnace	Dip
High Purity 1100 3003	4343 (713)[1]	1100–1140 (593–616)	Alcan Nocolok AMCO 33, 4015, 2724 Handy & Harmon Welco 10, 700	Alcan Nocolok AMCO 30, 53, 105, 300 Handy & Harmon	AMCO 34, 341, 501, 4024 Park E, D
	4047 (718)	1080–1095 (582–591)	Alcan Nocolok AMCO 33, 4015, 2724 Handy & Harmon Welco 10, 700	Alcan Nocolok AMCO 30, 53, 105, 300 4015, 2724 Handy & Harmon Welco 10, 700	AMCO 34, 341, 501, 4024
3004 5005 5050 6061 6063 6101 6951 7004 7005 710.0 Cast 711.0 Cast 712.0 Cast	4047 (718)	1080–1095 (582–591	Alcan Nocolok AMCO 33, 4015, 2724	Alcan Nocolok AMCO 30, 53, 105, 300, 4015, 2724 Handy & Harmon Welco 10, 700	AMCO 34, 341, 501, 4024
443.0 Cast 356.0-T4 Cast	4145 (716)	1060–1070 (560–571)	AMCO 33, 4040, 4056 Handy & Harmon Welco 10, 700	AMCO 33, 4015, 4040 Handy & Harmon Welco 10, 700	AMCO 34, 341, 501, 4024
No. 11 Brazing Sheet No. 12 Brazing Sheet	4343 (713)	1100–1140 (593–616)	—	Alcan Nocolok AMCO 30, 53, 105, 300	AMCO 34, 341, 501, 4024 Park E, D
No. 23 Brazing Sheet No. 24 Brazing Sheet	4045[2] (714)	1080–1120 (582–604)	—	Alcan Nocolok AMCO 30, 53, 105, 300, 4015, 2724 Handy & Harmon Welco 10, 700	AMCO 34, 341, 501, 4024

1. Old Brazing filler metal in parenthesis
2. Use alloy 4047 where additional filler metal is required.

The above relationships are approximate and are based in part on manufacturer's literature and field reports. Individual test are necessary to establish performance. This list is provided for the reader's convenience and is not to be considered all-inclusive nor does use here constitute an endorsement.

sprayed onto the joint. While a water paste is common, there are those who prefer to use alcohol instead of water, because alcohol evaporates more quickly and also because it avoids the generation of steam, which can move light gauge parts during the heating cycle. The dry, powdered flux is hygroscopic and must be kept tightly sealed until ready to be mixed and used. When manual brazing, the melting point of the flux is used as an indicator that the brazing temperature has been reached. For automatic brazing, the joint temperature must be controlled by process parameters, or thermostatically. Torch brazing fluxes, which are intended for a relatively short acting time at brazing temperature, are formulated to be more active than furnace brazing fluxes, which must be able to remain active over longer times. Dip brazing fluxes are the least active because the flux is molten at all times and must not be overly aggressive.

7.4.6 Fluoride Fluxes

Fluoride fluxes act in a different manner from chloride fluxes to remove the aluminum oxide. They contain sodium aluminum fluoride, which in its molten state dissolves the oxide. One such flux, Alcan Nocolok®, has been found to provide very effective oxide removal and to have some advantages over chloride fluxes. The principal of these advantages is that it is noncorrosive to aluminum; thus flux residues do not need to be removed after brazing to avoid subsequent corrosion. Fluoride fluxes are nonhygroscopic and possess unlimited shelf life. Their main disadvantage is that they are not suitable for brazing those alloys that contain more than about 0.5% magnesium, for 2xxx series alloys or for casting alloys that have solidus temperatures below the melting point of the flux [approximately 1070°F (576°C)].

7.4.7 Torch Brazing

Torch brazing uses the heat from an Oxyfuel flame or flames. It may be performed manually or automatically. The components are lightly coated with flux and the filler rod is dipped in flux as needed. Manual brazing with a single flame requires that the torch be moved continuously around the components during preheating so as not to overheat anyone area. When the flux melts, the filler rod is touched to the joint in one or more places and the flame used to help flow it to all locations. Automatic torch brazing is often performed on a rotary indexing fixture, where flames at several stations are used to bring the parts up to temperature gradually and then one station completes the brazing operation. Filler metal is provided as pre-placed shims, rings or other forms. Fluxing is done during component assembly. Heating rates and maximum temperatures are controlled by a combination of flame control and fixture rotation speed. The first station following brazing is usually a water spray to quench the parts, which when applied to some alloys can increase metal strength. Water quenching also helps to begin removing flux from the parts.

7.4.8 Furnace Brazing

Furnace brazing is most commonly used for volume production of those assemblies that are too complicated for flame brazing, such as heat exchangers. Parts are cleaned, fluxed and assembled before beginning a trip through the furnace on a conveyor. Heat may be supplied from gas or oil flames, or from electric heaters. The hot air is circulated to ensure uniform heating. Accurate temperature regulation is necessary, usually to plus or minus 5°F (3°C), and the time at temperature is also closely controlled. Furnace brazing with chloride fluxes is done in an air atmosphere. With fluoride fluxes, brazing is done in a dry nitrogen atmosphere to reduce the amount of flux required.

7.4.9 Induction Brazing

Induction brazing locates the assembly to be brazed in an induction coil and uses high-frequency electrical energy to induce a current to flow in it. The electrical resistance of the metal produces the heat necessary for brazing. This is a rapid brazing method and is best used for large quantities of relatively small components.

7.4.10 Dip Brazing

Very complicated assemblies that have internal joints and are difficult to heat uniformly are the most suited to dip brazing. The assemblies are preheated and then immersed in a bath of molten chloride flux for a controlled interval. Assembly components often are made of brazing sheet so that the filler metal is available as soon as the assembly reaches brazing temperature. Pre-placed wire or shims as well as powder slurries of brazing alloy are also used to supply the filler. Dip brazing pots are heated by the electrical resistance of the flux to an alternating current. A low voltage, high current transformer supplies power through nickel, nickel alloy, or carbon electrodes in the bath. The buoyancy of the flux bath permits long vertical brazing alloy flow, most uniform size fillets in all positions and uniform heating of complex assemblies.

7.4.11 Vacuum Brazing

Vacuum brazing avoids the corrosion problem caused by chloride flux residues. Brazing is done by heating the components in furnaces that can sustain a vacuum of 5 × 10 5torr. When an aluminum assembly is heated in such a vacuum under the proper conditions, the oxide crazes as the metal expands and the filler alloy penetrates the oxide without need for flux. The process requires that the brazing sheet contain significant amounts of magnesium, which vaporizes as the metal is heated and performs as a getter during the heating cycle. The recommended brazing sheet types are #7 and #8 having 4004 alloy cladding on a 3003 alloy core, and #13 and #14 having 4004 alloy cladding on a 6951 alloy core. Magnesium can also be added separately into the furnace for assemblies not using brazing sheet. Vacuum brazing is used for producing a variety of aluminum products, although the main emphasis is on heat exchangers (especially those with a very small matrix, which would be difficult to clean of residual flux). Vacuum brazing gives clean, good appearing joints needing no further operations. Much more detailed information on this process is contained in the publication *Aluminum Fluxless Vacuum Brazing,* which is available from the Aluminum Association.

