

Welding Handbook

Ninth Edition

Volume 5

MATERIALS AND APPLICATIONS, PART 2

Prepared under the direction of
the Welding Handbook
Committee

Annette O'Brien, Editor Kathy



American Welding Society

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DEDICATION

The Welding Handbook Committee dedicates this book jointly to Bernhard J. (Bernie) Bastian, long-term member of the Welding Handbook Committee, and Annette O'Brien, Senior Editor, in recognition of their contributions to the five volumes of the 9th edition of the *Welding Handbook* for the American Welding Society.

B. J. Bastian

B. J. Bastian, M.S., P.E., welding consultant, teacher, writer, mentor, and contributor to the technology of automotive welding, has generously shared the expertise acquired during his 50-year career in the welding industry by serving on the Welding Handbook Committee. He has provided valuable guidance to the Committee on the organization and technical content of the *Welding Handbook*, and was responsible for oversight and final reviews of various chapters of each of the five volumes of the 9th edition.

Bernie's career includes work with Ford Motor Company and Chrysler Corporation, not only in welding engineering and management, but also as an instructor and coach for welders and technicians. He has a Bachelor of Science degree in mechanical engineering and a Master's degree in metallurgical engineering from Rensselaer Polytechnic Institute. He added postgraduate studies at the University of Michigan. He taught welding and related courses at Henry Ford Community College for 17 years, and has written instructive articles for a number of technical publications.

He is a Fellow of the American Welding Society and was also honored as a Life Member in recognition of his work as a volunteer with AWS. He is a past member of the AWS Board of Directors.

Annette O'Brien

Annette O'Brien served as Editor for all five volumes of the Ninth Edition of the *Welding Handbook*. For more than 15 years she diligently and patiently guided the volumes, each containing over 700 pages, through many stages of editing, proofing, review, and final approval necessary to produce one of the finest series of reference books in the welding industry.

Annette also served as Secretary to the Welding Handbook Committee, organizing meetings, preparing minutes, expediting and distributing chapters for peer reviews, and communicating the information necessary to keep the committee informed and on schedule. Her many years of commitment to the *Welding Handbook* have been invaluable to the American Welding Society.

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This volume was compiled by the members the Welding Handbook Volume 5 Committee and the WH5 Chapter Committees, with oversight by the Welding Handbook Committee. Chapter committee chairs, chapter committee members, and oversight persons are recognized on the title pages of the chapters.

The Welding Handbook Committee and the editors recognize and appreciate the AWS technical committees who developed the consensus standards that pertain to this volume, and acknowledge the work of the editors of the Eighth Edition of the *Welding Handbook*: L. P. Connor, Volume 1; R. L. O'Brien, Volume 2; and W. R. Oates, Volumes 3 and 4. The Welding Handbook Committee is grateful to members of the AWS Technical Activities Committee and the AWS Safety and Health Committee for their reviews of the chapters. The editors appreciate the AWS Technical Services staff for their assistance during the preparation of this volume.

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PREFACE

This is Volume 5, the last in the series of the Ninth Edition of the *Welding Handbook*. It is *Materials and Applications, Part 2*, presented in ten peer-reviewed chapters covering the welding of nonferrous metals and materials. The titles of the chapters in this book indicate the variety of challenges presented to welders, designers, welding engineers, and others in the welding workplace.

The scientists who examine the microstructures of metals and other materials, identify constituents, and determine how the properties of these materials can be used and controlled during welding have contributed to the expanded information in this book. Some of the best scientists in the welding industry from universities, government and private research laboratories, metals-producing companies, fabricators, consulting firms, and testing facilities have stepped forward as volunteers to update this volume. They are recognized on the title pages of their respective chapters.

This volume covers the technicalities of joining aluminum; magnesium; copper; nickel and cobalt; lead and zinc; titanium; reactive, refractory, and precious metals; plastics; ceramics; and composites. Each chapter includes a thorough explanation of the metal or other material, details of the welding processes used to join it, and a comprehensive bibliography. A section on safe practices pertinent to the specific metal or material is included in each chapter.

Two appendices provide supplemental information. Appendix A is a list of sources of safety codes and standards, with contact information of the publishers. Appendix B is a reference guide to Ninth Edition Volumes 1, 2, 3, and 4, included to accommodate the frequent references to the chapters of these books.

This volume concludes the Ninth edition of the *Welding Handbook*, following the four published volumes: Volume 1, *Welding Science and Technology*, which provides the foundation for successful welding and allied processes; Volume 2, *Welding Processes, Part 1*, which contains the technical details of arc welding and cutting, the gas processes, brazing, and soldering; Volume 3, *Welding Processes, Part 2*, comprised of the resistance, solid-state, and other welding processes; and Volume 4, *Materials and Applications, Part 1*, which covers the ferrous metals. Volume 5, *Materials and Applications, Part 2*, covers nonferrous metals and materials, including ceramics, plastics, and composites.

These five books, all peer-reviewed, are made up of 67 chapters; overall, they represent the collaborative work of a total of 428 volunteers who generously spent many hours of personal time to provide authentic technical information from their specific areas of expertise. The Welding Handbook Committee extends its gratitude to each of these volunteers.

The Welding Handbook Committee welcomes your comments and suggestions. Please address them to the Editor, Welding Handbook, American Welding Society, 8669 NW 36 St, # 130, Miami, FL 33126.

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CHAPTER 1

ALUMINUM AND
ALUMINUM
ALLOYS



Photograph courtesy of Miller Electric Company
Gas Metal Arc Welding an Aluminum Seat Frame for a Racing Car

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CHAPTER 1

ALUMINUM AND ALUMINUM ALLOYS

INTRODUCTION

Aluminum (Al), one of the most plentiful elements mined from the earth, is found in its oxidized form in bauxite, which, when refined, yields 40% to 60% alumina (aluminum oxide, Al_2O_3). The aluminum is separated from the oxygen using the Hall-Héroult electrolysis process, which was invented in 1886. This process made possible the production of aluminum on an industrial scale, increasing availability and drastically reducing the cost from the prevalent price of \$600/lb in the years before. Aluminum usage in the world has grown exponentially since then, driven by the development of new joining technology and new applications.

Aluminum is highly ranked among the most useful metals known to manufacturers and fabricators. The strength of some aluminum alloys exceeds that of mild steel; aluminum can be cast, rolled, stamped, drawn, spun, stretched, or roll-formed. It can be hammered, forged, or machined with ease and speed, or extruded into a wide variety of shapes; then it can be given an equally wide variety of mechanical, electromechanical, chemical, or paint finishes.

Aluminum retains good ductility at subzero temperatures, is highly resistant to corrosion, and is not toxic. It has good electrical and thermal conductivity, is highly reflective of heat and light, and is nonsparking and nonmagnetic.

The properties of aluminum and aluminum alloys are valuable for critical applications in the space and aircraft, marine, and automotive industries; for structural applications; for vessels and storage tanks; and are also vital for countless consumer products. Processes to weld aluminum continue to improve and have contributed to the widespread use of this remarkable material.

Most of the common joining methods—welding, brazing, soldering, adhesive bonding, and mechanical fastening—can be used to join aluminum.¹ All processes, except mechanical fastening, are discussed in this chapter; a brief section on aluminum cutting is also included.^{2,3}

GENERAL CHARACTERISTICS OF ALUMINUM

Pure aluminum melts at 660°C (1220°F). Aluminum alloys have an approximate melting range of 480°C to 660°C (900°F to 1220°F), depending on the alloy. There is no color change in aluminum when heated to the welding or brazing temperature range, therefore the welder cannot be guided by color and must assume a position that will allow direct observation of the melting of the base and filler metals under the arc or flame.

1. For information on welding, brazing, soldering, and adhesive bonding processes, refer to American Welding Society (AWS) Welding Handbook Committee, 2004, *Welding Handbook*, 9th ed., ed. A. O'Brien, and *Welding Processes*, vol. 2, Part 1, ed. A. O'Brien, and *Welding Processes*, vol. 3, Part 2, 2007, ed. A. O'Brien and C. Guzman, Miami: American Welding Society. Refer to Appendix B of this volume for a list of chapter contents for the five volumes of *Welding Handbook*, 9th ed.

2. At the time this chapter was prepared, the referenced codes and other standards were valid. If a code or other standard is cited without a date of publication, it is understood that the latest edition of the document referred to applies. If a code or other standard is cited with the date of publication, the citation refers to that edition only, and it is understood that any future revisions or amendments to the code are not included; however, as codes and standards undergo frequent revision, the reader must consult the most recent edition.

3. Welding terms and definitions used throughout this chapter are from American Welding Society (AWS) Committee on Definitions and Symbols, 2010, *Standard Welding Terms and Definitions*, AWS A3.0M/A3.0:2010, Miami: American Welding Society.

For fusion welding, the high thermal conductivity of aluminum (compared to steel) necessitates a high rate of heat input. Thick sections may require preheating. For resistance spot welding, the high thermal and electrical conductivity of aluminum requires a higher current, a shorter weld time, and more precise control of welding variables than required for steel. Because aluminum is nonmagnetic and no arc blow occurs when welding with direct current, aluminum is often used for weld backing and for the construction of welding fixtures.

Aluminum and aluminum alloys develop an oxide film when exposed to air. This natural oxide film, which melts at about 2040°C (3700°F), can be broken up by the application of direct current electrode positive (DCEP) polarity during welding. Aluminum oxide can be chemically or mechanically removed. Exposure to elevated temperatures during thermal treatments or exposure to moist environments causes the aluminum oxide film to thicken significantly, necessitating mechanical or chemical removal prior to welding or joining.

Anodic electrolytic or anodized treatments applied to aluminum result in the formation of thick, dense oxide coatings that must be removed prior to joining with fusion welding, resistance welding, brazing, or soldering.⁴ Anodic coatings can resist 400 volts (V) or more, so a welding arc cannot be initiated. During preparations for arc welding, the oxide coating must be removed, not only from the joint, but also from the area adjacent to the workpiece lead.

The properties and performance of aluminum weldments are influenced by microstructural changes that occur during any elevated-temperature joining process. The original properties of strength, fatigue life, ductility, and formability in the workpieces can change, depending on the amount of annealing, over-aging, and cast-structure formation that occurs during the joining process. The results of these changes are presented in subsequent sections of this chapter devoted to specific joining processes.

ALUMINUM PRODUCT FORMS

Aluminum is supplied as wrought products (sheet, plate, extrusions, and forgings) or cast products. Pure aluminum is readily alloyed with many other metals to produce a wide range of physical and mechanical properties.

Aluminum alloys are classified according to the means by which the alloying elements strengthen the aluminum, which places the alloys into two categories: nonheat treatable and heat treatable. Cast aluminum

alloys are additionally classified by the method of casting: sand casting, permanent mold casting, and die casting. Wrought and cast aluminum alloys have similar joining characteristics, regardless of product form, so that essentially the same welding, brazing, and soldering practices are used on both cast and wrought aluminum, with one exception: welding or brazing is not recommended for joining conventional die castings. Conventional die castings can be joined by adhesive bonding and, to a limited extent, by soldering. Vacuum die casting technology has improved the quality of castings to the point that some castings may be satisfactorily joined by welding.

To increase corrosion resistance, some aluminum alloys are manufactured with a high-purity aluminum or a special aluminum alloy material applied to the product surfaces. The cladding process is accomplished by the application of cladding material to one or both sides of the workpieces in thicknesses ranging from 2.5% to 15% of the total thickness of the workpiece. Cladding not only protects the composite, but generally exerts a galvanic effect, which further protects the core alloy. Special cladding alloys are also available for brazing, soldering, and finishing purposes.

WROUGHT ALUMINUM ALLOYS

Wrought aluminum alloys are supplied as sheet, plate, extrusions, or forgings. Table 1.1 lists the major alloying elements in wrought aluminum alloys. A system of four-digit numerical designations is used to classify wrought aluminum alloys.

Table 1.1
Designations for Wrought Alloy Groups

Aluminum, 99.0% and greater	1XXX
Major Alloying Element	
Copper	2XXX
Manganese	3XXX
Silicon	4XXX
Magnesium	5XXX
Magnesium and Silicon	6XXX
Zinc	7XXX
Other elements	8XXX
Unused series	9XXX

Note: The second digit in all groups indicates consecutive modifications of an original alloy, such as 5154, 5254, 5454, and 5654 alloys. The last two digits in the 1xxx series indicate the minimum aluminum purity, e.g., 1060 is a 99.60% minimum Al. The last two digits in all other groups have no significance.

4. The term *coating* is used to describe a deliberate chemical buildup of aluminum oxide on aluminum surfaces that results in a very thick, dense oxide layer on the aluminum surface.

Aluminum Alloys and Alloying Elements

According to the four-digit numerical designation system, the first digit of the 1XXX series indicates the alloy group; the second digit indicates consecutive modifications of an original alloy; the last two digits indicate the minimum percentage of aluminum.

For alloys in the 2XXX through 9XXX series, the first digit indicates the alloy group. The second digit indicates the consecutive modifications to an original alloy, such as Alloys 5154, 5254, 5454, and 5654. The position of the last two digits in the 2XXX through 9XXX series has no special significance, but serves only to identify the aluminum alloys in the group.

1XXX Series. Alloys in the 1XXX series are often referred to as the pure aluminum alloys because they are required to have a minimum of 99.0% aluminum. These alloys are weldable, but because they have a narrow melting range, they require certain considerations when acceptable welding procedures are being developed. When considered for fabrication, these alloys are selected primarily for applications requiring superior corrosion resistance, such as specialized chemical tanks and piping, or excellent electrical conductivity, such as for bus bar applications. These alloys have relatively poor mechanical properties and usually would not be considered for general structural applications. The 1XXX base alloys are often welded with a matching filler metal chemistry or with filler alloys of the 4XXX series, depending on application and performance requirements. These alloys are not heat treatable and have an ultimate tensile strength ranging from 69 MPa to 186 MPa (10 ksi to 27 ksi).

2XXX Series. Alloys in the 2XXX series are the aluminum-copper (Al-Cu) group, with copper additions ranging from 0.7% to 6.8%. The 2XXX series high-strength alloys are often used for aerospace and aircraft applications because they maintain excellent strength over a wide range of temperatures. Some of the alloys in the 2XXX series are not considered weldable by arc welding processes because they are susceptible to hot cracking and stress-corrosion cracking; however, other alloys in this series can be readily welded with arc processes when correct procedures are used. As base metals, these alloys are often welded with high-strength filler alloys in the 2XXX series, which are designed to match base-metal performance characteristics. Depending on the application and service requirements, however, they can sometimes be welded with the filler metals in the 4XXX series, which contain silicon (Si) or silicon and copper. These alloys are heat treatable and have an ultimate tensile strength ranging from 186 MPa to

3XXX Series. The 3XXX series aluminum-manganese (Al-Mn) alloys, with manganese additions ranging from

0.05% to 1.8%, provide moderate strength, good corrosion resistance, and excellent formability, and are suited for use at elevated temperatures. One of the first uses of alloys in this series was in the manufacturing of kitchen utensils, pots, and pans; today these alloys are the major component of heat exchangers in vehicles and power plants. The moderate strength of these alloys, however, often precludes consideration for structural applications. These base alloys are welded with filler alloys from the 1XXX, 4XXX, and 5XXX series, depending on the specific chemistry, the particular application, and service requirements. These alloys are not heat treatable, and they have an ultimate tensile strength of 110 MPa to 283 MPa (16 ksi to 41 ksi).

4XXX Series. Alloys in the 4XXX series, which consist of aluminum-silicon (Al-Si) alloys where silicon additions range from 0.6% to 21.5%, include both heat-treatable and nonheat-treatable alloys. When added to aluminum, silicon lowers the melting point, and when melted, improves fluidity. Consequently, this series of alloys is predominantly used as filler metals for both fusion welding and brazing. Silicon, independently in aluminum, is not heat treatable; however, a number of the aluminum-silicon alloys have been designed to incorporate additions of magnesium or copper, which provide the ability to respond favorably to solution heat-treatment. Typically, these heat-treatable filler alloys are used only when a weldment is to be subjected to postweld thermal treatments. Alloys in the 4XXX series have ultimate tensile strengths ranging from 172 MPa to 379 MPa (25 ksi to 55 ksi).