7.4.12 Joint Designs

Joint designs suited for brazing are lap, flange, lock seam and tee. Butt and scarf joints are not generally recommended. Tee and line contact joints are excellent in that they allow capillary flow and the formation of fillets on both sides of the joint. For best efficiency, lap joints should overlap at least twice the thickness of the thinner member. On the other hand, an overlap greater than 1/4 inch (6.3 mm) may lead to voids or flux inclusions. Grooves or knurls, aligned with the direction of filler flow, can help to prevent the trapping of flux and the incomplete flow of filler. Optimum joint clearance depends on the lap width and on the brazing method. Clearances from 0.003 inch to 0.006 inch (0.08 mm to 0.15 mm) are common for dip brazing and vacuum brazing. With the other methods, clearances of 0.005 inch to 0.010 inch (0.13 mm to 0.25 mm) can be used for all except lap joints with more than 1/4 inch (6.3 mm) overlap. Greater overlaps need greater clearance to permit flux and filler metal flow; clearances up to 0.025 inch (0.6 mm) have been used.

7.4.13 Fixtures

Brazing requires that the parts be held in correct registration through the heating and cooling cycles. Whenever possible, the joints should be designed to be self- jigging. When fixtures are necessary, they should allow for expansion and contraction so that they will not distort the assembly. Springs can be used to hold the parts; stainless steel or Inconel are preferred spring metals. Fixtures can be made from mild steel or stainless steel, but for durability in furnace brazing or to avoid contamination of the flux bath in dip brazing, they are better made of nickel, Inconel or aluminum coated steel. As much as possible, there should be only line contact between the fixture and the aluminum assembly so that there is minimum heat transfer between them, which makes for more uniform heating of the assembly. If an assembly has hollow members that will be sealed by the brazing operation, it is essential to provide a venting hole, so that pressure or vacuum at different stages of the brazing cycle do not distort the members or prevent a sound brazed joint.

7.4.14 Metal Preparation

Metal cleanliness is essential for all brazing, except that fluoride fluxes can tolerate somewhat thicker oxide films than can chloride fluxes and thus seldom require a deoxidation pretreatment. The nonheat-treatable alloys, like 1100, 3003, and 3004, can usually be brazed with only degreasing as a pretreatment, but metal with a heavy oxide and the heat-treatable alloys also require a chemical treatment to remove the oxide film. Table 7.6 lists some chemical treatments that can be used for oxide removal.

7.4.15 Corrosion Resistance

The corrosion resistance of brazed joints that are completely free from traces of chloride flux is dependent on the solution potential differences between the alloys involved. Fortunately, most aluminum alloys that are brazed and the most commonly used brazing filler alloys (4045, 4047, and 4343) have only slight potential differences, and thus brazed joints have good corrosion resistance. However, if a chloride flux is not removed after brazing, it will absorb moisture and aggressive corrosion can result. Chloride free fluoride flux does not have to be removed but in many cases actually provides a measure of corrosion protection. This is especially beneficial in products that have multiple internal cavities and are therefore very difficult to rid of flux.

Table 7.6—Chemical Pretreatments for Aluminum to be Brazed

Type of Solution	Concentration	Temp.	Type of Container	Procedure	Purpose
Method A Technical grade Nitric Acid	50% water 50% nitric acid technical grade	Room	Stainless Steel-347	Immersion 15 min. Rinse in cold water. Rinse in hot water & dry.	For removing thin oxide film.
Method B 1. Sodium Hydroxide (caustic soda) followed by	1. 5%	1. 160°F (71°C)	1. Mild Steel	1. Immersion 10–60 seconds. Rinse in cold water.	Removes thick oxide film.
2. Technical grade Nitric Acid	2. Concentrated (use as received)	2. Room	1. Stainless Steel-347	2. Immerse for 30 seconds. Rinse in cold water. Rinse in hot water & dry.	
Method C Sulfuric-Chromic	H_2SO- 1 gal. (3.8 L) CrO_4- 15 oz. (425 g) water- 9 gal. (34 L)	160°F–180°F (71°C–82°C)	Antimonal lead-lined steel tank	Dip for 2-3 min. Rinse in cold water. Rinse in hot water & dry.	For removal of heat-treatment & annealing films, and stains & for stripping oxide coatings.
Method D Phosphoric-Chromic	H_2PO_3 (75%) 3.5 gal. (13.2 L) CrO_4- 1.75 lbs. (0.8 kg) water- 10 gal. (38 L)	200°F (93°C)	Stainless Steel-347	Dip for 5–10 min. Rinse in cold water. Rinse in hot water & dry.	For removing anodic coatings

Notes:
Extreme caution should be exercised when using Method B on brazing sheet. If left in the caustic too long, the brazing alloy can be etched away.
There are many proprietary materials and methods for removing aluminum oxides. Most of these are as efficient as the preparations listed.

7.4.16 Removal of Chloride Fluxes

Usually the first post braze cleaning step is the immersion of the part into boiling water. A chloride flux is highly soluble in water and the boiling water will remove most of it. The wash tank water must be changed constantly and either the part or the water should be agitated to force the water into all comers and crevices of the part. When the major portion of the adhering flux has been removed, the assembly may be rid of the balance of the flux by immersion into a chemical solution. Several flux removal solutions are listed in Table 7.7 However; there are a number of other acceptable solutions. The brazed assembly is rinsed thoroughly in cold or hot water following the chemical cleaning.

7.4.17 Soldering

Soldering is a group of joining processes that produces coalescence of materials by heating them to the soldering temperature and by using a filler metal having a liquidus

Table 7.7—Flux Removal Solutions

(A) Nitric Acid at room temperature, mixed 50/50 by volume with water is a very effective general purpose flux removing solution. It does its job in 10 to 20 seconds and the part can be later washed in cold or hot water. However, nitric acid reacts with flux to produce dangerous fumes which must be vented by a power fan and hood. Nitric acid also has a very low tolerance for flux. For these reasons, this solution is only used on small parts with little remaining flux. When the chloride concentration in the nitric acid water solution exceeds 5 grams per liter (0.04 lbs. per gal), thin gauge brazed assemblies may be perforated. Inhibitors such as 1% thiourea or 1% triethanolamine salt of sulfolauryalkyl benzoate may be added to prevent chloride contamination from attacking the parts being cleaned.

(B) Nitric acid mixed with hydrofluoric acid and water at room temperature will both etch the metal and remove flux in one immersion. Depth of etching is dependent on immersion time. Generally, 10 to 15 minutes is sufficient. Afterwards the parts are rinsed in cold water and then hot water. The hot water rinse, 168°F (76°C), should be limited to 3 minutes to prevent surface stains. The solution must be analyzed each week and discarded when its chloride content reaches 3 grams per liter (0.025 lbs. per gal), expressed as hydrochloric acid. The solution is made by mixing 1 gallon (3.8 liters) nitric acid, 1/2 pint (0.24 liter) hydrofluoric acid and 9 gallons (34 liters) of water.

(C) Hydrofluoric acid, mixed with room temperature water in the ratio of 2-1/2 pints (1.2 liters) of acid to 10 gallons (37.8 liters) of water, will remove flux effectively and rapidly. Dip time should not exceed 10 minutes as this solution dissolves the aluminum. This solution is not as quickly contaminated by flux as is nitric acid solution, but it does generate much more hydrogen gas, which must be vented. If the hydrofluoric acid discolors the aluminum it can be brightened with nitric acid.

(D) Nitric acid, sodium dichromate and water mixed in a ratio of 4-1/2 quarts (4.26 liters) of acid to8 pounds (3630 grams) of sodium dichromate and 9 gallons (34 liters) of water makes a solution useful for final cleaning of thin parts, and parts that must exhibit maximum resistance to corrosion. This solution is used at a temperature of 150°F (66°C). It does its job in 5 to 10 minutes and should be followed by a careful wash in hot water.

(E) 2% chromium trioxide and 5% phosphoric acid (both by weight) added to water at 180°F (82°C) is also used for very light gauge metal. This solution can be used until chloride contamination reaches a maximum of 100 grams per liter (.83 lbs. per gal), after which it should be discarded.

(F) U.S. Patent 3,074,824 W. W. Binger and B. Ponchel describes an **alkaline phosphate dichromate fluoride** solution devised to both etch and remove flux from very thin gauge aluminum with a minimum of seeper leaks.

not exceeding 450°C (840°F) and below the solidus of the base metal. The filler metal is distributed between closely fitted faying surfaces of the joint by capillary action. Most aluminum soldering is done with a flux, although there are techniques such as abrasion soldering and ultrasonic soldering that can remove, or at least disperse, the aluminum oxide sufficiently (without flux) to allow sound joints to be made.

7.4.18 Solderability

Aluminum alloys containing no more than 1% magnesium or 4% silicon are the most readily soldered. Alloys containing greater amounts of these elements have poor flux wetting characteristics but can be soldered by special techniques such as pre-plating before flux soldering or by abrasion soldering. Aluminum castings are generally unsuitable for soldering because of their compositions. Also cast surfaces are difficult to solder, both because they are hard to clean and because surface porosity can interfere with flux removal. Residual stresses from quenching or cold working aluminum may interfere with making satisfactory soldered joints, because stress accelerates solder penetration into the base metal along grain boundaries, and this can cause cracking and reduction in strength. Intergranular penetration can be reduced by stress relieving the metal at about 700°F (371°C) before soldering. High temperature soldering automatically provides this stress relief. Clad aluminum generally has better solderability than bare metal. Cladding of metal to be soldered can improve flux and solder wetting, and reduce diffusion of solder into the base metal. This is particularly helpful when soldering the 2xxx and 7xxx series alloys. Cladding aluminum with other metals can also be beneficial. For example, copper cladding will improve solderability. Copper can be electroplated or roll bonded to aluminum to give a surface that can be soldered with those solders and fluxes normally used for copper.

7.4.19 Solders

Aluminum soldering is divided into three classifications; low temperature soldering using solders that melt at temperatures between 300°F and 500°F (149°C and 260°C), intermediate temperature soldering using solders that melt at temperatures between 500°F and 700°F (260°C and 371°C) and high temperature soldering using solders that melt at temperatures between 700°F and 840°F (37°C and 449°C). Table 7.8 shows these classifications and compares them in terms of ease of soldering and the properties of soldered joints. Note that the lower temperature solders are easier to use but the higher temperature solders give stronger and more corrosion resistant joints. Table 7.9 gives the compositions, melting ranges and properties of the common solders for aluminum.

7.4.20 Fluxes

Fluxes for aluminum soldering are of two basic types: organic and inorganic. The organic fluxes are based upon organic fluoborates and heavy metal fluoborates plus an organic vehicle and usually do not contain chlorides. The flux of residues is usually non hygroscopic and is only very slightly corrosive. Often it is not removed except for very thin material [0.005 in. (0.1 mm) or less] and for improved electrical conductivity.

Organic fluxes are usually supplied as heavy syrups and can be used at full strength or diluted up to 50% with either ethyl or methyl alcohol. Distilled or deionized water

Table 7.8—Classification of Aluminum Solders

Type	Melting Range °F (°C)	Common Constituents	Ease of Application	Wetting of Aluminum	Relative Strength	Relative Corrosion Resistance
Low Temp.	300–500 (149–260)	Tin or Lead plus zinc and/or cadmium	Best	Poor to Fair	Low	Low
Inter-mediate Temp.	500–700 (260–371)	Zinc base plus cadmium or zinc-tin	Moderate	Good to Excellent	Moderate	Moderate
High Temp.	700–840 (371–449)	Zinc base plus aluminum, copper, etc.	Most Difficult	Good to Excellent	High	Good

Table 7.9—Compositions, Melting Ranges, and Properties of Common Aluminum Solders

	Solder System			
	1	2	3	4
Solder Composition	95Zn-5Al	90Zn-5Al-5Cu	91Sn-9Zn	83Cd-17Zn
Melting Point	720°F (382°C)	717°F (381°C)	390°F (199°C)	509°F (265°C)
Flux Type	Zink Chloride	Zink Chloride	Organic Base	Metal Chlorides
Reaction Range	700°F–730°F (371°C–388°C)	700°F–730°F (371°C–388°C)	350°F–500°F (177°C–260°C)	450°F–530°F (23°C–277°C)
Base Metal	3003-H14 (1100-H14)[1]	3003-H14 (1100-H14)[1]	1100-H14 (1) Zn-Sn Plate (2) Sn Plate	3003-1114 (1100-H14)[1]
Base Metal Precleaning	Etched, Rinsed, and Dried	Etched, Rinsed, and Dried	Degreased and Dried	Etched, Rinsed, and Dried
Solder Flow	Good–V. Good	Fair–V. Good	Very Good	Good–V. Good
Wetting	Fair–V. Good	Fair–V. Good	Good–V. Good	Good–V. Good
Soldering Fumes	Heavy, Not Toxic, Corrosive	Heavy, Not Toxic, Corrosive	Light, Toxic, Corrosive	Medium, Toxic, Corrosive
Residues, and Post-Cleaning Required	V. Corrosive Hot Water Rinse	V. Corrosive Hot Water Rinse	Corrosive Hot Water Rinse	V. Corrosive Hot Water Rinse

1. Although all unplated aluminum was 3003, the results are also applicable to 1100.

can also be used to dilute the flux particularly for high speed automated operations. The organic fluxes are less active than the inorganic fluxes and require the metal surfaces they contact to be cleaner and freer of oxide than do the inorganic fluxes. The organic fluxes are effective on alloys containing up to 1% magnesium and 4% silicon. They are not used on alloys containing higher percentages of these metals.

Organic formulations are compounded for temperatures of 350°F to 525°F (177°C to 274°C). Above this temperature the flux begins to carbonize at an ever increasing rate. The carbon produced by overheating the organic flux is an effective stop off to prevent the flow of solder. Care must be used when soldering with an iron or torch to keep the flux from direct contact with the source of heat. Thus, the heat should be applied away from the joint and conducted to the desired joint area.

During the soldering operation, the active reagent of the organic flux, in the form of gas, bubbles up through the molten flux. This makes it difficult to produce a void free lap joint with this type of flux. However, line contact joints and similar joints of narrow width can be made without voids as the gas has very little distance to travel to freedom. Inorganic fluxes, containing primarily chlorides along with some fluorides, are used with the intermediate and high temperature solders in the temperature range of 500°F to 840°F (260°C to 449°C). The inorganic fluxes are very hygroscopic. Any water they absorb causes the formation of oxychlorides, which reduce the fluxing action and hinder molten metal flow. Consequently, the vehicle used with this type of flux is normal propyl alcohol, normal butyl alcohol or methyl ethyl keytone. The flux residues of these chloride containing fluxes can be severely corrosive to aluminum and should be removed. Most of the inorganic fluxes are formulated with a high proportion of other halides in addition to the primary tin or zinc chloride in order to provide an effective flux activity over a specified temperature range. A wider range is desirable for manual soldering operations where the solder is added by hand than is required for automatic operations with a pre-placed filler. All of these react to varying degrees with the aluminum alloy to deposit a strong, thin, metallic layer to which the solder wets and bonds.

Fluxes containing a very high percentage of zinc chloride (approximately 90%) react at a specific temperature [approximately 720°F (382°C)] and can deposit sufficient zinc to form small fillets without the addition of separate filler. These are most commonly referred to as “reaction” fluxes and hand feeding of a solder to the joint is difficult because of the narrow temperature range of flux activity. Solder is best pre-placed at the joint or mixed as particles in the flux to increase the solder deposition.

All organic and inorganic soldering fluxes can generate large quantities of dense, white, irritating, corrosive fumes. Those produced by fluxes containing fluorides and/or cadmium are toxic as well. Forced ventilation is mandatory when any significant quantity of work is conducted indoors.