5XXX Series. Alloys in the 5XXX series consist of aluminum-magnesium (Al-Mg), with magnesium additions ranging from 0.2% to 6.2%; they have the highest strength of the alloys that are not heat treatable. This series of alloys is readily weldable and is used for a wide variety of structural applications, such as components of ships, vehicles, pressure vessels, bridges, and buildings. Base alloys of aluminum-magnesium are often welded with filler alloys, which are selected in consideration of the magnesium content of the base material, the application, and the intended service conditions of the welded component.

Alloys in the 5XXX series that contain more than 3.0% magnesium are not recommended for service at elevated temperatures (higher than 66°C [150°F]) because of the potential for sensitization and subsequent susceptibility to stress-corrosion cracking. Base alloys with less than approximately 2.5% magnesium are often welded successfully with filler metal from the 4XXX or 5XXX series. The base alloy 5052

content that can be welded with a filler metal made from the 4XXX series.

Materials that have magnesium contents higher than that of 5052 are generally welded only with 5XXX series filler alloys that closely match the magnesium in the base alloy material. These alloys are not heat treatable; they have a tensile strength in the range of 124 MPa to 352 MPa (18 ksi to 51 ksi).

6XXX Series. The 6XXX series, consisting of aluminum-magnesium-silicon (Al-Mg-Si) alloys (with magnesium and silicon additions of around 1.0%), is widely used throughout the welding fabrication industry. These alloys are used predominantly in the form of extrusions and are incorporated in many structural components. The addition of magnesium and silicon to aluminum produces a compound of magnesium-silicide that can be solution heat-treated for improved strength. Alloys in the 6XXX series are naturally sensitive to solidification cracking, so autogenous welds (made without filler metal) should not be used; filler metal is required. The addition of adequate amounts of filler metal during the arc welding process is essential to provide dilution of the base metal, thereby preventing the hot-cracking problem. The 6XXX alloys are welded with filler metals from the 4XXX and 5XXX series, with the selection depending on the application and service requirements. These alloys are heat treatable and have an ultimate tensile strength in the range of 124 MPa to 400 MPa (18 ksi to 58 ksi).

7XXX Series. The 7XXX series consists of the aluminum-zinc (Al-Zn) alloys, with zinc additions ranging from 0.8% to 12.0%. Alloys in this series are among the highest-strength aluminum alloys; they are often used in high-performance applications, such as aircraft and aerospace components and competitive sports equipment. Like the 2XXX alloy series, the 7XXX series incorporates some alloys that are considered unsuitable for arc welding and others that are often welded successfully with an arc welding process. The commonly welded base-metal alloys in this series, such as 7003 and 7005, are predominantly welded with filler alloys from the 5XXX series. These alloys are heat treatable and have an ultimate tensile strength range

Principle Effects of Alloying Elements

Alloying elements are added to pure aluminum to give the alloy unique characteristics, such as greater strength, better ductility, and improved fluidity. The effects of various alloys on the properties of aluminum are discussed in this section.

2XXX Series, Copper. The aluminum-copper (Al-Cu) alloys typically contain between 2% and 10% copper, with smaller additions of other elements, but the copper provides substantial increases in strength and facilitates precipitation hardening. The introduction of copper to aluminum may also reduce ductility and corrosion resistance. The susceptibility of aluminum-copper alloys to solidification cracking is increased; consequently, some of these alloys may be among the most challenging aluminum alloys to weld. The 2XXX alloy series includes some of the highest-strength, heat-treatable aluminum alloys. The most common applications for alloys in this series are in the defense and aerospace industry, such as for components of military vehicles and rocket fins.

3XXX Series, Manganese. The addition of manganese (Mn) to aluminum increases strength somewhat through solution strengthening and improves strain hardening (sometimes called *work hardening* or *cold working*) while not appreciably reducing ductility or corrosion resistance. These are moderate-strength, non-heat-treatable materials that retain strength at elevated temperatures and are not generally used for major structural applications. The most common applications for alloys in the 3XXX series are the fabrication of cooking utensils, radiators, air conditioning condensers, evaporators, heat exchangers, and associated piping systems.

4XXX Series, Silicon. The addition of silicon (Si) to aluminum reduces the melting temperature and improves fluidity. Silicon alone in aluminum produces an alloy that cannot be heat treated; however, in combination with magnesium, it produces a precipitation-hardening heat-treatable alloy. Consequently, both heat-treatable and nonheat-treatable alloys are included within the 4XXX series. Silicon additions to aluminum are commonly used for castings, but the most common applications for alloys in the 4XXX series are the manufacturing of welding filler metal electrodes produced for the fusion welding and brazing of aluminum.

5XXX Series, Magnesium. The addition of magnesium (Mg) to aluminum increases strength through solid-solution strengthening and improves the strain-hardening properties. These alloys are the highest strength, nonheat-treatable aluminum alloys available and are used extensively for structural applications. Alloys in the 5XXX series are produced primarily as sheet and plate. They are used only occasionally as extrusions because these alloys strain harden quickly and are difficult and expensive to extrude. Alloys in the 5XXX series are commonly used in the construction of truck and rail car bodies, buildings, armored vehicles,

ships and boats, chemical tankers, pressure vessels, and cryogenic tanks.

6XXX Series, Magnesium and Silicon. The addition of magnesium (Mg) and silicon (Si) to aluminum produces the compound magnesium-silicide (Mg_2Si). The formation of this compound makes it possible for the 6XXX series to respond to heat treatment. Alloys in the 6XXX series are easily and economically extruded and for these reasons are used in an extensive selection of extruded shapes. These alloys form an important complementary system with alloys in the 5XXX series. Aluminum plate in the 5XXX series and extruded forms of alloys in the 6XXX series are commonly joined. Typical applications for the 6XXX 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.

7XXX Series, Zinc. The addition of zinc (Zn) to aluminum (in combination with some other elements, primarily magnesium or copper, or both) produces heat-treatable aluminum alloys of high strength. The zinc substantially increases strength and permits precipitation hardening. Some of these alloys may be susceptible to stress-corrosion cracking, and for this reason they are not usually joined by fusion welding. Other alloys in this series are often fusion welded with excellent results. Common applications for alloys in the 7XXX series include aerospace components, armored vehicles, baseball bats, and bicycle frames.

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

Chromium. Chromium (Cr) 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 susceptibility to stress corrosion and improve toughness. It has a significant effect on electrical resistivity.

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

Titanium. Titanium (Ti) 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 the titanium is added as a master alloy containing boron

(largely combined as Ti-B₂). Titanium is a common addition to aluminum filler metal because it refines the weld structure and helps prevent weld cracking.

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

Lithium. The addition of lithium (Li) to aluminum substantially increases strength, and relative to Young's modulus, provides precipitation hardening and decreases density.

Lead and Bismuth. Lead (Pb) and bismuth (Bi) are added to aluminum to assist in chip formation and to improve machinability. These free-machining alloys are often not weldable because the lead and bismuth produce low-melting-point constituents that can induce poor mechanical properties or high sensitivity to cracking on solidification, or both.

Nonheat-Treatable Aluminum Alloys

The initial strength of the nonheat-treatable aluminum alloys depends primarily on the hardening effect of alloying elements, such as silicon, iron, manganese, and magnesium. These elements promote increases in strength, either as dispersed phases or by solid-solution strengthening. As shown in Table 1.2, the nonheat-treatable alloys are mainly within the 1XXX, 3XXX, 4XXX, and 5XXX series, depending on the major alloying elements.

Iron and silicon are the major impurities in commercially pure aluminum, but they add strength to alloys in the 1XXX series. Silicon is the major element in many welding and brazing filler alloys. Magnesium is the most effective solution-strengthening element in the nonheat-treatable alloys. Aluminum-magnesium alloys in the 5XXX series have relatively high strength in the annealed condition. The strength of all of the nonheat-treatable alloys can be improved by strain hardening.

To remove the effects of strain hardening and improve ductility, the nonheat-treatable alloys can be annealed by heating to a uniform temperature in the range of 340°C to 410°C (650°F to 775°F). The exact annealing schedule will depend on the alloy.

Although the rate of cooling from the annealing temperature is not critical, fixturing may be required to prevent distortion or warping. Basic temper designations applicable to the nonheat-treatable alloys are shown in Table 1.3.

When fusion welded, the nonheat-treatable alloys lose the effects of strain hardening in the narrow heat-affected zone (HAZ) adjacent to the weld; the strength in the HAZ will approach that of the annealed

Table 1.2
Composition and Typical Applications of Nonheat-Treatable Wrought Alloys

Aluminum Association Designation	Nominal Composition (% Alloying Element)				Typical Applications
	Cu	Mn	Mg	Cr	
1060	99.60% minimum aluminum				Chemical process equipment, tanks, piping.
1100	99.00% minimum aluminum				Architectural and decorative applications, furniture, deep drawn parts, spun hollow ware.
1350	99.50% minimum aluminum				Electrical conductor wire, bus and cable.
3003	0.12	1.2	—	—	General purpose applications where slightly higher strength than 1100 is required. Process and food handling equipment, chemical and petroleum drums and tanks.
3004	—	1.2	1.0	—	Sheet metal requiring higher strength than 3003.
5005	—	—	0.8	—	Electrical conductor and architectural applications.
5050	—	—	1.4	—	Similar to 3003 and 5005 but stronger. Has excellent finishing qualities.
5052, 5652	—	—	2.5	—	Sheet metal applications requiring higher strength than 5050. Formable and good corrosion resistance. Storage tanks, boats, appliances. Alloy 5652 has closer control of impurities for H ₂ O ₂ service.
5083	—	0.7	4.4	0.15	Marine components, tanks, unfired pressure vessels, cryogenics structures, railroad cars, drilling rigs.
5086	—	0.45	4.0	0.15	Marine components, tanks, tankers, truck frames.
5154, 5254	—	—	3.5	0.25	Unfired pressure vessels, tankers. Alloy 5254 has closer control of impurities for H ₂ O ₂ service.
5454	—	0.8	2.7	0.12	Structural applications and tanks for sustained high-temperature service.
5456	—	0.8	5.1	0.12	Structures, tanks, unfired pressure vessels, marine components.

Table 1.3
Basic Temper Designations Applicable to the Nonheat-Treatable Aluminum Alloys

Designation*	Description	Application
-0	Annealed, recrystallized	Applies to wrought products that are annealed to obtain the lowest strength temper, and to cast products that are annealed to improve ductility and dimensional stability.
-F	As fabricated	Applies to products of shaping processes in which no special control over thermal conditions or strain hardening is employed. For wrought products, there are no mechanical property limits.
-H1	Strain hardened only	Applies to products that are strain hardened to obtain the desired strength without supplementary thermal treatment. The number following this designation indicates the degree of strain hardening.
-H2	Strain hardened and then partially annealed	Applies to products that are strain hardened more than the desired final amount and then reduced in strength to the desired level by partially annealing. For alloys that age soften at room temperature, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H3 tempers. For other alloys, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H1 tempers and slightly higher elongation. The number following this designation indicates the degree of strain hardening remaining after the product has been partially annealed.
-H3	Strain hardened and then stabilized	Applies to products that are strain hardened and that have mechanical properties stabilized by a low-temperature thermal treatment, which results in slightly lowered tensile strength and improved ductility. This designation is applicable only to those alloys which, unless stabilized, gradually age soften at room temperature. The number following this designation indicates the degree of strain hardening before the stabilization treatment.

*The digit following the designation H1, H2, and H3 indicates the degree of strain hardening. Numeral 8 has been assigned to indicate tempers having an ultimate tensile strength equivalent to that achieved by a cold reduction of approximately 75% following a full anneal. Tempers between 0 (annealed) and 8 are designated by numerals 1 through 7. Material having an ultimate tensile strength about midway between that of the 0 temper and that of the 8 temper is designated by the numeral 4; about midway between the 0 and 4 tempers by the numeral 2; and about midway between the 4 and 8 tempers by the numeral 6. Numeral 9 designates tempers whose minimum tensile strength exceeds that of the 8 temper by 137.9 MPa (2.0 ksi) or more. For two-digit H tempers whose second digit is odd, the standard limits for ultimate tensile strength are exactly midway between those of the adjacent two-digit H tempers whose second digits are even. The third digit, when used, indicates a variation of a two-digit temper. It is used when the degree of control of temper or the mechanical properties are different from but close to those for the two-digit H temper designation to which it is added, or when some other characteristic is significantly affected.

condition. Table 1.4 contains information on process selection and the relative weldability of common non-heat-treatable wrought aluminum alloys in various tempers. The physical properties of the same alloys are shown in Table 1.5; the mechanical properties are shown in Table 1.6.

Heat-Treatable Aluminum Alloys

The initial strength of aluminum alloys in the heat-treatable group depends on the alloy composition, just as it does in the nonheat-treatable alloys. Because elements such as copper, magnesium, zinc, and silicon, either singularly or in various combinations, undergo a significant increase in solid solubility in aluminum with increasing temperature, it is possible to subject them to thermal treatments that will impart pronounced strengthening. Basic temper designations applicable to the heat-treatable alloys are shown in Table 1.7.

Properties of heat-treatable aluminum alloys are developed by solution heat-treating and quenching, followed by either natural or artificial aging. Cold working may add strength. The heat-treatable alloys can also be annealed to achieve maximum ductility. This treatment involves holding the alloy at an elevated tempera-

ture and controlling the cooling rate to achieve maximum softening.

The heat-treatable aluminum alloys are primarily in the 2XXX, 6XXX, and 7XXX series, although some alloys in the 4XXX series are heat treatable, depending on the combination of alloying elements. Some of the widely used heat-treatable alloys, nominal compositions, and general applications are listed in Table 1.8. The comparative weldability of heat-treatable wrought aluminum alloys is shown in Table 1.9.

The physical properties of heat-treatable wrought aluminum alloys are provided in Table 1.10. Typical mechanical properties of heat-treatable wrought aluminum alloys are listed in Table 1.11.

CAST ALUMINUM ALLOYS

Cast alloys are either nonheat-treatable or heat-treatable, based on the composition of the specific alloy, as previously described for the wrought alloys. The cast alloys also may be classified according to the casting method for which the alloy is suitable, i.e., sand casting, permanent-mold casting, or die casting. Table 1.12 shows the alloy designations for cast aluminum alloys.

Table 1.4
Compatibility Ratings for Welding, Brazing, and
Soldering of Nonheat-Treatable Wrought Aluminum Alloys^{1,2}

Aluminum Alloy	Oxyfuel Gas	Arc with Flux	Arc with Inert Gas	Resistance	Pressure	Brazing	Soldering with Flux
1060	A	A	A	B	A	A	A
1100	A	A	A	A	A	A	A
1350	A	A	A	B	A	A	A
3003	A	A	A	A	A	A	A
3004	B	A	A	A	B	B	B
5005	A	A	A	A	A	B	B
5050	A	A	A	A	A	B	B
5052, 5652	A	A	A	A	B	C	C
5083	C	C	A	A	C	X	X
5086	C	C	A	A	B	X	X
5154, 5254	B	B	A	A	B	X	X
5454	B	B	A	A	B	X	X
5456	C	C	A	A	C	X	X

1. Weldability ratings are based on the most weldable temper:

A. Readily weldable.

B. Weldable in most applications; may require special technique or preliminary trials to establish welding procedures, performance, or both.