7.4.21 Soldering with an Iron

Because of aluminum's high thermal conductivity, assemblies with any appreciable mass are difficult to heat with an iron. Iron soldering is generally used on small wire joints and sheet less than 1/16 inch (1.6 mm) thickness. A hot plate is often used to supply auxiliary heat. This process is used with the low temperature solders and an organic flux. The surfaces to be joined are degreased and deoxidized. The flux is applied to the joint and the solder is normally fed manually. The soldering iron must not touch the flux because it will char it, so as to reduce or destroy its effectiveness. The iron is placed in contact with the base metal at a distance from the joint and moved from one side to the other to heat the joint evenly. When the solder starts to melt and enter the joint, the iron can be brought closer or even onto the remaining solder and joint after the flux has done its job.

Iron clad soldering irons last about ten times longer than copper tipped irons. Care must be used when cleaning not to cut through the comparatively thin iron cladding.

7.4.22 Torch Soldering

Air fuel gas and oxy fuel gas torches can be used to solder aluminum with the low, intermediate, and high temperature solders, with organic, inorganic and reaction fluxes, and by manual or automatic means. Higher concentrations of heat can be generated by torch soldering than by iron soldering, so part size is not as great a restriction. However, thick or large units should be preheated in a furnace or oven. The joint area should be degreased and removed of thick oxides prior to soldering. The solder may be pre-placed or added manually. The joint area should be heated uniformly by continuous movement of the torch or part to conduct the heat into the joint, particularly with an organic flux, and to avoid localized overheating. Automatic flame soldering with pre-placed high temperature zinc alloy solder rings and a reaction flux has been used to assemble socketed return bend joints in millions of automotive air conditioning condensers.

7.4.23 Abrasion Soldering

Torch soldering can be accomplished without a flux by using an adequate sized solder rod. After heating to a desired temperature, the end of the solder can be rubbed against the aluminum with sufficient force to break up the aluminum oxide and form a metallurgical bond as the solder melts. This method may be used to “pre-tin” surfaces for subsequent joining operations. Abrasion soldering is used primarily with the intermediate and high temperature solders with the above technique. “Pre-tinning” with low temperature solders has been done by melting the solder onto the aluminum surface and then abrading the oxide through the solder with a stiff metal brush.

7.4.24 Ultrasonic Soldering

Ultrasonic soldering is a variation of abrasion soldering. Vibratory energy applied to the molten solder creates a “cavitation” effect to break up the aluminum oxide for proper fusion of the solder to the base metal without use of a flux. There are three basic methods for ultrasonic soldering:

(1) The solder is melted on the aluminum surface with an iron or air fuel gas torch, and an ultrasonic iron or probe is inserted into the molten solder to create the vibratory agitation and fusion.

(2) A pot of molten solder has a “sonotrode” immersed in the solder.

The item to be soldered, such as a pigtailed wire connection, is inserted into the bath in close proximity to the “sonotrode” to receive the vibratory energy. This method has been most commonly used with the low temperature solders.

(3) A pot of molten solder has the solder agitated by ultrasonic energy applied externally to the bottom or walls of the pot. Immersion of a preheated part permits single or multiple joints to be soldered simultaneously. Figure 16.2 shows a portion of an air conditioning condenser that had the socketed return bend joints ultrasonically dip soldered. This method has been used primarily with the high temperature zinc alloy solders.

Ultrasonic soldering can be accomplished in a few seconds, it can be manual or mechanized, and no post soldering cleaning is required, since no flux is used.

7.4.25 Furnace Soldering

Batch or conveyorized furnace soldering can be done in an air atmosphere with all classes of solders, but it is most commonly used for high-temperature soldering. A particular advantage of furnace soldering is that it applies heat uniformly, which reduces differential expansion and thus minimizes distortion. Flux is applied by spraying, brushing or dipping, and the solder is pre-placed at, or in, the joints. When using a reaction type flux, zinc alloy particles have been added to the flux mixture to provide increased zinc beyond that which occurs by the reaction alone. Furnace soldering produces copious quantities of fume, and care must be taken to provide removal of these fumes, as well as volatile vehicles, from the work area.

7.4.26 Dip Soldering

Dip soldering is well suited to aluminum because the solder pot is an excellent large-capacity heat source. It lends itself to high production rates, and the same layout and production schedules used for other metals can be retained for aluminum. Dip soldering can use all the conventional fluxes and solders by fluxing the joint prior to immersion into the solder. Fluxless variations of dip soldering are described in the "Ultrasonic Soldering" section.

7.4.27 Resistance Soldering

Resistance soldering may be used to join aluminum to itself or to other metals. It is particularly suited to spot or tack soldering. The flux is usually painted onto the joint area and the solder is pre-placed or added manually. Metal or carbon electrodes are then brought into contact with the joint area and an electrical current passed through the joint until solder flow occurs. Since the heat is generated within the aluminum, there is little danger of overheating the flux. As with the other flux methods, the chloride flux residues should be removed.

7.4.28 Joint Strengths

While the strength of soldered joints is often not as important as other factors, very good strengths are possible. Shear strengths depend on the type of solder, from soft solders at 6000 psi (41.4 MPa) up to hard solders at 40,000 psi (276.0 MPa). The intermediate and high temperature solders retain much of their strength at service temperatures up to the melting point of soft solder at about 360°F (201°C). High temperature solders can retain significant strength up to 600°F (315°C), but creep will result if constant stress is applied above 250°F (121°C).

7.4.29 Corrosion Resistance

The corrosion resistance of soldered joints ranges from excellent to poor, depending on the choice of solder alloy and on the care taken to remove all traces of chloride containing flux. With low temperature solders, a thin layer of either aluminum tin or aluminum lead alloy is formed at the solder aluminum interface, and corrosive attack is concentrated at this location. The presence of moisture accelerates the corrosion of soldered joints, and if the moisture contains chemicals such as salt to form an electrolyte, the corrosion will be more rapid. Painting or coating joints to keep them dry minimizes corrosion. Generally, solder systems with high zinc solders are resistant to corrosive attack. Assemblies soldered with pure zinc or zinc aluminum solders have been exposed to outdoor environments for many years, and thus they are considered satisfactory for most applications requiring extended outdoor service life. Assemblies joined with presently available intermediate or low temperature solders are usually considered satisfactory only for interior or protected applications.

7.4.30 Conclusion

Many aluminum alloys can be successfully brazed and soldered and there are a number of methods available for both of these joining methods. More complete information regarding brazing and soldering of aluminum may be obtained in the Aluminum Association's publications: *Aluminum Brazing Handbook* and *Aluminum Soldering Handbook*, respectively.

Chapter 8

Codes and Standards for Welding Aluminum

8.1 Codes and Standards for Welding Aluminum

8.1.1 Introduction

The general term “welding standard” is often used to refer to documents that govern and guide welding activities. Standards describe the technical requirements for a material, process, product, system, or service. They also provide, as appropriate, the procedures, methods, equipment, or testing used to determine that the requirements of the standard have been met. Standards may include codes, specifications, guides, methods, regulations, rules, and recommended practices. These documents have many similarities, and since no universally accepted definition appears to exist for these terms, they are often used on an interchangeable basis. Codes and specifications are typically similar types of standards that use the verbs “shall” and “will” to indicate the mandatory use of certain materials or actions, or both. Codes may differ from specifications in that their use may be mandated with the force of law by one or more governmental jurisdictions. The use of specifications typically becomes mandatory only when they are referenced by mandated codes or contractual documents. Guides and recommended practices are usually standards offered primarily as aids to the user. They use verbs such as “should” and “may” because their use is usually optional. However, if these guides and/or recommended practices are referenced by mandated codes or contractual agreements, their use may become mandatory.