C. Limited weldability.

X. This joining method is not recommended.

Table 1.5
Physical Properties of Non-Heat-Treatable Wrought Aluminum Alloys

Aluminum Alloy	Temper	Density		Approximate Melting Range		Thermal Conductivity ^a		Electrical Conductivity (% IACS) ^b
		kg/m ³	lb/in. ³	°C	°F	W/(m·K)	BTU/(h·ft·°F)	
1060	-O	2699	0.0975	646–657	1195–1215	234	135	62
	-H18					231	133	61
1100	-O	2713	0.098	643–657	1190–1215	222	128	59
	-H18					218	126	57
1350	-O	2699	0.0975	646–657	1195–1215	234	135	62
	-H19					234	135	62
3003	-O	2740	0.099	643–654	1190–1210	193	112	50
	-H14					158	92	41
	-H18					154	89	40
3004	-O	2713	0.098	629–654	1165–1210	163	94	42
	-H34					163	94	42
	-H38					163	94	42
5005	-O	2713	0.098	632–654	1170–1210	200	116	52
	-H34					200	116	52
	-H38					200	116	52
5050	-O	2685	0.097	624–652	1155–1205	193	112	50
	-H34					193	112	50
	-H38					193	112	50
5052, 5652	-O	2685	0.097	607–649	1125–1200	138	80	35
	-H34					138	80	35
	-H38					138	80	35
5083	-O	2657	0.096	574–638	1065–1180	117	68	29
5086	-O	2657	0.096	585–641	1085–1185	125	72	31
5154, 5254	-O	2657	0.096	593–643	1100–1190	125	72	32
	-H12					125	72	32
	-H34					125	72	32
	-H38					125	72	32
5454	-O	2685	0.097	602–646	1115–1195	134	77	34
	-H32					134	77	34
	-H34					134	77	34
5456	-O	2657	0.096	568–638	1055–1180	117	68	29

a. Thermal conductivity at 25°C (77°F).

b. Percentage of International Annealed Copper Standard (IACS) value for Volume Electrical Conductivity, which equals 100% at 20°C (68°F).

Table 1.6
Typical Mechanical Properties of Non-Heat-Treatable Wrought Aluminum Alloys

Aluminum Alloy	Temper	Ultimate Tensile Strength		Yield Strength (0.2% Offset)		Elongation % in 50.8 mm (2 in.)		Shear Strength		Fatigue Strength ^a		Brinnell Hardness ^b (500 kg load)
		MPa	ksi	MPa	ksi	12.7 mm (0.500 in.) Round	1.6 mm (0.062 in.) Sheet	MPa	ksi	MPa	ksi	
1060	-O	69	10	28	4	—	43	48	7	21	3	19
	-H18	131	19	124	18	—	6	76	11	45	7	35
1100	-O	90	13	34	5	45	35	62	9	34	5	23
	-H18	166	24	152	22	15	5	90	13	62	9	44
1350	-O	83	12	28	4	23	—	55	8	—	—	—
	-H19	186	27	166	24	1.5	—	103	15	48	7	—
3003	-O	110	16	41	6	40	30	76	11	48	7	28
	-H14	152	22	145	21	16	8	96	14	62	9	40
	-H18	200	29	186	27	10	4	110	16	69	10	55
3004	-O	179	26	69	10	25	20	110	16	96	14	46
	-H34	241	35	200	29	12	9	124	18	103	15	63
	-H38	283	41	248	36	6	5	145	21	110	16	77
5005	-O	124	18	41	6	—	25	76	11	—	—	28
	-H34	159	23	138	20	—	8	96	14	—	—	41
	-H38	200	29	186	27	—	5	110	16	—	—	51
5050	-O	145	21	55	8	—	24	103	15	83	12	36
	-H34	193	28	166	24	—	8	124	18	90	13	53
	-H38	221	32	200	29	—	6	138	20	96	14	63
5052, 5652	-O	193	28	90	13	30	25	124	18	110	16	47
	-H34	262	38	214	31	14	10	145	21	124	18	68
	-H38	290	42	255	37	8	7	166	24	138	20	77
5083	-O	290	42	145	21	22	—	172	25	—	—	—
	-H116	317	46	228	33	16	—	—	—	159	23	—
	-H321	317	46	228	33	16	—	—	—	159	23	—
5086	-O	262	38	117	17	—	22	159	23	—	—	—
	-H116	290	42	207	30	—	12	—	—	—	—	—
	-H34	324	47	255	37	—	10	186	27	—	—	—
5154, 5254	-O	241	35	117	17	—	27	152	22	117	17	58
	-H112	241	35	117	17	—	25	—	—	117	17	63
	-H34	290	42	228	33	—	13	166	24	131	19	73
	-H38	331	48	269	39	—	10	193	28	145	21	80
5454	-O	248	36	117	17	—	22	159	23	—	—	62
	-H32	276	40	207	30	—	10	166	24	—	—	73
	-H34	303	44	241	35	—	10	179	26	—	—	81
5456	-O	310	45	159	23	24	—	—	—	—	—	—
	-H112	310	45	166	24	22	—	—	—	—	—	—
	-H116	352	51	255	37	16	—	207	30	—	—	90

a. Fatigue strength for round specimens and 500 million cycles.

b. 10 mm (0.40 in.) ball used.

Table 1.7
Basic Temper Designations Applicable to the Heat-Treatable Aluminum Alloys

Designation*	Description	Application
-0	Annealed	Applies to wrought products that are annealed to obtain the lowest strength temper, and to cast products that are annealed to improve ductility and dimensional stability. The 0 may be followed by a digit other than zero.
-F	As fabricated	Applies to products of shaping processes that employ no special control over thermal conditions or strain hardening. For wrought products, there are no mechanical property limits.
-W	Solution heat treated	An unstable temper applicable only to alloys that spontaneously age at room temperature after solution heat treatment. This designation is specific only when the period of natural aging is indicated, for example: W 0.5 h.
-T1		Cooled from an elevated-temperature shaping process and naturally aged to a substantially stable condition. Applies to products that are not cold worked after cooling from an elevated-temperature shaping process, or when the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.
-T2		Cooled from an elevated-temperature shaping process, cold worked, and naturally aged to a substantially stable condition. Applies to products that are cold worked to improve strength after cooling from an elevated-temperature shaping process, or when the effect of cold work in flattening or straightening is recognized in mechanical property limits.
-T3		Solution heat treated, cold worked, and naturally aged to a substantially stable condition. Applies to products that are cold worked to improve strength after solution heat treatment, or when the effect of cold work in flattening or straightening is recognized in mechanical property limits.
-T4		Solution heat treated and naturally aged to a substantially stable condition. Applies to products that are not cold worked after solution heat treatment, or when the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.
-T5		Cooled from an elevated-temperature shaping process and then artificially aged. Applies to products that are not cold worked after cooling from an elevated-temperature shaping process, or when the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.
-T6		Solution heat treated and stabilized. Applies to products that are not cold worked after solution heat treatment, or when the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.
-T7		Solution heat treated and stabilized. Applies to products that are stabilized after solution heat treatment to carry them beyond the point of maximum strength to provide control of some special characteristic.
-T8		Solution heat treated, cold worked, and then artificially aged. Applies to products that are cold worked to improve strength, or when the effect of cold work in flattening or straightening is recognized in mechanical property limits.
-T9		Solution heat treated, artificially aged, and then cold worked. Applies to products that are cold worked to improve strength.
-T10		Cooled from an elevated-temperature shaping process, cold worked, and then artificially aged. Applies to products that are cold worked to improve strength, or when the effect of cold work in flattening or straightening is recognized in mechanical property limits.

*Additional digits, the first of which shall not be zero, may be added to designation T1 through T10 to indicate a variation in treatment which significantly alters the characteristics of the product.

Table 1.8
Composition and Typical Applications of Heat-Treatable Wrought Aluminum Alloys

Base Alloy	Nominal Composition (% Alloying Element)							Typical Applications
	Cu	Si	Mn	Mg	Zn	Ni	Cr	
2014	4.4	0.8	0.8	0.50	—	—	—	Structures, structural and hydraulic fittings, hardware, and heavy-duty forgings for aircraft or automotive uses.
2017	4.0	0.50	0.7	0.6	—	—	—	Same as 2014; screw machine parts.
2024	4.4	—	0.6	1.5	—	—	—	Structural, aircraft sheet construction, truck wheels; often clad for strength with good corrosion resistance
2036	2.6	—	0.25	0.45	—	—	—	Automotive body sheet.
2090 ^a	2.7	—	—	—	—	—	—	Structural; high strength and damage tolerant aerospace applications.
2218	4.0	—	—	1.5	—	2.0	—	Forging alloy; engine cylinder heads, pistons, parts requiring good strength and hardness at elevated temperature.
2219 ^b	6.3	—	0.30	—	—	—	—	Structural; high-temperature strength; aerospace tanks; good weldability.
2519 ^c	5.8	—	0.30	0.17	0.06	—	—	Structural; high-strength armor.
2618 ^d	2.3	0.18	—	1.6	—	1.0	—	Same as 2218.
6005	—	0.8	—	0.50	—	—	—	Structural and architectural.
6009	0.40	0.8	0.50	0.6	0.25	—	0.10	Automotive body sheet.
6010	0.40	1.0	0.50	0.8	0.25	—	0.10	Automotive body sheet.
6013	0.9	0.25	0.35	0.95	—	—	—	General structural applications, improved strength over 6061.
6061	0.25	0.6	—	1.0	—	—	0.20	Structural, architectural, automotive, railway, and marine applications; pipe and pipe fittings; good formability, weldability, corrosion resistance, strength.
6063	—	0.40	—	0.7	—	—	—	Pipe, railings, hardware, architectural applications.
6070	—	1.4	—	0.8	—	—	—	Structural applications; piping.
6101	0.50	—	—	0.6	—	—	—	Electrical conductors.
6262 ^e	0.28	—	—	1.0	—	—	0.09	Screw machine products, fittings.
6351	—	1.0	0.6	0.6	—	—	—	Same as 6061.
6951	—	0.35	—	0.6	—	—	—	Brazing sheet core alloy.
7004 ^f	—	—	—	1.5	4.2	—	—	Truck trailer, railcar extruded shapes.
7005 ^g	—	—	0.45	1.4	4.5	—	0.13	Truck trailer, railcar extruded shapes.
7039	—	—	0.30	2.8	4.0	—	0.20	Armor plate; military bridges.
7075	1.6	—	—	2.5	5.6	—	0.23	High-strength aircraft and other applications; cladding gives good corrosion resistance.
7079	0.6	—	—	3.3	4.3	—	0.20	Strongest aluminum alloy where section thickness exceeds 76.2 mm (3 in.), large and massive parts for aircraft and allied construction.
7178	2.0	—	—	2.8	6.8	—	0.23	Aircraft construction; slightly higher strength than 7075.

a. Also 2.2 Li and 0.12 Zr.

b. Also 0.06 Ti, 0.10 V, and 0.18 Zr.

c. Also 0.06 Ti 0.17 Zr, and 0.10 Va.

d. Also 1.1 Fe and 0.07 Ti.

e. Also 0.6 Pb and 0.6 Bi.

f. Also 0.15 Zr.

g. Also 0.15 Zr and 0.035 Ti.

Table 1.9
Compatibility Ratings for Welding, Brazing, and
Soldering of Heat-Treatable Wrought Aluminum Alloys^{1,2}

Aluminum Alloy	Oxyfuel Gas	Arc with Flux	Arc with Inert Gas	Resistance	Pressure	Brazing	Soldering with Flux
2014	X	C	C	B	C	X	C
2017	X	C	C	B	C	X	C
2024	X	C	C	B	C	X	C
2036	X	C	B	B	C	X	C
2090	X	X	B	B	C	X	C
2218	X	C	C	B	C	X	C
2219	X	C	A	B	C	X	C
2519	X	C	B	B	C	X	C
2618	X	C	C	B	C	X	C
6005	A	A	A	A	B	A	B
6009	C	C	B	B	B	X	C
6010	C	C	B	B	B	X	C
6013	C	C	B	A	B	X	C
6061	A	A	A	A	B	A	B
6063	A	A	A	A	B	A	B
6070	C	C	B	B	B	X	C
6101	A	A	A	A	A	A	A
6262	C	C	B	A	B	B	B
6351	A	A	A	A	B	A	B
6951	A	A	A	A	A	A	A
7004	X	X	A	A	B	B	B
7005	X	X	A	A	B	B	B
7039	X	X	A	A	B	C	B
7075	X	X	C	B	C	X	C
7079	X	X	C	B	C	X	C
7178	X	X	C	B	C	X	C

1. Weldability ratings are based on the most weldable temper:

A. Readily weldable.

B. Weldable in most applications; may require special technique or preliminary trials to establish welding procedures, performance, or both.

C. Limited weldability.

X. This joining method is not recommended.

Detailed information for cast aluminum alloys is provided in tabular form as follows:

Table 1.13 shows the composition, casting method, and typical applications of nonheat-treatable cast aluminum alloys.

Table 1.14 shows the composition, casting method, and typical applications for heat-treatable cast aluminum alloys.

Table 1.15 shows the comparative weldability of non-heat-treatable cast aluminum alloys for various joining processes.

Table 1.16 shows the physical properties of nonheat-treatable cast aluminum alloys;

Table 1.17 lists typical mechanical properties of non-heat-treatable cast aluminum alloys.

Table 1.18 shows heat-treatable cast aluminum alloys and joining process selection.

Table 1.10
Physical Properties of Heat-Treatable Wrought Aluminum Alloys

Aluminum Alloy	Temper	Density		Approximate Melting Range		Thermal Conductivity ^a		Electrical Conductivity (% IACS) ^b
		kg/m ³	lb/in. ³	°C	°F	W/(m·K)	BTU/(ft·h·°F)	
2014	-O	2796	0.101	507–638	945–1180	77.5	193	50
	-T4					112	134	34
	-T6					89	154	40
2017	-O	2796	0.101	513–641	955–1185	77.5	193	50
	-T4					112	134	34
2024	-O	2796	0.101	502–638	935–1180	70	193	50
	-T3					112	121	30
	-T4					70	121	30
	-T361					70	121	30
2036	-T4	2768	0.100	554–649	1030–1200	159	92	41
2090	-T8	2574	0.093	561–589	1042–1091	88	51	17
2218	-T72	2796	0.101	507–638	945–1180	154	89	40
2219	-O	2851	0.103	543–643	1010–1190	99	172	44
	-T31					65	112	28
	-T62					70	121	30
	-T81					70	121	30
	-T87					70	121	30
2519	-T87	2823	0.102	554–643	1030–1190	133	76.7	33
2618	-T61	2768	0.100	549–638	1020–1180	150	86.7	39
6005	-T1	2685	0.097	607–654	1125–1210	109	180	47
	-T5					104	189	49
6009	-T4	2713	0.098	560–649	1040–1200	167	96.7	44
6010	-T4	2713	0.098	560–649	1040–1200	150	86.7	39
6013	-T4	2713	0.098	579–649	1075–1200	86.7	150	38
	-T6					94	163	42
6061	-O	2713	0.098	582–652	1080–1205	89	180	47
	-T4					104	154	40
	-T6					96.7	167	43
6063	-O	2685	0.097	616–655	1140–1210	112	218	58
	-T1					126	193	50
	-T5					121	209	55
	-T6					116	200	53
6070	-T6	2713	0.098	566–649	1050–1200	172	99	44
6101	-H111	2685	0.097	621–654	1150–1210	—	—	—
	-T6					126	218	57
6262	-T9	2713	0.098	582–652	1080–1205	172	99	44
6351	-T5	2713	0.098	596–652	1105–1205	102	176	46
	-T6					102	176	46
6951	-O	2713	0.098	616–654	1040–1210	114	198	56
	-F6					114	198	52
7004	-T5	2768	0.100	—	—	—	—	—
	-T6					198	114	52
7005	-T53	2768	0.100	607–646	1125–1195	—	—	—
7039	-T64	2740	0.099	577–638	1070–1180	154	89	34
7075	-O	2796	0.101	477–635	890–1175	75	99	87
	-T6					—	—	—
	-T73					—	—	—
7079	-O	2740	0.099	482–638	900–1180	125	72.5	32
	-T6					—	—	—
7178	-O	2823	0.102	477–629	890–1165	—	—	31
	-T6					—	—	31

a. Thermal conductivity at 25°C (77°F).

b. Percentage of International Annealed Copper Standard (IACS) value for Volume Electrical Conductivity, which equals 100% at 20°C (68°F).

Table 1.11
Typical Mechanical Properties of Heat-Treatable Wrought Aluminum Alloys

Aluminum Alloy	Temper	Ultimate Tensile Strength		Yield Strength (0.2% Offset)		% Elongation in 50.8 mm (2 in.)		Shear Strength		Fatigue Strength ^a		Brinell Hardness ^b (500 kg load)
		MPa	ksi	MPa	ksi	1.6 mm (0.062 in.) Sheet	12.7 mm (0.500 in.) Round	MPa	ksi	MPa	ksi	
2014	-0	186	27	96	14	—	18	124	18	89.6	13	45
	-T4	428	62	290	42	—	20	262	38	138	20	105
	-T6	483	70	414	60	—	13	290	42	124	18	135
2017	-0	180	26	69	10	—	22	124	18	89.6	13	45
	-T4	428	62	276	40	—	22	262	38	124	18	105
2024	-0	186	27	76	11	20	22	124	18	89.6	13	45
	-T3	483	70	345	50	18	—	283	41	138	20	120
	-T4	469	68	324	47	20	19	283	41	138	20	120
	-T361	496	72	393	57	13	—	290	42	124	18	120
2036	-T4	338	49	193	28	24	—	—	—	124	18	—
2090	-T8	538	78	496	72	7.5	6	—	—	—	—	—
2218	-T72	331	48	255	37	—	11	207	30	—	—	95
2219	-0	172	25	76	11	18	—	—	—	—	—	—
	-T31	358	52	248	36	17	—	—	—	—	—	—
	-T62	414	60	290	42	10	—	—	—	103	15	—
	-T81	455	66	352	51	10	—	—	—	103	15	—
	-T87	476	69	393	57	10	—	—	—	103	15	—
2519	-T87	496	72	441	64	10	—	303	44	189	28	132
2618	-T61	441	64	372	54	—	10	262	38	124	18	115
6005	-T1	193	28	124	18	—	18	—	—	—	—	—
	-T5	303	44	269	39	—	12	179	26	—	—	—
6009	-T4	228	33	124	18	25	—	152	22	117	17	—
6010	-T4	290	42	172	25	24	—	193	28	124	18	—
6013	-T4	296	43	159	23	22	—	—	—	—	—	—
	-T6	407	59	372	54	9	—	234	34	—	—	—
6061	-0	124	18	55	8	25	30	83	12	62.1	9	30
	-T4	241	35	145	21	22	25	166	24	96.5	14	65
	-T6	310	45	276	40	12	17	207	30	96.5	14	95
6063	-0	90	13	48	7	—	—	69	10	55.2	8	25
	-T1	152	22	90	13	20	—	96	14	62.1	9	42
	-T5	186	27	145	21	12	—	117	17	68.9	10	60
	-T6		35		31	12	—	—	22	68.9	10	73
6070	-T6	379	55	352	51	10	—	234	34	96.5	14	—
6101	-H111	96	14	76	11	—	—	—	—	—	—	—
	-T6	221	32	193	28	15	—	138	20	—	—	71

(Continued)

Table 1.11 (Continued)
Typical Mechanical Properties of Heat-Treatable Wrought Aluminum Alloys

Aluminum Alloy	Temper	Ultimate Tensile Strength		Yield Strength (0.2% Offset)		% Elongation in 50.8 mm (2 in.)		Shear Strength		Fatigue Strength ^a		Brinnell Hardness ^b (500 kg load)
		MPa	ksi	MPa	ksi	1.6 mm (0.062 in.) Sheet	12.7 mm (0.500 in.) Round	MPa	ksi	MPa	ksi	
6262	-T9	400	58	379	55	—	10	241	35	89.6	13	120
6351	-T5	310	45	283	41	—	12	186	27	—	—	—
	-T6	331	48	310	45	—	11	186	27	—	—	—
6951	-O	110	16	41.4	6	30	—	76	11	—	—	28
	-T6	269	39	228	33	13	—	179	26	—	—	82
7004	-T5	393	57	331	48	—	—	234	34	—	—	—
7005	-T53	365	53	324	47	—	12	207	30	—	—	—
7039	-T64	448	65	379	55	13	10	262	38	—	—	120
7075	-O	228	33	103	15	17	16	152	22	—	—	60
	-T6	572	83	503	73	11	11	331	48	159	23	150
	-T73	503	73	434	63	—	13	303	44	152	22	—
7079	-O	228	33	103	15	17	16	—	—	—	—	—
	-T6	538	78	469	68	—	14	310	45	159	23	145
7178	-O	228	33	103	15	15	16	152	22	—	—	60
	-T6	607	88	538	78	10	11	358	52	152	22	160

a. Fatigue strength for round specimens and 500 million cycles.

b. 10 mm (0.40 in.) ball used.

Table 1.12
Designations for Cast Aluminum Alloy Groups

Aluminum, 99.00% and greater	1XX.X
Major Alloying Element	
Copper	2XX.X
Silicon, with added Copper, Magnesium, or both	3XX.X
Silicon	4XX.X
Magnesium	5XX.X
Zinc	7XX.X
Tin	8XX.X
Other Element	9XX.X
Unused series	6XX.X

For the 1XX.X series, The first digit indicates the alloy group. The second two digits identify the minimum aluminum percentage. For all castings, the last digit, which is separated from the others by a decimal point, indicates the product form. Castings are indicated by XXX.0. Ingot types are indicated by XXX.1 and XXX.2. A modification of the original alloy or impurity limits is indicated by a serial letter before the numerical designation. The serial letters are assigned in alphabetical sequence starting with "A." "X" is reserved for experimental alloys.

Table 1.19 shows the comparative weldability of heat-treatable cast aluminum alloys for various joining processes.

Table 1.20 lists the physical properties of heat-treatable cast aluminum alloys.

FILLER METALS AND FILLER METAL SELECTION

A fundamental difference between the arc welding of steel and the arc welding of aluminum is the evaluation method used during the filler metal selection process. Many aluminum base metals can be welded successfully with any number of different filler metals. As an example, the base metal 6061-T6 is commonly welded with at least four very different filler metals and can be welded successfully with even more.

(Continued on page 25)

Table 1.13
Composition, Casting Type, and Typical Applications of Nonheat-Treatable Cast Aluminum Alloys

Base Alloy	Nominal Composition (% Alloying Element)				Suitable Types of Castings			Typical Applications
	Cu	Si	Mg	Zn	Sand	Permanent Mold	Die	
208.0	4.0	3.0	—	—	X	X	—	General-purpose alloy; manifolds, valve housings, and applications requiring pressure tightness.
213.0	7.0	2.0	—	—	X	X	—	—
238.0	10.0	4.0	0.25	—	—	X	—	High as-cast hardness. Sole plates for electric hand irons.
360.0	—	9.5	0.5	—	—	—	X	General-purpose die castings, cover plates, and instrument cases. Excellent casting characteristics.
380.0	3.5	8.5	—	—	—	—	X	General purpose. Good casting characteristics and mechanical properties.
413.0	—	12.0	—	—	—	—	X	General-purpose die casting alloy for large, intricate parts with thin sections, as typewriter frames, instrument cases, etc. Excellent casting characteristics; very good corrosion resistance.
443.0	0.6 max.	5.25	—	—	X	X	—	General-purpose alloy, cooking utensils, pipe fittings, architectural and marine applications. Excellent castability and pressure tightness.
A443.0	0.3 max.	5.25	—	—	X	X	—	
B443.0	0.15 max.	5.25	—	—	X	X	—	
A444.0	—	7.0	—	—	—	X	—	Structural applications (AASHTO)
511.0	—	0.5	4.0	—	X	—	—	Anodically treated architectural parts and ornamental hardware. Takes uniform anodic finish.
512.0	—	1.8	4.0	—	X	—	—	Cooking utensils and pipe fittings.
513.0	—	—	4.0	1.8	—	X	—	Cooking utensils and ornamental hardware; takes uniform anodic finish.
514.0	—	—	4.0	—	X	—	—	Chemical process fittings, special food-handling equipment, and marine hardware. Excellent corrosion resistance.
518.0	—	—	8.0	—	—	—	X	Marine fittings and hardware. High strength, ductility, and resistance to corrosion.
535.0 ^a	—	—	6.9	—	X	—	—	High welded strength and ductility.
710.0	0.5	—	0.7	6.5	X	—	—	General-purpose sand castings for subsequent brazing. Good machinability.
711.0 ^b	0.5	—	0.35	6.5	—	X	—	Torque converter blades and brazed parts. Good machinability.
712.0 ^c	—	—	0.6	5.8	X	—	—	Same as 710.0 above, good corrosion resistance.

a. Also 0.18 Mn, 18 Ti, and 0.005 Be.

b. Also 1.0 Fe.

c. Also 0.5 Cr.

Table 1.14
Composition, Casting Type, and Typical Applications of Heat-Treatable Cast Aluminum Alloys

Base Alloy	Nominal Composition (% Alloying Element)					Suitable Types of Castings (X)	Typical Applications
	Cu	Si	Mg	Ni	Sand		
A201.0 ^a	4.5	—	0.25	—	X	—	—
222.0	10.0	—	0.25	—	X	X	Bushings, bearing caps, meter parts, and air-cooled cylinder heads. Retains strength at elevated temperatures.
240.0 ^b	8.0	—	6.0	0.50	X	—	—
242.0	4.0	—	1.5	2.0	X	X	Heavy-duty pistons and air-cooled cylinder heads. Good strength at elevated temperatures.
A242.0 ^c	4.1	—	1.5	2.0	X	—	Heavy-duty pistons and air-cooled cylinder heads. Good strength at elevated temperatures.
295.0	4.5	1.1	—	—	X	—	Machinery and aircraft structural members, crankcases, and wheels.
319.0	3.5	6.0	—	—	X	X	General purpose, engine parts, automobile cylinder heads, piano plates.
332.0 ^d	3.0	9.5	1.0	—	—	X	Automotive pistons. Good properties at elevated operating temperatures.
333.0	3.5	9.0	0.30	—	—	X	Engine parts, gas meter housing, regulator parts, and general purpose.
336.0	1.0	12.0	1.0	2.5	—	X	Heavy-duty diesel pistons. Good strength at elevated temperatures.
354.0	1.8	9.0	0.50	—	—	X	Aircraft, missile, and other applications requiring premium-strength castings.
355.0	1.3	5.0	0.50	—	X	X	General-purpose castings, crankcases, accessory housings, and aircraft fittings.
C355.0	1.3	5.0	0.50	—	X	X	Aircraft, missile, and other structural applications requiring high strength.
356.0	—	7.0	0.35	—	X	X	General-purpose castings, transmission cases, truck-axle housings and wheels, cylinder blocks, railway tank-car fittings, marine hardware, bridge railing parts, architectural uses.
A356.0	—	7.0	0.35	—	X	X	Aircraft, missile, and other structural applications and aircraft fittings.
A357.0 ^e	—	7.0	0.55	—	X	X	Aircraft, missile, and other structural applications requiring high strength.
359.0	—	9.0	0.6	—	X	X	Aircraft, missile, and other structural applications requiring high strength.
520.0	—	—	10.0	—	X	—	Sand castings requiring strength and shock resistance, such as aircraft structural members. Excellent corrosion resistance. Not recommended for use over 121°C (250°F).

a. Also 0.7 Ag, 0.30 Mn, and 0.25 Ti.

b. Also 0.5 Mn.

c. Also 0.20 Cr.

d. Also 1.0 Zn.

e. Also 0.05 Be.

Table 1.15
Compatibility Ratings for Welding, Brazing, and
Soldering of Nonheat-Treatable Cast Aluminum Alloys^{1,2}

Aluminum Alloy	Oxyfuel Gas	Arc with Flux	Arc with Inert Gas	Resistance	Pressure	Brazing	Soldering with Flux
Sand Castings							
208.0	C	C	B	B	X	X	C
213.0	C	C	B	B	X	X	C
430.0	A	A	A	A	X	C	C
443.0	A	A	A	A	X	C	C
A443.0	A	A	A	A	X	C	C
B443.0	A	A	A	A	X	C	C
511.0	X	X	A	A	X	C	C
512.0	X	X	B	B	X	C	C
514.0	X	X	A	A	X	C	C
535.0	X	X	A	A	X	X	C
710.0	C	C	B	B	X	A	B
712.0	C	C	A	B	X	A	B
Permanent Mold Castings							
208.0	C	C	B	B	X	X	C
213.0	C	C	B	B	X	X	C
238.0	C	C	B	A	X	X	C
443.0	A	A	A	A	X	C	C
B443.0	A	A	A	A	X	C	C
A444.0	B	B	A	A	X	C	C
513.0	X	X	A	A	X	C	C
711.0	C	C	A	A	X	A	C
Die Castings							
360.0	C	X	C	B	X	X	X
380.0	C	X	C	B	X	X	X
413.0	C	C	C	B	X	X	X
518.0	X	X	C	B	X	X	X

1. Weldability ratings are based on the most weldable temper:

A. Readily weldable.

B. Weldable in most applications; may require special technique or preliminary trials to establish welding procedures, performance, or both.

C. Limited weldability.

X. This joining method is not recommended.

Table 1.16
Physical Properties of Nonheat-Treatable Aluminum Alloys

Aluminum Alloy ^c	Density		Approximate Melting Range		Thermal Conductivity ^{a, c}		Electrical Conductivity (% IACS) ^{b, c}
	kg/m ³	lb/in. ³	°C	°F	W/(m·K)	BTU/(ft·h·°F)	
Sand Castings							
208.0	2796	0.101	521–632	970–1170	121	70	31
213.0	2934	0.106	518–627	965–1160	121	70	30
430.0	2685	0.097	577–632	1070–1170	146	84	37
A443.0	2685	0.097	577–632	1070–1170	146	84	37
B443.0	2685	0.097	577–632	1070–1170	146	84	37
511.0	2658	0.096	588–638	1090–1180	141	82	36
512.0	2658	0.096	588–632	1090–1170	146	84	38
514.0	2658	0.096	599–638	1110–1180	137	79	35
535.0	2519	0.091	549–632	1020–1170	100	58	23
710.0	2823	0.102	599–649	1110–1200	137	79	35
712.0	2823	0.102	599–638	1110–1180	158	92	40
Permanent Mold Castings							
208.0	2796	0.101	521–632	970–1170	121	70	31
213.0	2934	0.106	518–627	965–1160	121	70	30
238.0	2962	0.107	510–599	950–1110	104	60	25
443.0	2685	0.097	577–632	1070–1170	146	84	37
B443.0	2685	0.097	577–632	1070–1170	146	84	37
A444.0	2685	0.097	577–632	1070–1170	158	92	41
513.0	2685	0.097	583–638	1080–1180	133	77	34
711.0	2851	0.103	599–644	1110–1190	158	92	40
Die Castings							
360.0	2685	0.097	515–588	960–1090	146	84	37
380.0	2740	0.099	521–588	970–1090	108	62	27
413.0	2658	0.096	577–588	1070–1090	154	89	39
518.0	2519	0.091	538–621	1000–1150	100	58	24

a. Thermal conductivity at 25°C (77°F).

b. Percentage of International Annealed Copper Standard (IACS) value for Volume Electrical Conductivity, which equals 100% at 20°C (68°F).

c. All casting alloys are in the “F” temper.