8.1.2 Sources

Private and governmental organizations develop, issue and update codes and standards that apply to their particular interests. Many codes and standards that are concerned with welding, brazing, and allied processes are prepared and controlled by the American Welding Society (AWS) because these subjects are of primary interest to the members. Other national organizations such as the American Society of Mechanical Engineers (ASME) and the American Petroleum Institute (API) are involved in the preparation of standards for welding. Other bodies outside of the U.S. such as the Canadian Welding Bureau (CWB), the European Welding Federation (EWF), and the International Institute of Welding (IIW) are also involved with the preparation of standards for welding. Each organization that prepares codes and standards has committees or task groups that perform this function. Members of these committees or groups are specialists in their field. They typically prepare drafts of codes and standards that are then reviewed and approved by a larger group. The review group is usually selected to include persons with diverse ranges of interests including, for example, producers, users, and government representatives. To avoid control or undue influence by any one interest group, agreement must be achieved by a high percentage of all members.

8.1.3 American Welding Society (AWS)

The primary source for welding codes and standards, used in the U.S. for the welding of aluminum, is the American Welding Society (AWS). AWS has produced many welding codes and specifications. Listed below are those that have most relevance to the joining of aluminum:

AWS A5.3, *Aluminum Alloy Electrodes for Shielded Metal Arc Welding*—Prescribes requirements for classification of aluminum and aluminum alloy electrodes for shielded arc welding.

AWS A5.8, *Specification for Filler Metals for Brazing and Braze Welding*—Requirements for classification of filler metals for brazing and braze welding.

AWS A5.10, *Aluminum and Aluminum Alloy Bare Welding Rod and Electrodes*—Covers the manufacturing, chemistry, dimensional tolerances, packaging, and inspection and testing for aluminum bare welding rod and electrodes.

AWS B2.1.015, *Gas Tungsten Arc Welding of Aluminum*—Provides standard welding procedure specifications for GTAW of aluminum.

AWS C3.7, *Specification for Aluminum Brazing*—Provides minimum fabrication and quality requirements for brazing aluminum and aluminum alloys.

AWS D1.2, *Structural Welding Code—Aluminum*—Addresses the welding requirements for aluminum alloy structures. It has sections on design, qualification, fabrication, inspection and testing.

AWS D3.7, —*Guide for Aluminum Hull Welding*—Provides information of proven processes, techniques, and procedures for welding aluminum hulls and related ship structures.

AWS D8.8, *Specification for Automotive and Light Truck Component Weld Quality—Arc Welding*—Provides the general minimum quality requirements necessary for automotive frames, light truck and components arc welding.

AWS D10.7, *Recommended Practices for Gas Shielded Arc Welding of Aluminum and Aluminum Alloy Pipe*—Provides information on welding characteristics, welding processes and equipment, welding materials, welding preparation, and welding techniques.

8.1.4 American Society of Mechanical Engineers (ASME)

The American Society of Mechanical Engineers (ASME) concerns itself with the development and control of codes and standards that address pressure vessels and pressure piping. While these standards are by no means exclusive to aluminum, and address the use of many material types, aluminum is sometimes used for fabrication under these requirements.

The ASME *Boiler and Pressure Vessel Code*, Sections I, III, IV, VIII, and X, covers the design, construction, and inspection of boilers and pressure vessels or nuclear power plant components. Sections VI, VII, and XI cover the care and operation of boilers. The remaining Sections II, V, and IX cover material specifications, nondestructive examination, and welding and brazing qualifications, respectively.

- Section I—*Power Boilers*—Covers power electric, and miniature boilers; high-temperature boilers used in stationary service; and power boilers used in locomotive, portable, and traction service.

- Section II—*Material Specifications*—Contains the specifications for acceptable ferrous and nonferrous base metals and for acceptable welding and brazing filler metals and fluxes. Many of these specifications are identical to, and have the same numerical designation as, ASTM and AWS 19.2 specifications for base metals and welding consumables, respectively.

- Section III—*Nuclear Power Plant Components*—Addresses the various components required by the nuclear power industry.

- Section IV—*Heating Boilers*—Applies to steam heating and hot water supply boilers that are directly fired by oil, gas, electricity, or coal.

- Section V—*Nondestructive Examination*—Covers methods and standards for nondestructive examination of boilers and pressure vessels.

- Section VI—*Recommended Rules for Care and Operation of Heating Boilers*.

- Section VII—*Recommended Guidelines for the Care of Power Boilers*.

- Section VIII—*Pressure Vessels*—Covers unfired pressure vessels.

- Section IX—*Welding and Brazing Qualifications*—Covers the qualification of (1) welders, welding operators, brazers, brazing operators, and (2) the welding and brazing procedures that are going to be employed for the welding and brazing of boilers or pressure vessels. This section of the code is often cited by other codes and standards, and by regulatory bodies, as the welding and brazing qualification standard for other types of welded or brazed products.

- Section X—*Fiber Reinforced Plastic Pressure Vessels*.

- Section XI—*Rules for Inspection of Nuclear Power Plant Components*.

8.1.5 Conclusion

There are many codes and standards that may be used for the control of aluminum welding, some of which are listed above. It is important to select a welding code or standard that matches your application as closely as possible. Welding codes and standards can provide the information that is needed to formulate a reliable quality control system for welding. Such information may include the design requirements for welded connections, welding procedure qualification testing requirements, welder performance qualification testing requirements, inspection and testing methods to be used and the criteria for determining acceptable weld quality for both qualification test samples and production welding.

8.2 The Structural Welding Code for Aluminum

8.2.1 Introduction

AWS D1.2, *Structural Welding Code—Aluminum*

Most welding fabricators are familiar with AWS D1.1, *Structural Welding Code—Steel*, but comparatively few realize there is a similar welding code for aluminum.

Having a structural welding code is an important requirement for metal fabrication in large structures, such as bridges, buildings, overhead highway signs, and other infrastructure. This is because engineers who design structures for use by the public should specify nationally recognized welding codes and standards to assure the quality of welds in the structures they design.

Requiring welding per AWS D1.2 provides a framework for process control, which can be an important part of a quality system. Qualification of welding procedures and welding personnel can reduce rework and improve quality. Improved manufacturing efficiency can also enhance profitability and help to produce a safe and dependable welded aluminum structure.

AWS D1.2, *Structural Welding Code—Aluminum*, is an American National Standard. All AWS standards (codes, specifications, recommended practices, methods, classifications, and guides) are voluntary consensus standards that have been developed in accordance with the rules of AWS and the American National Standards Institute.

The general term “welding code” refers to a document that governs and guides welding activities. These standards describe the technical requirements for a material, process, product, system, or service. They also provide, as appropriate, the procedures, methods, equipment, or testing used to determine that the requirements of the standard have been achieved.

AWS has been developing codes for the welding of various steel structures since 1928. In the early 1970s, the need for developing a code for the structural welding of aluminum was recognized. Because of the interest of both *The Aluminum Association* and AWS, it was decided to begin in the mid-70s, the task of developing a structural welding code for aluminum. Initially, a task force from *The Aluminum Association* undertook the effort. In 1979, this task force became a subcommittee of the AWS Structural Welding Committee, and the AWS D1.2, *Structural Welding Code—Aluminum*, resulted from the continued activity of that subcommittee.