Table 1.17
Typical Mechanical Properties of Nonheat-Treatable Cast Aluminum Alloys

Aluminum Alloy	Temper	Ultimate Tensile Strength		Yield Strength (0.2% Offset)		Elongation % in 50.8 mm (2 in.)	Shear Strength		Fatigue Strength ^a		Brinnell Hardness (500 kg load) ^b
		MPa	ksi	MPa	ksi	12.7 mm (0.500 in.) Diameter Round	MPa	ksi	MPa	ksi	
Sand Castings											
208.0	F	145	21	96	14	2.5	117	17	76	11	55
213.0	F	166	24	103	15	1.5	138	20	62	9	70
430.0	F	131	19	55	8	8.0	96	14	55	8	40
A443.0	F	131	19	55	8	8.0	96	14	55	8	40
B443.0	F	131	19	55	8	8.0	96	14	55	8	40
511.0	F	145	21	83	12	3.0	117	17	55	8	50
512.0	F	138	20	90	13	2.0	117	17	59	8.5 ^c	50
514.0	F	172	25	83	12	9.0	138	20	48	7	50
535.0	F	248	36	124	18	9.0	—	—	—	—	65
710.0 ^c	F	241	35	172	25	5.0	179	26	55	8	75
712.0 ^c	F	241	35	172	25	5.0	179	26	62	9	75
Permanent Mold Castings											
208.0	F	193	28	110	16	2.0	152	22	90	13	70
213.0	F	207	30	166	24	1.5	166	24	66	9.5	85
238.0	F	207	30	166	24	1.5	166	24	—	—	100
443.0	F	159	23	62	9	10.0	110	16	55	8	45
B443.0	F	159	23	62	9	10.0	110	16	55	8	45
A444.0	F	241	35	124	18	8.0	—	—	76	11	70
513.0	F	186	27	110	16	7.0	152	22	69	10	60
711.0 ^c	F	241	35	124	18	8.0	—	—	76	11	70
Die Castings											
360.0	F	324	47	172	25	3.0	307	30	131	19	75
380.0	F	331	48	166	24	3.0	214	31	145	21	80
413.0	F	296	43	145	21	2.5	193	28	131	19	80
518.0	F	310	45	186	27	8.0	200	29	138	20	80

a. Fatigue strength for round specimens and 500 million cycles.

b. 10 mm (0.40 in.) ball used.

c. Tests made approximately 30 days after casting.

Table 1.18
Compatibility Ratings for Welding, Brazing, and Soldering of Heat-Treatable Cast Aluminum Alloys^{1,2}

Aluminum Alloy	Oxyfuel Gas	Arc with Flux	Arc with Inert Gas	Resistance	Pressure	Brazing	Soldering with Flux
Sand Castings							
A201.0	C	C	B	B	X	X	C
222.0	X	C	B	B	X	X	X
240.0	X	X	C	B	X	X	X
242.0	X	X	C	B	X	X	X
A242.0	X	X	C	B	X	X	X
295.0	C	C	B	B	X	X	X
319.0	C	C	B	B	X	X	X
355.0	B	B	B	B	X	X	X
C355.0	B	B	B	B	X	X	X
356.0	A	A	A	A	X	C	C
A356.0	A	A	A	A	X	C	C
A357.0	B	B	A	A	X	C	C
359.0	B	B	A	A	X	C	C
520.0	X	X	B	C	X	X	X
Permanent Mold Castings							
222.0	X	C	B	B	X	X	X
242.0	X	X	C	B	X	X	X
319.0	C	C	B	B	X	X	X
332.0	X	X	B	B	X	X	X
333.0	X	X	B	B	X	X	X
336.0	C	C	B	B	X	X	X
354.0	C	C	B	B	X	X	X
355.0	B	B	B	B	X	X	X
C355.0	B	B	B	B	X	X	X
356.0	A	A	A	A	X	C	C
A356.0	A	A	A	A	X	C	C
A357.0	B	B	A	A	X	C	C
359.0	B	B	A	A	X	C	C

1. Weldability ratings are based on the most weldable temper:

A. Readily weldable.

B. Weldable in most applications; may require special technique or preliminary trials to establish welding procedures and performance.

C. Limited weldability.

X. This joining method is not recommended.

Table 1.19
Typical Mechanical Properties of Heat-Treatable Cast Aluminum Alloys

Aluminum Alloy	Temper	Ultimate Tensile Strength		Yield Strength (0.2% Offset)		Elongation % in 50.8 mm (2 in.)	Shear Strength		Fatigue Strength ^a		Brinnell Hardness (500 kg load) ^b
		MPa	ksi	MPa	ksi	12.7 mm (0.500 in.) Diameter Round	MPa	ksi	MPa	ksi	
Sand Castings											
A201.0	-T6	448	65	379	55	8.0	290	42	—	—	130
222.0	-T61	283	41	276	40	<0.5	221	32	59	8.5	115
240.0	-F	234	34	193	28	1.0	—	—	—	—	90
242.0	-T77	207	30	159	23	2.0	166	24	72	10.5	75
	-7571	221	32	207	30	0.5	179	26	76	11	85
A242.0	-T75	214	31	—	—	2.0	—	—	—	—	—
295.0	-T4	221	32	110	16	8.5	179	26	48	7	60
	-T62	283	41	221	32	2.0	228	33	55	8	90
319.0	-T5	207	30	179	26	1.5	166	24	76	11	80
	-T6	248	36	166	24	2.0	200	29	76	11	80
355.0	-T51	193	28	159	23	1.5	152	22	55	8	65
	-T6	241	35	172	25	3.0	193	28	62	9	80
	-T7	262	38	179	26	0.5	193	28	69	10	85
C355.0	-T6	269	39	200	29	5.0	—	—	—	—	85
356.0	-T51	172	25	138	20	2.0	138	20	55	8	60
	-T6	228	33	166	24	3.5	179	26	59	8.5	70
	-T7	234	34	207	30	2.0	166	24	62	9	75
A356.0	-T6	276	40	207	30	6.0	—	—	—	—	75
A357.0	-T6	317	46	248	36	3.0	276	40	83	12	85
359.0	-T6	—	—	—	—	—	—	—	—	—	—
520.0	-T4	331	48	179	26	16.0	234	34	55	8	75
Permanent Mold Castings											
222.0	-T65	331	48	248	36	<0.5	179	26	62	9	140
242.0	-T571	276	40	234	34	1.0	207	30	72	10.5	105
	-T61	324	47	290	42	0.5	241	35	66	9.5	110
319.0	-T6	276	40	186	27	3.0	—	—	—	—	95
332.0	-T5	248	36	193	28	1.0	—	—	—	—	105
333.0	-T5	234	34	172	25	1.0	186	27	83	12	100
	-T6	290	42	207	30	1.5	228	33	103	15	105
	-T7	255	37	193	28	2.0	193	28	83	12	90
336.0	-T551	248	36	193	28	0.5	193	28	93	13.5	105
	-T65	324	47	296	43	0.5	248	36	—	—	125
354.0	-T62	393	57	317	46	3.0	276	40	—	—	110
355.0	-T6	290	42	186	27	4.0	234	34	69	10	90
C355.0	-T61	317	46	234	34	6.0	221	32	96	14	100
356.0	-T6	262	38	186	27	5.0	207	30	80	13	80
	-T7	221	32	234	24	6.0	172	25	76	11	70
A356.0	-T61	283	41	207	30	10.0	193	28	90	13	90
A357.0	-T6	358	52	310	45	5.0	241	35	103	15	100
359.0	-T62	345	50	290	42	5.5	—	—	110	16	—

a. Fatigue strength for round specimens and 500 million cycles.

b. 10 mm (0.40 in.) ball used.

Table 1.20
Physical Properties of Heat-Treatable Cast Aluminum Alloys

Aluminum Alloy	Temper	Density		Approximate Melting Range		Thermal Conductivity ^a		Electrical Conductivity (% IACS) ^b
		kg/m ³	lb/in. ³	°C	°F	W/(m·K)	BTU/(ft·hr·°F)	
Sand Castings								
A201.0	-T6	2796	0.101	571–649	1060–1200	1452	840	30
222.0	-T61	2962	0.107	521–627	970–1160	1539	890	33
240.0	-F	2768	0.100	516–604	960–1120	1141	660	23
242.0	-T77	2823	0.102	527–638	980–1180	1798	1040	38
	-T571	—	—	—	—	1591	920	34
A242.0	-T75	2823	0.102	527–638	980–1180	—	—	—
295.0	-T4	2823	0.102	521–643	970–1190	1642	950	35
	-T62	—	—	—	—	1694	980	35
319.0	-T5	2796	0.101	521–604	970–1120	—	—	—
	-T6	—	—	—	—	—	—	—
355.0	-T51	2713	0.098	549–621	1020–1150	2006	1160	43
	-T6	—	—	—	—	1694	980	36
	-T7	—	—	—	—	1954	1130	42
C355.0	-T6	2713	0.098	549–621	1020–1150	1746	1010	39
356.0	-T51	2685	0.097	560–616	1040–1140	2006	1160	43
	-T6	—	—	—	—	1798	1040	39
	-T7	—	—	—	—	1850	1070	40
A356.0	-T6	2713	0.098	560–610	1040–1130	1798	1040	40
A357.0	-T6	2713	0.098	554–610	1030–1130	1902	1100	40
359.0	-T6	2713	0.097	566–599	1050–1110	1642	950	35
520.0	-T4	2574	0.093	449–599	840–1110	1037	600	21
Permanent Mold Castings								
222.0	-T65	2962	0.107	521–627	970–1160	1556	900	33
242.0	-T571	2823	0.102	527–638	980–1180	1591	920	34
	-T61	—	—	—	—	1591	920	33
319.0	-T6	2796	0.101	527–604	970–1120	—	—	—
332.0	-T5	2768	0.100	527–638	970–1180	1245	720	26
333.0	-T5	2768	0.100	527–643	970–1090	1452	840	29
	-T6	—	—	—	—	1400	810	29
	-T7	—	—	—	—	1694	980	35
336.0	-T551	2713	0.098	538–627	1000–1060	1400	810	29
	-T65	—	—	—	—	—	—	—
354.0	-T62	2713	0.098	538–599	1000–1110	1504	870	32
355.0	-T6	2713	0.098	549–621	1020–1150	1798	1040	39
C355.0	-T61	2713	0.098	549–621	1020–1150	1746	1010	39
356.0	-T6	2685	0.097	560–616	1040–1140	1798	1040	41
	-T7	—	—	—	—	1850	1070	40
A356.0	-T61	2713	0.098	560–610	1040–1130	1798	1040	40
A357.0	-T6	2713	0.098	554–610	1030–1130	1902	1100	40
359.0	-T62	2685	0.097	566–599	1050–1110	1642	950	35

a. Thermal conductivity at 25°C (77°F).

b. Percentage of International Annealed Copper Standard (IACS) value for Volume Electrical Conductivity, which equals 100% at 20°C (68°F).

Choosing an aluminum filler metal that will work best for a particular welded component requires an understanding of the component and the expected performance in service, and then determining which of the characteristics associated with weld performance is most important. It should be noted that selecting a filler metal that is not recommended for the specific application may result in inadequate service performance that could cause premature failure of the welded joint.

The following characteristics should be considered when evaluating a filler metal for the arc welding of aluminum:

1. Crack sensitivity: This characteristic pertains to the avoidance of hot cracking. The crack-sensitivity rating of the weld metal can be established by using hot cracking sensitivity curves that have been developed for the various aluminum alloys, and by assessing the amount of dilution that occurs between the filler metal and base metal.
2. Strength of the welded joint: The tensile strength of groove welds and the shear strength of fillet welds can be determined by making trial welds with different filler alloys; this can provide extremely important parameters to be included in the design of the weld. Various filler metals may exceed the as-welded tensile strength of the base material, but may produce significantly different results in shear strength performance.
3. Ductility: This is a consideration when forming operations are to be used during fabrication and may also be a design consideration for service if fatigue or shock loading, or both, are of importance. In general, filler metals in the 5XXX series have higher ductility than those in the 4XXX series.
4. Corrosion resistance: This property of an aluminum weldment is a vital consideration if it will be exposed to adverse environmental conditions, such as exposure to fresh water or salt water.
5. Sustained temperature service: The reaction of some filler metals at sustained elevated temperature (higher than 66°C [150°F]) may promote premature failure of the component due to stress corrosion cracking. Any of the filler metals in the 5XXX series with more than 3% Mg content may be susceptible to this condition.
6. Color match: Matching the colors of the base metal and filler metal after anodizing can be of major concern in applications requiring enhanced appearance. For example, when welding base metals in the 6XXX series, filler metals in the 4XXX series will produce a very dark gray color after anodizing that will not match the base series will more closely match the base metal color after anodizing.
7. Postweld heat treatment (PWHT): Some filler alloys will not respond favorably to postweld heat treatment; other alloys have been developed specifically to respond well to postweld heat. Thus, when designing a welding procedure, it is important to consider the chemistry of the filler alloy and how it responds to postweld heat treatment.

The extent and complexity of filler metal selection can be demonstrated by using one of the many aluminum base metals, 6061-T6 in this example, for three different applications:

1. Alloy 6061-T6 tubing was used for a hand rail that was to be clear-coat anodized after welding. The filler metal was selected with color match after anodizing as the prime consideration. The most appropriate filler for this application was Alloy 5356. Filler metals 4043, 4047, or 4643 are often considered to be suitable for this base metal, but if these were used, the weld would become dark gray after anodizing and would not be an acceptable match to the bright silver appearance of the hand-rail tubing.
2. Alloy 6061-T6 extruded angle bar was used as a welded attachment bracket for a heating component that is to operate consistently at 120°C (250°F). Filler alloys suitable for elevated-temperature service were investigated. Filler metals 5554, 4043, or 4047 are all suitable for elevated-temperature service. Filler metals 5356, 5183, or 5556 are often considered to be suitable for this base material, but if one of these were used, it could introduce the possibility of sensitization of the magnesium in these alloys, run the risk of stress corrosion, and might cause premature failure of the welded component.
3. Alloy 6061-T6 was used to fabricate a large safety-critical lifting device that was 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. In this application, the strength of the weld after it had been exposed to postweld heat treatment was a concern. Most filler metals commonly used for welding this base material will not respond favorably to heat treatment. Filler metals 5356, 5183, and 5556 are nonheat-treatable alloys that can undergo undesirable changes if subjected to this form of heat treatment. Filler alloy 4043, on its own, is

the base material to achieve any significant response to the heat-treatment. The use of Alloy 4643 or Alloy 4943 filler metal was considered. Both are heat treatable and respond well to postweld heat treatment, and both would provide weld strength comparable to that of the base metal.

Each of the characteristics specific to the application should be evaluated in detail. Filler metal selection charts resulting from careful consideration of all the variables have been developed and often provide a rating system for each variable. A basic filler metal selection chart, shown in Table 1.21 is published by the American Welding Society (AWS).⁵ The chemical composition of solid wires and rods is shown in Table 1.22. A number of such charts are available in AWS documents and from aluminum filler metal manufacturers. As previously noted, many base metals can be welded using any one of several filler metals, but only one may be ideal for a specific application.

Cracking

The nonheat-treatable aluminum alloys typically can be welded with a filler metal of the same basic composition as the base alloy. The metallurgy of heat-treatable alloys is somewhat more complex and these alloys are more sensitive to intergranular, or grain-boundary, cracking during the weld cooling cycle.

Generally, a dissimilar filler metal with a lower melting temperature and similar or lower strength compared to the base metal can be used for the heat-treatable alloys, e.g., Alloy 4043 with a solidus of 577°C (1070°F) or Alloy 4145 with a solidus of 510°C (970°F). By allowing the constituents of the base metal adjacent to the weld to solidify before the weld metal (base alloy mixed with filler metal) solidifies, stresses are minimized in the base metal during cooling, thus intergranular cracking tendencies are minimized.

The relative sensitivity to cracking, based on the composition of weld metal of the alloys in the Al-Si 4XXX series, the Al-Mg 5XXX series, the Al-Cu 2XXX series, and the Al-Mg₂Si 6XXX series, are shown in Figure 1.1. These curves show that the aluminum alloys with high silicon content and those with high magnesium content are successfully welded because they have a low sensitivity to cracking. If the chemistry of the weld metal falls within the crack sensitivity peaks, weld cracking could be a problem.