8.2.2 About the D1.2 Code

The AWS D1.2, S*tructural Welding Code—Aluminum*, contains 10 sections and Annexes A through J, and also a comprehensive Commentary prepared to generate better understanding in the application of the code to welding in aluminum construction. Sections 1 through 6 and 10 constitute a body of rules for the regulation of welding on aluminum structures. Sections 7, 8, and 9 contain additional rules applicable to specific types of nontubular and tubular structures and should be used as a supplement to the first six sections. Key features of each of these sections are the list of dimensional tolerances and the weld quality requirements. These are provided for nontubular structures under static and dynamic loadings. For tubular structures, two classes of structures are identified. Class I structures are those in the general class of luminaries, traffic signals and overhead sign supports. All other tubular structures are Class II. Many of the requirements (dimensional and weld quality) are more stringent for Class II structures.

Recommended joint details have been prepared for various complete joint penetration and partial joint penetration groove welded joints. Herein lies one of the major differences between the Structural Welding Code—Steel and the Structural Welding Code—Aluminum. While the steel code allows for prequalified welding procedures, the code for aluminum does not. This is mainly because of the many varied possible welding conditions that can be obtained with the semiautomatic welding variables most often used with aluminum, and the wide range of both heat-treatable and non-heat-treatable alloys that may be welded under this code. Therefore, all of the joint details and the welding procedures used with the code shall be individually qualified and included in the Welding Procedure Specification (WPS).

Procedures and standards are outlined in the code for several methods of nondestructive testing. Methods included are visual, radiographic and dye-penetrant. Ultrasonic testing is permitted, but the procedure and acceptance criteria shall be specified in the contract documents.

Unlike the steel structural code, AWS D1.1, the aluminum structural code, AWS D1.2, does not cover design considerations such as the allowable stresses for load-carrying members. This information is covered by reference to the *Aluminum Design Manual*, published by The Aluminum Association.

The AWS D1.2, *Structural Welding Code—Aluminum*, provides the user with three of the most fundamental requirements necessary for the establishment of a welding control system. The first is the requirement for welding procedure qualifications. This is the process of establishing and verifying that the welding parameters and techniques that are to be used in production are capable of meeting the minimum quality/performance requirements. Second is the requirement for qualifying welders. This is the process used to test, verify, and certify that the production welders are capable of producing welds that meet the quality requirements of the code. The third item that the code provides is the acceptance criteria for the production weld quality. Without these criteria, there is no practical way of evaluating weld quality or identifying the type and extent of weld discontinuities that may seriously affect the welded component's performance in service.

8.2.3 Conclusion

Any manufacturer considering fabrication of aluminum alloy structures should consider using the AWS D1.2, *Structural Welding Code—Aluminum*, for the basis of controlling their welding operations.

8.3 What is the AWS A5.10 Specification for Bare Aluminum and Aluminum-Alloy Welding Electrodes and Rods?

I was using a spool of aluminum MIG wire and on the spool label it stated that the wire conforms to specification AWS A5.10 and that the wire classification was ER4043. What are the requirements of this specification and how does the classification system work?

8.3.1 The A5 Series Specifications

The American Welding Society has over thirty specifications in the A5 series; these documents all address filler alloys, electrodes, rods, fluxes, and other consumables used in welding. The two specifications in this series that are directly related to aluminum are AWS A5.3, *Specification for Aluminum and Aluminum-Alloy Electrodes for Shielded Metal Arc Welding*, and AWS A5.10, *Specification for Bare Aluminum and Aluminum-Alloy Welding Electrodes and Rods*. Any reputable manufacturer of aluminum filler metal will manufacture their product in accordance with the requirements of this national standard.

8.3.2 All About the Specification

The AWS A5.10 Specification contains the following sections:

8.3.2.1 Part A—General Requirements

In this section, the standard addresses Normative References and describes the classification system. It states that any filler metal tested and classified as an electrode (ER) shall also be classified as a rod (R). However, filler metal tested and classified only as a rod shall not be classified as an electrode. It also states that electrodes and rods classified under this specification are intended for gas metal arc, gas tungsten arc, oxyfuel gas, and plasma arc welding, but that is not to prohibit their use with any other process for which they are found suitable. This section of the standard contains Table 1 which provides the chemical composition requirements for aluminum electrodes and rods. It also contains Table 2, which are the required tests. This table indicates the testing requirements for each classification of electrodes and rods.

8.3.2.2 Part B—Tests, Procedures, and Requirements

In this section, we find the detailed test requirements. It states that the purpose of the tests are to determine the chemical composition of the filler metal, soundness of the weld metal produced by gas metal arc welding electrodes, and the deposition characteristics of the welding rods. Section 9 describes the two different weld test assemblies, the groove weld for soundness and usability of electrodes, and the bead-on-plate weld test for usability of welding rods. Section 10 addresses the method to be used for chemical analysis of a sample of filler metal or the stock from which it is made. Section 11 addresses radiographic testing and provides the standard method for controlling quality of radiographic testing. Figure 1 of the standard shows the groove weld test assembly for radiographic tests, providing dimensional requirements and joint geometry. Figures 2A and 2B provide a graphical representation of radiographic acceptance standards for test assemblies in the overhead welding position, showing assorted rounded indications, medium rounded indications and small rounded indications. The acceptance standards stipulate that indications which do not exceed 1/64 in [0.4 mm] diameter or length, or both, shall be disregarded during interpretation. For 3/16 in [4.8 mm] and 1/4 in [6.4 mm] thick test assemblies, the maximum total area of porosity in 6 in [150 mm] length of weld is 0.0225 in^2 [14.52 mm^2] based on 1.5% T per in [25 mm], where T is the base metal thickness. For 3/8 in [10 mm] thick test assemblies, the total area of porosity in 6 in [150 mm] length of weld is 0.0337 in^2 [21.7 mm^2] based on 1.5% T per in [25 mm], where T is the base metal thickness. These radiographic acceptance standards are identical to those previously in MIL-E-16053L (Amendment 2, 20 October 1980) and as Class 3 NAVSEA 0900-LP-003-9000.

The specification requires that electrode diameters of 1/16 in [1.6 mm] and below be tested in the overhead position and electrode diameters above 1/16 in [1.6 mm] the flat position. A bead-on-plate test is required for rod testing. The rod is required to produce weld metal that flows freely and uniformly without sputtering or other irregularities. The resultant weld metal shall be smooth and uniform with no visible evidence of cracks or porosity to pass the test.

8.3.2.3 Part C—Manufacture, Identification, and Packaging

Standard sizes, diameters, and dimensional tolerances for round filler metal in different forms of straight length, coils without support, and spools are as shown in Table 4 of the standard. The requirements for finish and uniformity are that all filler metal shall have a smooth finish that is free from slivers, depressions, scratches, scale, seams, laps, and foreign matter that would adversely affect the welding characteristics, the operation of the welding equipment, or the properties of the weld metal.

Standard package dimensions and weights for each product form are given in Table 6, and the dimensions of the standard spool sizes shall be as shown in Figures 4 and 5 of the standard. Spools are required to be designed and constructed to prevent distortion to themselves and the filler metal during normal handling and use and shall be clean and dry enough to maintain the cleanliness of the filler metal. The following product information (as a minimum) shall be legibly marked so as to be visible from the outside of each unit package:

1. AWS specification and classification designation;

2. Suppliers name and trade designation;

3. Size and net weight; and

4. Lot, control, or heat number.

Minimum precautionary information which is required to be predominantly displayed in legible print on all packages of welding material is also provided in the specification.

8.3.3 Conclusion

As stated earlier, any reputable manufacturer of aluminum filler metal will manufacture their product in accordance with the requirements of this national standard. But does the AWS A5.10 specification marked on a box of aluminum wire guarantee that you will have a quality product that will consistently meet your requirements? Not necessarily. However, it is one of the very important controls that can help to guarantee high-quality aluminum welding wire. The AWS A5.10 standard testing methods along with good manufacturing procedures, suitable and well maintained manufacturing equipment, trained and experienced manufacturing personnel, all supported by a suitably designed and implemented quality management system is really needed to produce consistently good quality aluminum welding wire.

8.4 Is there a specification available specifically for Friction Stir Welding?

? I am currently involved with an aerospace project that requires the development of welding procedures to be used for Friction Stir Welding aluminum alloys. I am looking for information relating to the type of tests I can perform and appropriate acceptance criterion that may be used for the inspection and testing of joints made by the Friction Stir Welding process. In the past I have used AWS D1.2 Structural Welding Code—Aluminum for my aluminum arc welding procedure qualifications. However, the AWS D1.2 Code does not include Friction Stir Welding as a designated welding process. I have been unable to find a specification that will provide me with precise guidelines for Friction Stir Welding, is there a specification available specifically for this welding process?

You are quite correct the AWS D1.2:2008 Structural Welding Code—Aluminum provides requirements for four welding process that are listed in section 4.1 of the code. These are Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding with Variable Polarity (PAW-VP), and Stud Welding (SW).

8.4.1 Friction Stir Welding Specifications

There have been limited resources available in the form of an American National Standard Welding Specification that addresses a procedure qualification and inspection criteria for Friction Stir Welding (FSW), due to the fact that in terms of welding processes, FSW is a relatively new process. This process was conceived, developed, and subsequently patented in 1991 by The Welding Institute (TWI) in Cambridge, UK. It has taken time since the conception of this welding process for it to be tested, further developed, and recognized by the industry. After the need for a welding standard for FSW was recognized, additional time has been spent in the development and approval of a suitable specification. In late 2009 the American Welding Society (AWS) released the first specification for Friction Stir Welding (FSW) of aluminum alloys. This new specification was created for aerospace applications. I have been informed by TWI that the International Institute of Welding (IIW) is currently working on a standard for Friction Stir Welding (FSW) that covers FSW of Aluminum and is intended for use by all industries using the process. The standard (ISO 25239) is in the final stages of agreement and is expected to be issued in 2010. As the inventor of Friction Stir Welding (FSW) TWI has historically and presently committed to working with manufacturing organizations to assist in the development of welding procedures associated with Friction Stir Welding (FSW) and also assisting in achieving approval of procedures through third party organizations.

8.4.2 AWS D17.3/D17.3M:2010 Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications

The AWS D17 Committee on Welding in the Aircraft and Aerospace Industries determined that it was necessary to form a subcommittee to write a specification for Friction Stir Welding (FSW). It was appropriate that the setting for the subcommittee's kickoff meeting in October 1999 was at the Kennedy Space Center in Florida. Kennedy Space Center is where the first Friction Stir Welded commercial aerospace component, the fuel tank for the Delta launch vehicle, went into service. Representatives from industry, welding institutes, government agencies, and universities met to dedicate themselves to form a specification for the Friction Stir Welding of aluminum for aerospace applications. AWS D17.1:2001, *Specification for Fusion Welding for Aerospace Applications* served as the model for this specification.

8.4.3 Specification Content

1. Scope

The scope of the specification is quite brief — *This specification contains the requirements for designing, friction stir welding, and inspecting aerospace hardware* — followed by a description of the process — *Friction Stir Welding (FSW) produces a weld between two abutting work pieces by the friction heating and plastic material displacement caused by a rotating tool that traverses along the weld joint.* (See Figure 1)

2. Normative References

The normative references list various standards that contain provisions, which through reference in the standard constitute mandatory provisions of the AWS Standard.

3. Terms and Definitions

This section provides some very useful material, six full pages of definitions supported by illustrations to help interpretation. Many of these definitions are specific to the FSW process and are therefore very important to the understanding of this relatively new welding process and the use of the standard.

4. General Requirements

This section of the specification deals with the classification of welds, Class A — Critical, Class B — Semi-critical, and Class C — Non-critical. It also addresses, approval, drawing precedence, and specification precedence.

5. Design of Weld Joints

This section addresses information about weldment design data, drawing information requirements (listing essential information that will be specified on drawings), weld dimensions and inspection requirements.

6. Development and Qualification of a Welding Procedure

This is a very comprehensive section of the specification, providing all the information required for the development of a Preliminary Welding Procedure Specification (pWPS), Welding Procedure Qualification Record (WPQR), and Welding Procedure Specification (WPS). This section includes information on the sequence for qualifying a welding procedure, selection of a welding procedure qualification method, preparation of a preliminary WPS with required variables, evaluation of test welds, visual inspection, destructive tests, acceptance criteria, and WPS variables. All this material is supported by a flow chart and a number of comprehensive figures and tables providing details of test specimens for various joint designs.

7. Welding Operator Qualification

This section addresses operator qualification requirements, vision testing, test weld requirement, inspection, qualification limitations, qualification/certification validity, and test records. This material is supported by various drawings that show test plate detail.

8. Fabrication

The fabrication section of the specification provides information on welding equipment requirements, FSW tools, pre-weld joint preparation and fit-up, pre-heat temperature control, tack welding, postweld surface preparation, weld identification requirements, and acceptance inspection.

9. Inspection

This section begins with a discussion on the three quality levels that are used by the standard to facilitate the application of a wide range of welded construction.

It also includes requirements for inspection personnel qualification, visual weld inspection, nondestructive testing (penetrant testing, radiographic testing, ultrasonic testing and provision for other NDT methods). The topic of acceptance criteria is also included in this section primarily addressed by section 9.5.1 that provides the general rules for acceptance criteria and table 9.1 - Acceptance Levels for Discontinuities. The table is divided into three quality levels for class A, B, and C welds and addresses the following discontinuities; cracks, incomplete joint penetration, inclusions, internal cavity, or cavity open to the surface, linear mismatch across joint, overlap, angular distortion of the joint, underfill, and weld flash.

Annex A — Illustrations of test specimens and test fixtures

Annex A provided drawings and tables that outline the requirements for reduced section tension specimens both rectangular and round as well as an alternate tension specimen for pipe.

Annex B — Example of a Welding Operator Qualification Test Record Form

A typical qualification test record is provided for information purposes only.

Annex C — Examples of Welding Procedure Specification Forms

This section provides examples for a preliminary procedure specification form and an example of a welding specification form.

Annex D — Examples of Welding Procedure Qualification Record Forms

This section contains two examples of welding procedure qualification record forms.

Figure 8.1—Friction Stir Welding

In the FSW process the parts intended for joining are usually arranged in a butt configuration. The rotating tool is then brought into contact with the work pieces. The tool has two basic components: the probe, which protrudes from the lower surface of the tool, and the shoulder, which is of relatively large diameter. The length of the probe is typically designed to match closely the thickness of the work pieces. Welding is initiated by first plunging the rotating probe into the work pieces until the shoulder is in close contact with the component top surface. Friction heat is generated as the rotating shoulder rubs on the top surface under an applied force. Once sufficient heat is generated and conducted into the work piece, the rotating tool is propelled forward. Material is softened by the heating action of the shoulder, and transported by the probe across the bondline, facilitating the joint.

8.4.4 Conclusion

The AWS D17.3/D17.3M:2010 Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications is the first National standard for Friction Stir Welding, but others will no doubt follow. AWS D17.3 would appear to provide the information you are inquiring about, which may make it very appropriate for your project. I would suggest that you acquire a copy of this specification and evaluate it for your application.

About the Author

Tony Anderson began his career in 1968 when he joined Vickers Shipbuilding in Barrow-in-Furness, England as an apprentice welder. While working for Vickers Shipbuilding, predominantly employed on the welding of nuclear submarines, he attended technical college for four years and received the highest qualification at that time awarded by the City and Guilds of London Institute in Welding Engineering. In his late twenties, he relocated to Southern Africa where he spent 15 years employed as a Welding Inspector, Welding Engineer, NDT Manager, Quality Assurance Manager, and Welding Engineering Consultant. Most recently Anderson has resided in the U.S. during this time he has been actively involved with aluminum welding technology. He was employed by AlcoTec Wire Corporation (Alcoa) where he held the position as Technical Director before being transferred to ESAB Welding and Cutting Products as Corporate Technical Training Manager—ESAB North America.