5. American Welding Society (AWS) Committee on Filler Metals and Allied Materials, 2012, *Specification for Bare Aluminum and Aluminum-Alloy Welding Electrodes and Rods*, AWS A5.10/AWS 5.10M:2012 (ISO 18273:2004 MOD) an American National Standard, Miami: American Welding Society.

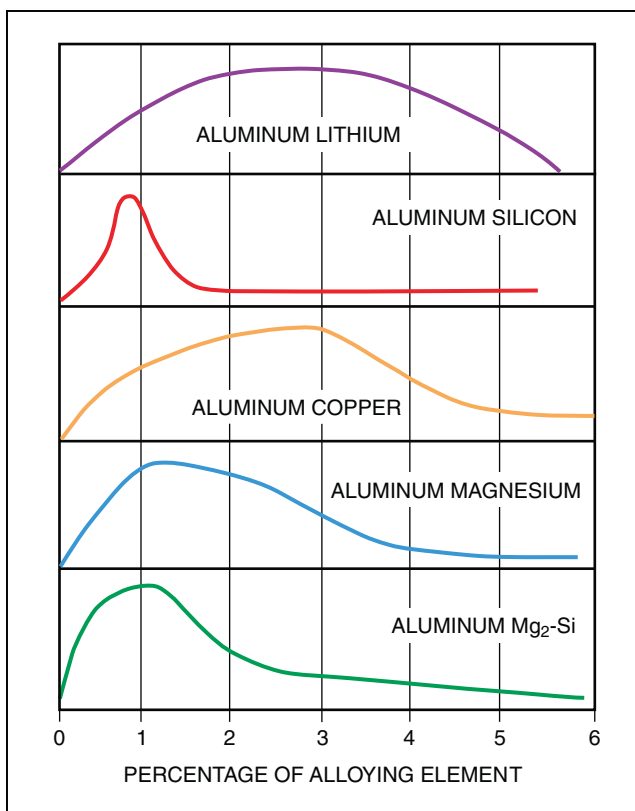


Figure 1.1—Relative Sensitivity to Hot Cracking of Welds in Aluminum Alloyed with (A) Lithium, (B) Silicon, (C) Copper, (D) Magnesium, and (E) Magnesium-Silicide

The heat-treatable Alloy 2219 (6.3% Cu) is easily welded using companion Alloy 2319 filler metal. Alloys in the 6XXX series are very sensitive to cracking if the weld metal composition remains close to the base metal composition, as shown in the square groove joint in Figure 1.2. These alloys can be easily welded if the edges are beveled to permit an excess amount of filler metal to mix with the base metal. For Alloy 6061, the weld metal should be composed of at least 50% Alloy 4043 filler metal or 70% Alloy 5356 filler metal. Fillet welds naturally permit mixing of filler metal, provided the base metal is not excessively melted. Autogenous welding of base metals in the 6XXX series is not recommended, as illustrated in Figure 1.3.

Alloy 4145 filler metal provides the least susceptibility to cracking when welding base metal alloys in the 2XXX series, such as 2014 and 2618, and also the Al-Cu and Al-Si-Cu cast alloys, such as 319.0 and 355.0.

Table 1.21
Guide to the Choice of Filler Metal for General Purpose Welding

Base Metal	201.0 206.0 224.0	319.0, 333.0, 354.0, 355.0, C355.0	356.0, A356.0 357.0, A357.0 413.0, 443.0, A444.0	511.0, 512.0, 513.0, 514.0, 535.0	7004, 7005, 7039, 710.0, 712.0	6009 6010 6070	6005, 6061, 6063, 6101, 6151, 6201, 6351, 6951	5456	5454
1060, 1070, 1080, 1350	ER4145	ER4145	ER4043 ^{a,b}	ER5356 ^{c,d}	ER5356 ^{c,d}	ER4043 ^{a,b}	ER4043 ^b	ER5356 ^d	ER4043 ^{b,d}
1100, 3003, Al ^c 3003	ER4145	ER4145	ER4043 ^{a,b}	ER5356 ^{c,d}	ER5356 ^{c,d}	ER4043 ^{a,b}	ER4043 ^b	ER5356 ^d	ER4043 ^{b,d}
2014, 2036	ER4145 ^e	ER4145 ^e	ER4145	—	—	ER4145	ER4145	—	—
2219	ER2319 ^a	ER4145 ^e	ER4145 ^{b,c}	ER4043	ER4043	ER4043 ^{a,b}	ER4043 ^{a,b}	—	ER4043 ^b
3004, Al ^c 3004	—	ER4043 ^b	ER4043 ^b	ER5356 ^f	ER5356 ^f	ER4043 ^b	ER4043 ^{b,f}	ER5356 ^d	ER5356 ^f
5005, 5050	—	ER4043 ^b	ER4043 ^b	ER5356 ^f	ER5356 ^f	ER4043 ^b	ER4043 ^{b,f}	ER5356 ^d	ER5356 ^f
5052, 5652 ⁱ	—	ER4043 ^b	ER4043 ^f	ER5356 ^f	ER5356 ^f	ER4043 ^b	ER5356 ^{c,f}	ER5356 ^f	ER5356 ^f
5083	—	—	ER5356 ^{c,d}	ER5356 ^d	ER5183 ^d	—	ER5356 ^d	ER5183 ^d	ER5356 ^d
5086	—	—	ER5356 ^{c,d}	ER5356 ^d	ER5356 ^d	—	ER5356 ^d	ER5356 ^d	ER5356 ^d
5154, 5254 ⁱ	—	—	ER4043 ^f	ER5356 ^f	ER5356 ^f	—	ER5356 ^f	ER5356 ^f	ER5356 ^f
5454	—	ER4043 ^b	ER4043 ^f	ER5356 ^f	ER5356 ^f	ER4043 ^b	ER5356 ^{c,f}	ER5356 ^f	ER5554 ^{c,f}
5456	—	—	ER5356 ^{c,d}	ER5356 ^d	ER5556 ^d	—	ER5356 ^d	ER5556 ^d	ER5556 ^d
6005, 6061, 6063	ER4145	ER4145 ^{b,c}	ER4043 ^{b,f,g}	ER5356 ^f	ER5356 ^{c,f}	ER4043 ^{a,b,g}	ER4043 ^{b,f,g}	—	—
6101, 6151, 6201									
6351, 6951									
6009, 6010, 6070	ER4145	ER4145 ^{b,c}	ER4043 ^{a,b,g}	ER4043	ER4043	ER4043 ^{a,b,g}	ER4043 ^{a,b,g}	—	—
7004, 7005, 7039	—	ER4043 ^b	ER4043 ^{b,f}	ER5356 ^f	ER5356 ^d	—	—	—	—
710.0, 712.0									
511.0, 512.0, 513.0	—	—	ER4043 ^f	ER5356 ^f	—	—	—	—	—
514.0, 535.0									
356.0, A356.0, 357.0	ER4145	ER4145 ^{b,c}	ER4043 ^{b,h}	—	—	—	—	—	—
A357.0, 413.0									
443.0, A444.0									
319.0, 333.0	ER4145 ^c	ER4145 ^{b,c,h}	—	—	—	—	—	—	—
354.0, 355.0									
C355.0									
201.0, 206.0, 224.0	ER2319 ^{a,h}	—	—	—	—	—	—	—	—

(Continued)

Table 1.21 (Continued)
Guide to the Choice of Filler Metal for General Purpose Welding

Base Metal	5154 5254 ⁱ	5086	5083	5052 5652 ⁱ	5005 5050	3004 Alc. 3004	2014 2036	1100 3003 Alc. 3003	1060 1070 1080 1350
1060, 1070, 1080, 1350	ER5356 ^{c,d}	ER5356 ^d	ER5356 ^d	ER4043 ^{b,d}	ER1100 ^{b,c}	ER4043 ^{b,d}	ER4145 ^{b,c}	ER1100 ^{b,c}	ER1188 ^{b,c,h,j}
1100, 3003, Al ^c 3003	ER5356 ^{c,d}	ER5356 ^d	ER5356 ^d	ER4043 ^{b,d}	ER1100 ^{b,c}	ER4043 ^{b,d}	ER4145 ^{b,c}	ER1100 ^{b,c}	
2014, 2036	—	—	—	—	ER4145	ER4145	ER4145 ^e		
2219	ER4043	—	—	ER4043 ^b	ER4043 ^{a,b}	ER4043 ^{a,b}	ER2319 ^a		
3004, Al ^c 3004	ER5356 ^f	ER5356 ^d	ER5356 ^d	ER5356 ^{c,f}	ER5356 ^{c,f}	ER5356 ^{c,f}			
5005, 5050	ER5356 ^f	ER5356 ^d	ER5356 ^d	ER5356 ^{c,d}	ER5356 ^{c,f}				
5052, 5652 ⁱ	ER5356 ^f	ER5356 ^d	ER5356 ^d	ER5654 ^{c,f,i}					
5083	ER5356 ^d	ER5356 ^d	ER5183 ^d						
5086	ER5356 ^d	ER5356 ^d							
5154, 5254 ⁱ	ER5356 ^{f,i}								

Note: ISO Classifications different from AWS Classifications have not been added to this table.

- ER4145 may be used for some applications.
- ER4047 may be used for some applications.
- ER4043 may be used for some applications.
- ER5183, ER5356, or ER5556 may be used.
- ER2319 may be used for some applications. It can supply high strength when the weldment is postweld solution heat-treated and aged.
- ER5183, ER5356, ER5554, ER5556, and ER5654 may be used. In some cases, they provide: (1) improved color match after anodizing treatment, (2) highest weld ductility, and (3) higher weld strength. ER5554 is suitable for sustained elevated temperature service.
- ER4643 and ER4943 will provide higher strength than ER4043 in 12 mm (0.500 in.) and thicker groove welds in 6XXX base alloys when postweld solution heat-treated and aged. They will also provide higher strength fillet welds than ER4043 in the as welded, postweld aged, or postweld heat-treated and aged conditions.
- Filler metal with the same analysis as the base metal is sometimes used. The following wrought filler metals possess the same chemical composition limits as cast filler alloys: ER4009 and R4009 as R-C355.0; ER4010 and R4010 as R-A356.0; and R4011 as R-A357.0.
- Base metal Alloys 5254 and 5652 are used for hydrogen peroxide service. ER5654 filler metal is used for welding both alloys for service temperatures below 66°C (150°F).
- ER1100 may be used for some applications.

Notes:

- ER4047, ER4643, or ER4943 may be used in some applications when alloy ER4043 is specified.
- Service conditions such as immersion in fresh or salt water, exposure to specific chemicals, or a sustained high temperature (over 66°C [(150°F)] may limit the choice of filler metals. Filler metals ER5183, ER5356, and ER5556 are not recommended for sustained elevated temperature service.
- Recommendations in this table apply to gas shielded arc welding processes. For oxyfuel gas welding, only ER1188, ER1100, ER4043, ER4047, and ER4145 filler metals are ordinarily used.
- Where no filler metal is listed, the base metal combination is not recommended for welding.

Source: Adapted from American Welding Society (AWS) Committee on Filler Metals and Allied Materials, 2012, *Specification for Bare Aluminum and Aluminum-Alloy Welding Electrodes and Rods*, A5.10/A5.10M:2012 (ISO 18273:2004 MOD), Miami: American Welding Society, Table 1.

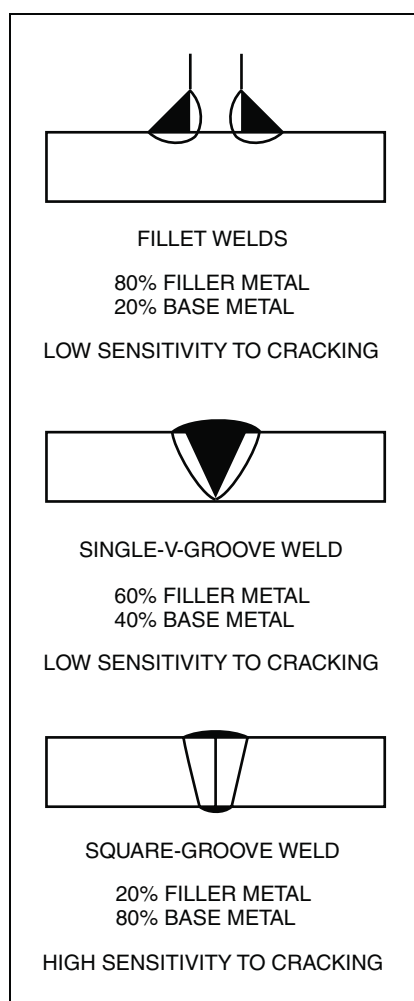
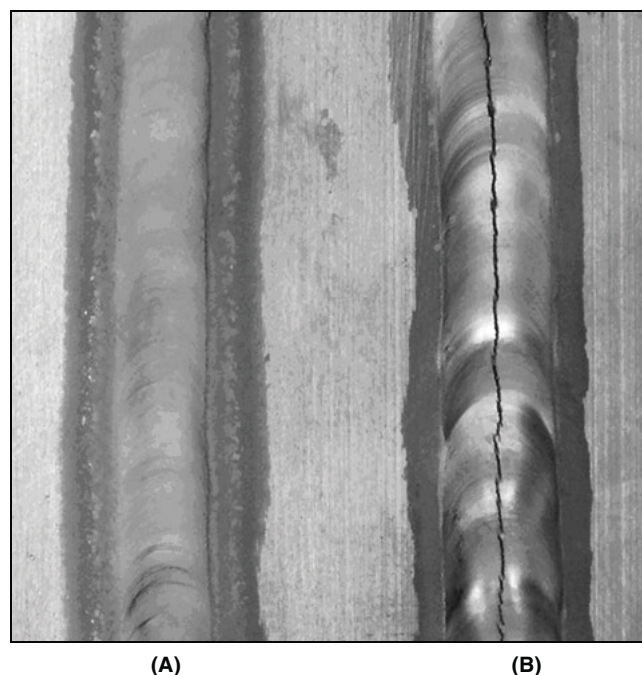


Figure 1.2—Admixture of Base Metal and Filler Metal in Typical Weld Joints

Alloys in the 7XXX series exhibit a wide range of sensitivity to cracking because of a relatively high copper content. Base metal alloys with a lower copper content (e.g., Alloys 7004, 7005, and 7039) are welded with filler metal 5356, 5183, or 5556. Aluminum alloys with higher copper content (e.g., 7075 and 7178) are not acceptable for arc welding.

Filler metals with high silicon content (i.e., the 4XXX series) should not be used to weld alloys in the 5XXX series with high magnesium content because the excessive magnesium-silicide eutectics that develop in the weld structure decrease ductility and increase crack sensitivity. Mixing high-magnesium-content alloys with high-copper-content alloys results in high sensitivity to weld cracking and low ductility in the weld.



Photograph courtesy of ITW Welding North America

Figure 1.3—Differences in Welded Joint in Alloy 6061 (A) with Filler Metal (No Cracking) and (B) without Filler Metal (Cracking)

Strength

In many cases, several filler metals are available that meet the minimum required as-welded mechanical properties. Typical all-weld-metal minimum shear strengths and ultimate tensile strengths of several filler metals are listed in Table 1.23. The diffusion of alloying elements from the base metal into the weld metal may increase the as-welded mechanical properties.