Mr. Anderson has held the position of Chair of the Aluminum Association Technical Advisory Committee for Welding and Joining and has held various positions on the following AWS Committees:

AWS D10.7, *Arc Welding of Aluminum Alloy Pipe* (Chair)

AWS A5.10, *Bare Aluminum and Aluminum-Alloy Welding Electrodes and Rods* (Chair)

AWS A5.3, *Aluminum and Aluminum Alloy Electrodes for Shielded Metal Arc Welding* (Chair)

AWS D3.7, *Guide for Aluminum Hull Welding* (Chair)

AWS D8.14, *Automotive and Light Truck Weld Quality—Aluminum* (Chair)

AWS D1.2, *Structural Welding Code—Aluminum* (Vice Chair)

AWS Conference Committee (Vice Chair)

Anderson has a Master of Science degree in Industrial Engineering Management and Quality Assurance and a Bachelor of Science degree in Welding Engineering. He is a Fellow of The British Welding Institute (TWI) and a Registered Chartered Engineer (CEng) with the British Engineering Council (EC–UK). He is an American Welding Society Certified Welding Inspector (CWI), Certified Welding Educator (CWE), and Certified Welding Engineer (CWEng). He has had numerous technical articles relating to welding engineering published in many journals and magazines over the years and has presented technical papers internationally at many conferences and seminars. In 2004 Anderson was awarded the American Welding Society's "Individual Achievement Award" in recognition of excellent service to the advancement of the image of welding.

Annex A

References and Sources for Further Information

The Aluminum Association (www.aluminum.org)

1525 Wilson Blvd., Suite 600, Arlington, VA 22209

Aluminum Brazing Handbook

Aluminum Design Manual, Specification & Guidelines for Aluminum Structures

Aluminum Soldering Handbook

Aluminum Standards and Data

Aluminum Technology, Applications, and Environment—A Profile of a Modern Metal—Dietrich G. Altenpohl

Care of Aluminum

Designation System for Aluminum Finishes

Designations and Chemical Composition Limits for Aluminum Alloys in the Form of Castings and Ingot

Forming and Machining Aluminum

Guidelines for the Use of Aluminum with Food and Chemicals

International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys

Welding Aluminum Theory and Practice

American National Standards Institute (ANSI) (www.ansi.org)

25 West 43rd Street, 4th Floor, New York, NY 10036-7406

ANSI H35.1/H35.1(M), *Alloy and Temper Designation System for Aluminum*

American Society for Testing and Materials (ASTM) (www.astm.org)

100 Barr Harbor Drive, West Conshohocken, PA 19428-2959

ASTM B 918-01, *Standard Practice for Heat Treatment of Wrought Aluminum Alloys*

American Welding Society (www.aws.org)

550 N.W. LeJeune Road, Miami, FL 33126

AWS A5.3/A5.3M, *Specification for Aluminum and Aluminum-Alloy Electrodes for Shielded Metal Arc Welding*—Prescribes requirements for classification of aluminum and aluminum alloy electrodes for shielded arc welding.

AWS A5.8/A5.8M, *Specification for Filler Metals for Brazing and Braze Welding*—Requirements for classification of filler metals for brazing and braze welding.

AWS A5.10/A5.10M, *Specification for Bare Aluminum and Aluminum Alloy Welding Electrodes and Rods*—Covers the manufacturing, chemistry, dimensional tolerances, packaging, and inspection and testing for aluminum bare welding rod and electrodes.

AWS B2.1-22-015, *Standard Welding Procedure Specification (SWPS) for Gas Tungsten Arc Welding of Aluminum (M/P/S-22 to M/P/S-22), 18 through 10 Gauge, in the As-Welded Condition, with or without Backing*—Provides standard welding procedure specifications for GTAW of aluminum.

AWS C3.7M/C3.7, *Specification for Aluminum Brazing*—Provides minimum fabrication and quality requirements for brazing aluminum and aluminum alloys.

AWS D1.2/D1.2M, *Structural Welding Code—Aluminum*—Addresses the welding requirements for aluminum alloy structures. It has sections on design, qualification, fabrication, inspection and testing.

AWS D3.7, *Guide for Aluminum Hull Welding*—Provides information of proven processes, techniques, and procedures for welding aluminum hulls and related ship structures.

AWS D8.8M, *Specification for Automotive Weld Quality—Arc Welding of Steel*—Provides the general minimum quality requirements necessary for automotive frames, light truck and components arc welding.

AWS D10.7M/D10.7, *Guide for the Gas Shielded Arc Welding of Aluminum and Aluminum Alloys*—Provides information on welding characteristics, welding processes and equipment, welding materials, welding preparation, and welding techniques.

AWS D17.3/D17.3M, *Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications*—Contains the requirements for designing welding procedures and inspection requirements for Friction Stir Welding Aerospace hardware.

AWS *Welding Handbook*

ASM International (www.asminternational.org)

9639 Kisman Road, Materials Park, OH 44073-0002

Aluminum: Properties and Physical Metallurgy

ASM Specialty Handbook—*Aluminum and Aluminum Alloys*

Other

Aluminum-Schlussel—Aluminum-Verlag—Germany

The Welding of Aluminum Alloys—Gene Mathers, Woodhead Publishing Limited Cambridge England

Basic Safety Precautions

Burn Protection. Molten metal, sparks, slag, and hot work surfaces are produced by welding, cutting, and allied processes. These can cause burns if precautionary measures are not used. Workers should wear protective clothing made of fire-resistant material. Pant cuffs, open pockets, or other places on clothing that can catch and retain molten metal or sparks should not be worn. High-top shoes or leather leggings and fire resistant gloves should be worn. Pant legs should be worn over the outside of high-top shoes. Helmets or hand shields that provide protection for the face, neck, and ears, and a head covering to protect the head should be used. In addition, appropriate eye protection should be used.

Electrical Hazards. Electric shock can kill. However, it can be avoided. Live electrical parts should not be touched. The manufacturer's instructions and recommended safe practices should be read and understood. Faulty installation, improper grounding, and incorrect operation and maintenance of electrical equipment are all sources of danger. All electrical equipment and the workpiece should be grounded. The workpiece lead is not a ground lead. It is used only to complete the welding circuit. A separate connection is required to ground the workpiece. The workpiece should not be mistaken for a ground connection.

Fumes and Gases. Many welding, cutting, and allied processes produce fumes and gases which may be harmful to health. Avoid breathing the air in the fume plume directly above the arc. Do not weld in a confined area without a ventilation system. Use point-of-welding fume removal when welding galvanized steel, zinc, lead, cadmium, chromium, manganese, brass, or bronze. Do not weld on piping or containers that have held hazardous materials unless the containers have been inerted properly.

Compressed Gas Cylinders. Keep caps on cylinders when not in use. Make sure that gas cylinders are chained to a wall or other structural support. Do not weld on cylinders.

Radiation. Arc welding may produce ultraviolet, infrared, or light radiation. Always wear protective clothing and eye protection to protect the skin and eyes from radiation. Shield others from light radiation from your welding operation. The use of filtering masks or airline respirators will be required if it is determined that personnel are being exposed to excessive pollutants.

Additional information on welding safety may be obtained from the American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126. ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*, and the AWS *Safety and Health Fact Sheets* are available online and free of charge on the AWS website: http://www.aws.org/technical/facts/.

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