The selection of filler metal is more limited when weldments in heat-treatable alloys are to be postweld heat treated. When welding base metal Alloys 2219 and 2014, the heat-treatable filler metal 2319 will provide the highest strength. In most cases, a filler metal that is not a heat-treatable composition or is only mildly responsive to strengthening by thermal treatments can be used. For example, when welding base metal Alloy 6061-T6 that is less than 12.7 mm (0.5 in.) thick with Alloy 4043 filler metal, the magnesium in Alloy 6061-T6 migrates into the weld metal and produces enough magnesium-silicide to respond to heat treatment. In thicker groove welds, the wider bevels can prevent the diffusion of magnesium to the center of the weld, and little or no response results from postweld heat

Table 1.22
Chemical Composition of Solid Wires and Rods

Alloy Symbol			Chemical Composition in Weight Percent ^{a, b}													
AWS Classification	ISO 18273 Numerical	ISO 18273 Chemical	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ga, V	Ti	Zr	Al _{min.}	Be	Other Each	Other Total
ALUMINIUM-LOW ALLOYED																
ER1070, R1070	Al 1070	Al99.7	0.20	0.25	0.04	0.03	0.03	—	0.04	V 0.05	0.03	—	99.70	0.0003	0.03	—
ER1080A, R1080A	Al 1080A	Al99.8(A)	0.15	0.15	0.03	0.02	0.02	—	0.06	Ga 0.03	0.02	—	99.80	0.0003	0.02	—
ER1100, R1100	Al 1100	Al99.0Cu	Si + Fe 0.95	0.05–0.20	0.05	0.05	—	—	0.10	—	—	—	99.00	0.0003	0.05	0.15
ER1188, R1188	Al 1188	Al 99.88	0.06	0.06	0.005	0.01	0.01	—	0.03	Ga 0.03 V 0.05	0.01	—	99.88	0.0003	0.01	—
ER1200, R1200	Al 1200	Al99.0	Si + Fe 1.00	0.05	0.05	0.05	—	—	0.10	—	0.05	—	99.00	0.0003	0.05	0.15
ER1450, R1450	Al 1450	Al99.5Ti	0.25	0.40	0.05	0.05	0.05	—	0.07	—	0.10–0.20	—	99.50	0.0003	0.03	—
ALUMINIUM-COPPER																
R-206.0 ^c	—	—	0.10	0.15	4.2–5.0	0.20–0.50	0.15–0.35	—	0.10	—	0.15–0.30	—	Rem	—	0.05	0.15
ER2319, R2319	Al 2319	AlCu6MnZrTi	0.20	0.30	5.8–6.8	0.20–0.40	0.02	—	0.10	V 0.05–0.15	0.10–0.20	0.10–0.25	Rem	0.0003	0.05	0.15
ALUMINIUM-MANGANESE																
ER3103, R3103	Al 3103	AlMn 1	0.50	0.7	0.10	0.9–1.5	0.30	0.10	0.20	—	Ti + Zr 0.10	—	Rem	0.0003	0.05	0.15
ALUMINIUM-SILICON																
R-C355.0	—	—	4.5–5.5	0.20	1.0–1.5	0.10	0.40–0.6	—	0.10	—	0.20	—	Rem	—	0.05	0.15
R-A356.0	—	—	6.5–7.5	0.20	0.20	0.10	0.25–0.45	—	0.10	—	0.20	—	Rem	—	0.05	0.15
R-357.0	—	—	6.5–7.5	0.15	0.05	0.03	0.45–0.6	—	0.05	—	0.20	—	Rem	—	0.05	0.15
R-A357.0	—	—	6.5–7.5	0.20	0.20	0.10	0.40–0.7	—	0.10	—	0.04–0.20	—	Rem	0.04–0.07	0.05	0.15
ER4009, R4009	Al 4009	AlSi5Cu1Mg	4.5–5.5	0.20	1.0–1.5	0.10	0.45–0.6	—	0.10	—	0.20	—	Rem	0.0003	0.05	0.15
ER4010, R4010	Al 4010	AlSi7Mg	6.5–7.5	0.20	0.20	0.10	0.30–0.45	—	0.10	—	0.20	—	Rem	0.0003	0.05	0.15
R4011	Al 4011	AlSi7Mg0.5Ti	6.5–7.5	0.20	0.20	0.10	0.45–0.7	—	0.10	—	0.04–0.20	—	Rem	0.04–0.07	0.05	0.15
ER4018, R4018	Al 4018	AlSi7Mg	6.5–7.5	0.20	0.05	0.10	0.50–0.8	—	0.10	—	0.20	—	Rem	0.0003	0.05	0.15
ER4043, R4043	Al 4043	AlSi5	4.5–6.0	0.8	0.30	0.05	0.05	—	0.10	—	0.20	—	Rem	0.0003	0.05	0.15
ER4043A, R4043A	Al 4043A	AlSi5(A)	4.5–6.0	0.6	0.30	0.15	0.20	—	0.10	—	0.15	—	Rem	0.0003	0.05	0.15
ER4046, R4046	Al 4046	AlSi10Mg	9.0–11.0	0.50	0.03	0.40	0.20–0.50	—	0.10	—	0.15	—	Rem	0.0003	0.05	0.15
ER4047, R4047	Al 4047	AlSi12	11.0–13.0	0.8	0.30	0.15	0.10	—	0.20	—	—	—	Rem	0.0003	0.05	0.15
ER4047A, R4047A	Al 4047A	AlSi12(A)	11.0–13.0	0.6	0.30	0.15	0.10	—	0.20	—	0.15	—	Rem	0.0003	0.05	0.15

(Continued)

Table 1.22 (Continued)
Chemical Composition of Solid Wires and Rods

Alloy Symbol			Chemical Composition in Weight Percent ^{a, b}													Other Each	Other Total
AWS Classification	ISO 18273 Numerical	ISO 18273 Chemical	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ga, V	Ti	Zr	Al _{min.}	Be			
ALUMINIUM-SILICON (Continued)																	
ER4145, R4145	Al 4145	AlSi10Cu4	9.3–10.7	0.8	3.3–4.7	0.15	0.15	0.15	0.20	—	—	—	Rem	0.0003	0.05	0.15	
ER4643, R4643	Al 4643	AlSi4Mg	3.6–4.6	0.8	0.10	0.05	0.10–0.30	—	0.10	—	0.15	—	Rem	0.0003	0.05	0.15	
ER4943, ^d R4943 ^d	—	—	5.0–6.0	0.40	0.10	0.05	0.10–0.50	—	0.10	—	0.15	—	Rem	0.0003	0.05	0.15	
ALUMINIUM-MAGNESIUM																	
ER5087, R5087	Al 5087	AlMg4.5MnZr	0.25	0.40	0.05	0.7–1.1	4.5–5.2	0.05–0.25	0.25	—	0.15	0.10–0.20	Rem	0.0003	0.05	0.15	
ER5183, R5183	Al 5183	AlMg4.5Mn0.7(A)	0.40	0.40	0.10	0.50–1.0	4.3–5.2	0.05–0.25	0.25	—	0.15	—	Rem	0.0003	0.05	0.15	
ER5183A, R5183A	Al 5183A	AlMg4.5Mn0.7(A)	0.40	0.40	0.10	0.50–1.0	4.3–5.2	0.05–0.25	0.25	—	0.15	—	Rem	0.0005	0.05	0.15	
ER5187, R5187	Al 5187	AlMg4.5MnZr	0.25	0.40	0.05	0.7–1.1	4.5–5.2	0.05–0.25	0.25	—	0.15	0.10–0.20	Rem	0.0005	0.05	0.15	
ER5249, R5249	Al 5249	AlMg2Mn0.8Zr	0.25	0.40	0.05	0.50–1.1	1.6–2.5	0.30	0.20	—	0.15	0.10–0.20	Rem	0.0003	0.05	0.15	
ER5356, R5356	Al 5356	AlMg5Cr(A)	0.25	0.40	0.10	0.05–0.20	4.5–5.5	0.05–0.20	0.10	—	0.06–0.20	—	Rem	0.0003	0.05	0.15	
ER5356A, R5356A	Al 5356A	AlMg5Cr(A)	0.25	0.40	0.10	0.05–0.20	4.5–5.5	0.05–0.20	0.10	—	0.06–0.20	—	Rem	0.0005	0.05	0.15	
ER5554, R5554	Al 5554	AlMg2.7Mn	0.25	0.40	0.10	0.50–1.0	2.4–3.0	0.05–0.20	0.25	—	0.05–0.20	—	Rem	0.0003	0.05	0.15	
ER5556, R5556	Al 5556	AlMg5Mn1Ti	0.25	0.40	0.10	0.50–1.0	4.7–5.5	0.05–0.20	0.25	—	0.05–0.20	—	Rem	0.0003	0.05	0.15	
ER5556A, R5556A	Al 5556A	AlMg5Mn	0.25	0.40	0.10	0.6–1.0	5.0–5.5	0.05–0.20	0.20	—	0.05–0.20	—	Rem	0.0003	0.05	0.15	
ER5556B, R5556B	Al 5556B	AlMg5Mn	0.25	0.40	0.10	0.6–1.0	5.0–5.5	0.05–0.20	0.20	—	0.05–0.20	—	Rem	0.0005	0.05	0.15	
ER5556C, R5556C	Al 5556C	AlMg5Mn1Ti	0.25	0.40	0.10	0.50–1.0	4.7–5.5	0.05–0.20	0.25	—	0.05–0.20	—	Rem	0.0005	0.05	0.15	
ER5654, R5654	Al 5654	AlMg3.5Ti	Si + Fe 0.45	0.05	0.05	0.01	3.1–3.9	0.15–0.35	0.20	—	0.05–0.15	—	Rem	0.0003	0.05	0.15	
ER5654A, R5654A	Al 5654A	AlMg3.5Ti	Si + Fe 0.45	0.05	0.05	0.01	3.1–3.9	0.15–0.35	0.20	—	0.05–0.15	—	Rem	0.0005	0.05	0.15	
ER5754, R5754	Al 5754 ^e	AlMg3	0.40	0.40	0.10	0.50	2.6–3.6	0.30	0.20	—	0.15	—	Rem	0.0003	0.05	0.15	

a. Single values shown in the table are maximum values, except for Al.
b. The results shall be rounded to the same number of significant figures as in the specified value using the rules in accordance with ISO 80000-1 or ASTM E29.
c. For R-206.0, Ni = 0.05 max. and Sn = 0.05 max.
d. These classifications have patent application pending.
e. Alloy Al 5754 also limits the sum (Mn + Cr): 0.10 to 0.6.

Source: Adapted from American Welding Society, AWS A5.10/A5.10M:2012 (ISO 18273:2004 MOD), Table 1.

Table 1.23
Typical Properties of Aluminum Filler Metals (As-Welded Condition)

Filler Alloy	Minimum Shear Strength		All-Weld-Metal Ultimate Tensile Strength	
	MPa	ksi	MPa	ksi
1100	52	7.5	93	13.5
2319	110	16	258	37.5
4043	79	11.5	200	29
5183	128	18.5	283	41
5356	117	17	262	38
5554	117	17	230	33
5556	138	20	290	42
5654	83	12	221	32

treatments. Filler metal 4643 and filler metal 4943 contain sufficient magnesium so that a weld in base metal Alloy 6061 that is 76 mm (3 in.) thick will attain a transverse ultimate tensile strength of 440 MPa (45 ksi) when postweld heat treated and aged to meet the original properties of Alloy 6061-T6.

The strength of fillet welds is highly dependent on the filler metal composition and minimum shear strength values (refer to Table 1.23). Filler metal 5356, 5183, and 5556 provide high shear strength for structural fillet welds.

The 1XXX and 5XXX series filler metals produce very ductile welds and are preferred when the weldment is subjected to forming or spinning operations, or postweld straightening operations.

Elevated and Cryogenic Temperature Service

Filler metals containing a composition of magnesium nominally in excess of 3% (i.e., Alloys 5183, 5356, 5556, and 5654) are not suitable for applications in which temperatures are sustained higher than 66°C (150°F) because these filler metals can be sensitized to stress-corrosion cracking. This sustained temperature would include the length of time required for aging treatments used in postweld thermal treatments in addition to service temperatures higher than 66°C (150°F). All aluminum filler metals are suitable for cryogenic temperature applications.

Corrosion Resistance, Filler Metals

Assemblies, vessels, drums, and tanks for use in certain corrosive environments or with certain chemicals may require welding with special filler metals. These special alloys may be of higher purity, such as Alloy 1188 filler metal than for welding chemical drums made of Alloy 1060 base metal, or may have closer composition limits on some alloying elements. A good example is the tight control over copper and manganese impurities in base Alloy 5254 plate with Alloy 5654 filler metal used for fabrication in hydrogen peroxide service.

Aluminum-magnesium filler metals are highly resistant to general corrosion when used with base alloys that have similar magnesium content. The 5XXX series filler metals, however, can be anodic to base metal alloys in the 1XXX, 3XXX, and 6XXX series with which they might be used. In immersed service, the weld metal will pit and corrode at varying rates, based on the difference in electrical potential of the weld metal and the base metal. Thus, an aluminum-silicon filler metal, such as Alloy 4043 or Alloy 4047, would be preferred over Alloy 5356 filler metal for improved corrosion resistance and for protection of the base metal when welding Alloy 6061 base metal for an immersed-service application.

Color Match

Color match between the weld metal and base metal is often required for ornamental or architectural applications for which the weldments are given chemical or electrochemical finishes. The final color is highly dependent on the composition of the filler alloy and how closely it matches specific elements in the base alloy. The two elements of primary interest are silicon and chromium.

Silicon in an alloy will create a gray-to-black color that varies with increasing percentages of silicon. Thus, welds made with aluminum-silicon filler metal will exhibit a sharp color contrast with all base alloys except those clad with an aluminum-silicon alloy or with one of the aluminum-silicon casting alloys. Chromium causes an alloy to develop a yellow or gold shade when anodically treated, so a filler metal in the 5XXX series with chromium content similar to the base metal would be preferred. Copper and manganese in aluminum alloys produce slight darkening effects that need to be considered.

Alloy 1188 filler metal will produce a good color match in welds in alloys of the 1XXX series and also with Alloys 3003, 5005, and 5050. Alloy 5356 filler metal is a good choice for welding base metal alloys in the 5XXX and 6XXX series when a color match is needed.

POROSITY

Porosity can often be a problem when welding aluminum. It is caused by hydrogen gas becoming entrapped within the solidifying aluminum weld pool, resulting in voids in the completed weld. An example of this condition is shown in a cross-section of a fillet weld in aluminum in Figure 1.11.

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. The solubility of hydrogen in aluminum is illustrated in Figure 1.12.

Hydrogen is sometimes introduced unintentionally during the welding operation through contaminants within the welding area. It is important to thoroughly understand the many sources of these contaminants in order to detect the cause and take the necessary action to resolve porosity problems.

Shielding During the Welding Operation

Contamination may occur because of inadequate shielding gas coverage during welding. Exposure to the surrounding atmosphere and contamination of the molten weld metal during the welding operation are possibilities to consider when examining a porosity problem. Examples of the causes of contamination include the following:

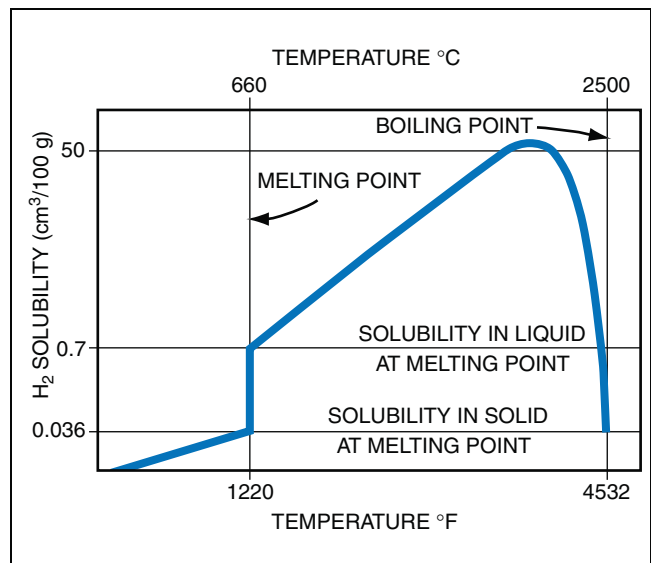


Figure 1.5—Solubility of Hydrogen in Aluminum



Figure 1.4—Porosity in a Cross Section of a Fillet Weld in Aluminum

1. Welding in drafty conditions, such as strong drafts from open doors or fans directed at the welding area, can remove the shielding gas during welding;
2. Excessive spatter buildup inside the gas nozzle when gas metal arc welding can restrict gas flow and reduce the efficiency of the shielding gas;
3. Incorrect standoff distance (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; and
4. Establishing and maintaining the correct shielding gas flow rate will provide the most efficient gas coverage; it should be high enough to ensure adequate shielding, but not so high that it can cause turbulence in the weld pool during welding.

Reducing the level of porosity is sometimes achievable by using argon-helium shielding gas mixtures. The advantage of an argon-helium mixture is that it provides additional heat during welding, and consequently allows a greater opportunity for the hydrogen to escape prior to solidification. The use of helium as an additive, sometimes up to 75%, can help to reduce porosity levels; however, the best recourse against unacceptable porosity levels is to remove the source of hydrogen contamination.

Hydrocarbons

Hydrocarbons that may be present on the surface of the aluminum plate or on the welding wire are sources of hydrogen-related porosity. Some precautions include the following:

1. Thoroughly cleaning plate surfaces prior to welding to remove contaminants, such as lubricants, grease, oil or paint;
2. Ensuring that exhaust contaminants, such as oil and moisture derived from compressed air tools used during weld preparation are removed from the surface of the plate;
3. Ensuring that the quality of the aluminum welding wire is satisfactory and that the welding wire is clean and free of any residual oil used during the wire manufacturing process, otherwise it may be virtually impossible to produce welds with acceptable porosity levels; and
4. Anti-spatter compounds applied to the welding nozzle or to the plate surface are not usually recommended for aluminum welding when low

Moisture

Moisture (H_2O) can be a cause of contamination to the weld area of an aluminum plate. The following are potential sources:

1. Water leaks that occur within the welding equipment, if using a water-cooled welding system;
2. The use of inadequately pure shielding gas that does not meet the minimum purity requirements specified by the appropriate code or standard;
3. Moisture caused by imperfections within the gas delivery line, such as leaking pipes or hoses;
4. High atmospheric humidity or a change in temperature, (crossing a dew point) can result in condensation on the plate. When welding in high humidity, moisture is readily acquired, even from small fluctuations in temperature; and
5. Hydrated aluminum oxide is a source of moisture that can result in porosity.

Hydrated Aluminum Oxide. Aluminum has a protective layer of aluminum oxide that is relatively thin and naturally forms on any exposed surface. The oxide layer is porous and can absorb moisture, grow in

also on the welding wire; however, properly stored aluminum with a thin uncontaminated oxide layer can be easily welded with the gas shielding processes gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) processes, which break down and remove the oxide during welding. When the aluminum oxide has been exposed to moisture, it becomes hydrated and potential problems with porosity arise.

Material Preparation

Other potential contamination problems are associated with preparation of the workpieces for welding. Cutting or grinding methods that may deposit contaminants onto the plate surface or subsurface, cutting fluids, debris from grinding discs, and lubricants on discs or saw blade are areas of concern.

Material preparation methods must be evaluated as a control element of the welding procedure that must not be 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 materials should be stored in an area that will prevent contamination by hydrocarbons or moisture.

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 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 avoid high levels of porosity, it is important to incorporate degreasing and oxide removal. Typically, this can be achieved through a combination of chemical cleaning or the use of solvents to remove hydrocarbons, followed by brushing with a stainless steel wire brush to remove contaminated aluminum oxide.

Finding and eliminating the cause of porosity within a specific welding operation is not always a straightforward exercise; it is often a time-consuming and frustrating process. Correct cleaning of the workpieces prior to welding is essential, in addition to the use of proven surface preparation procedures. It is also essential to use well-maintained equipment, a high quality of shielding gas, and a high quality of aluminum welding wire that is free from contamination. All are important variables if a low level of porosity is to be achieved.

Storage and Use of Aluminum Filler Metal

A major step toward producing good aluminum welds is the use of quality filler metal of the correct size and alloy composition. Filler metal should be free of gas and nonmetallic impurities and have a clean, smooth surface that is free of moisture, lubricant, or other contaminants. Preventive care is required during storage and use to avoid contamination that would cause poor welds.

The quality of the filler metal is particularly important when using the gas metal arc welding process. In this consumable-electrode process, relatively small-diameter filler wire is fed through the welding gun at a high rate of speed. To feed properly, the filler metal must be free from slivers, scratches, inclusions, kinks, waves, or sharp bends; it must be uniform in diameter, of a suitable temper, and spooled so that it is free to unwind without restriction. Proper pitch and cast also are important to prevent wandering of the wire as it emerges from the contact tip. If the electrode surface is not clean, the high rate of wire feed can carry a relatively large amount of foreign material into the weld pool, resulting in porosity or poor-quality welds.

To avoid contamination, supplies of filler metal must be kept covered and stored in a dry place at a relatively uniform temperature. Electrode spools temporarily left on the welding machine (e.g., between work shifts) should be covered with a clean cloth or plastic bag if the feed unit does not have a built-in cover. If a spool of wire will not be used overnight, it should be returned to the original carton and tightly sealed, unless it is in a spool enclosure that provides a dry or protective atmosphere. Original containers of electrodes should not be opened until the contents are to be used. Electrodes in the 5XXX series are most likely to develop a hydrated surface oxide; therefore when these electrodes are not in use, they should be stored in cabinets that maintain a low (less than 35%) relative humidity.

Information on the manufacture, packaging, testing, and selection of bare aluminum filler materials is contained in *Specification for Bare Aluminum and Aluminum-Alloy Welding Electrodes and Rods*, AWS A5.10/A5.10M:2012, published by the American Welding Society.⁶

6. American Welding Society (AWS) Committee on Filler Metals and Allied Materials, 2012, *Specification for Bare Aluminum and Aluminum-Alloy Welding Electrodes and Rods*, AWS A5.10/A5.10M:2012 (ISO 1873:2004 MOD), an American National Standard, Miami: American Welding Society.

SURFACE PREPARATION

Quality arc welds in aluminum require the metals to be clean, dry, and coated with a thin oxide film. Aluminum materials must be properly stored to maintain this condition. Any moisture or hydrocarbons in the arc area during welding will dissociate and produce hydrogen, which is the primary cause of porosity in aluminum welds. Hydrated oxides and water stains on aluminum that has been improperly stored can be particularly troublesome because the moisture penetrates and causes inward oxide growth. This hydrated-oxide layer contains chemically combined water, which causes porosity. Also, the thickened oxide is difficult to remove by arc cleaning action (the oxide melts at 2038°C [3700°F]), which is significantly higher than the melting point of aluminum alloys) and prevents proper fusion.

Aluminum materials should be properly stored when they are received to minimize future cleaning operations. Storing layers of aluminum outdoors or in buildings without adequate climate control will result in moisture condensation on the metal, which permits moisture to be drawn between the layers by capillary action. If the product is interleaved with paper, a wicking action can occur which will further contribute to water stains and hydrated-oxide conditions. Good storage practice is to position aluminum sheets vertically and far enough apart to permit moisture to run off and to allow air circulation to dry the surfaces.

Prior to welding, the first operation should be to remove all grease, oil, dirt, paint, and other surface contaminants that can generate hydrogen or interfere with weld fusion. The materials can be degreased by wiping, spraying, dipping, or steam cleaning.

The cleaning and welding areas must be well ventilated. If chlorinated solvents are used for degreasing, this should take place at a location remote from the welding area. Highly toxic phosgene gas can result from the dissociation of the vapors of chlorinated hydrocarbons (e.g., trichloroethylene and other chlorinated hydrocarbons) by arc radiation. (Refer to the Safe Practices section of this chapter.)

Petroleum-base solvents leave little residue and are nontoxic when used in a well-ventilated welding area, but these solvents have low flash points and require special storage and handling. Instructions for the safe handling and use of the solvent provided by the manufacturer in the safety data sheet (SDS) should be carefully followed.

The thin aluminum-oxide film is naturally formed on the surface of aluminum and is removed by the arc of the gas shielded processes or by the fluxes used in other joining methods. The thick oxide film or coating resulting from thermal, chemical, or electrochemical treatments, or poor storage conditions must be removed and the surfaces cleaned before welding.

Oxide removal is accomplished with caustic soda, acids, or proprietary solutions. Some of these are listed in Table 1.24. The rinsing and drying cycles require special attention to avoid residual chemicals or production of a hydrated oxide. If the metal surface is rough from machining, sawing, forming, or improper handling, the welding surface may have folds that could entrap oxide or lubricants. Chemical etching is often used to open and remove any metal folds or burrs. (Refer to the Safe Practices section of this chapter for information on the safe handling of chemical cleaning and etching agents.)

Mechanical oxide removal, although not as consistent as chemical means, is usually satisfactory if performed properly. These methods include wire brushing, scraping, or filing. Grinding or sanding with wheels or

discs can be done with proper equipment, although abrasive particles can be easily embedded in the aluminum surface, which may result in unacceptable inclusions in the weld. Contamination of the surface with a binder compound may create poor fusion or porosity in the weld.

Wire brushing is, by far, the most widely used method for removing oxides. Stainless steel brushes with bristle diameters of 0.25 mm to 0.38 mm (0.010 in. to 0.015 in.) provide good abrasive action. The brush must be kept clean of all contaminants, and it should be used with a light pressure to avoid burnishing the aluminum surface and entrapping oxide particles. Hand brushes are as effective as power brushes.

Table 1.24
Chemical Treatments for Oxide Removal Prior to Welding or Brazing Aluminum*

Type of Solution	Concentration	Temperature	Type of Container	Procedure	Purpose
1. Sodium Hydroxide (Caustic Soda)	1. NaOH 50 grams (1.76 oz) 1 L (0.26 per gal) of water	1. 60°C–71°C (140°F–160°F)	1. Mild steel	1. Immerse for 10 seconds to 60 seconds. Rinse in cold water.	Removes thick oxide for all welding and brazing procedures. Active etchant.
followed by					
2. Nitric Acid	2. Equal parts of HNO ₃ (68%) and water	2. Room	2. Type 347 stainless steel	2. Immerse for 30 seconds. Rinse in cold water. Rinse in hot water and dry.	
Sulfuric-Chromic	H ₂ SO ₄ — 3.79 L (1 gal) CrO ₃ — 1.28 kg (45 oz) Water— 34.1 L (9 gal)	60°C–82°C (160°F–180°F)	Antimonial lead lined steel tank	Dip for 2 minutes to 3 minutes. Rinse in cold water. Rinse in hot water and dry.	For removal of heat-treatment and annealing films and stains and for stripping oxide coatings.
Phosphoric-Chromic	H ₃ PO ₄ (75%)— 13.3 L (3.5 gal) CrO ₃ — 79.4 grams (1.75 lb) Water— 379 L (100 gal)	93°C (200°F)	Type 347 stainless steel	Dip for 5 minutes to 10 minutes. Rinse in cold water. Rinse in hot water and dry.	For removal of heat-treatment and annealing films and stains and for stripping oxide coatings.
Sulfuric Acid	H ₂ SO ₄ — 165 grams (5.81 oz) Water— 1 L (0.26 gal)	73°C (165°F)	Polypropylene-lined steel tank	Immerse for 5 minutes to 10 minutes. Rinse in cold water. Rinse in hot water and dry.	Oxide removal. Mild etchant.
Ferrous Sulfate	Fe ₂ SO ₄ H ₂ O 10% by volume	26.7°C (80°F)	Polypropylene	Immerse for 5 minutes to 10 minutes. Rinse in cold water. Rinse in hot water and dry.	Oxide removal.

*All chemicals used as etchants are potentially dangerous. All persons using any of these etchants should be thoroughly familiar with all of the chemicals involved and the proper procedures for handling and mixing these chemicals. Always add the chemicals to water. Never add the water to the chemicals. Safety glasses must be worn at all times when using chemical etchants. Avoid contact with the skin. When working with unfamiliar chemicals or cleaning products, the Safety Data Sheet (SDS) for the specific product should always be consulted before use. These are available from the suppliers and must be available to all employees for guidance on the proper handling of the materials.

Abrasive pads or belts should not be used when preparing for arc welding because they will leave a residue (hydrocarbon) that leads to porosity in the welds.

It should be noted that chemical cleaning and brushing of joint components should be done prior to assembly for welding; fitted joints may retain solvents or contaminants that result in weld discontinuities.

PROPERTIES AND PERFORMANCE OF ALUMINUM WELDMENTS

The properties and performance of a welded joint in aluminum are influenced by many factors, including the composition, form, and temper of the base metals, the filler metal used, the welding process, rate of cooling, joint design, postweld mechanical or thermal treatments, and the service environment.

METALLURGICAL EFFECTS

The effect of the heat of welding, which causes the softening of the base metal adjacent to the weld, is generally the controlling factor relative to the as-welded strength of an aluminum weldment. The composition and structure of the weld metal can also significantly affect final strength, ductility, and toughness.

Weld Metal

The properties of the deposited aluminum weld metal are influenced by the composition and rate of solidification. The solidification rate depends on the welding process and technique, in addition to all the factors affecting heat input and the rate of heat transfer away from the weld pool. A higher rate of solidification generally produces a finer-grained microstructure with greater strength and decreased tendency for hot cracking.

The composition of the weld metal depends on the chemical composition of the base metal and filler metal, and the resultant mixture is influenced by the joint design, welding process, and procedure employed. When welding the nonheat-treatable aluminum alloys, a filler metal with a chemical composition similar to that of the base metal is generally selected. The melting range of the heat-treatable aluminum alloys is much wider and these alloys are more sensitive to hot cracking. A dissimilar filler metal with a lower solidus temperature than that of the base metal is generally employed; this will allow the heat-treatable base metal

to completely solidify and develop strength along the fusion zone before weld solidification shrinkage stresses occur.

The molten weld metal exhibits a high solubility for hydrogen. Hydrogen can be introduced into the weld metal from residual hydrocarbons or hydrated oxides on the surfaces of the base and filler metals, and also from faulty welding equipment or improper gas shielding that permits moist atmospheric contamination. During solidification of the weld, hydrogen precipitates out of the solidifying molten aluminum and becomes entrapped in the solid weld metal as porosity. Thus, it becomes very important to eliminate sources of hydrogen from the weld area when using welding procedures that result in rapid solidification of the weld metal. Bare filler wire must be properly cleaned and stored in a dry environment until needed for production.

Heat-Affected Zone

The effect of the heat of welding on aluminum base alloys varies with the distance from the weld and may be divided roughly into areas that are represented by the temperature attained by the metal. The length of time at a specific temperature can be significant for the heat-treatable alloys. The width of the heat-affected zone (HAZ) in all alloys and the extent of metallurgical changes in the heat-treatable alloys depend on the rate of heat input and heat dissipation. These are influenced by the welding process, the thickness or geometry of the workpiece, the speed of welding, the preheat and interpass temperatures, and the types of backing or fixturing. Figure 1.4 illustrates the effect of three heat-input conditions on the properties of the heat-affected zone and the width of the HAZ in heat-treatable Alloy 6061-T6.

The recrystallization of cold-worked metal and some grain growth are likely to occur in the HAZ of nonheat-treatable alloys. The strength of the HAZ will be similar to that of the annealed material because the portion of the HAZ subjected to temperatures higher than the annealing temperature will be instantaneously annealed. Time at temperature and cooling rate are not critical variables for these alloys. The mechanical properties of welds in butt joints in nonheat-treatable aluminum alloys are shown in Table 1.25.

A typical metallurgical structure across the weld of a nonheat-treatable alloy is illustrated in Figure 1.5. Very little change in microstructure can be noted in the base metal. The service performance of the weldment when stressed parallel to the weld will depend somewhat on the ratio of the width of the HAZ relative to that of the unaffected base metal; when stressed transverse to the weld, the mechanical properties obtained are independent of the welding process and technique employed in making the weld.

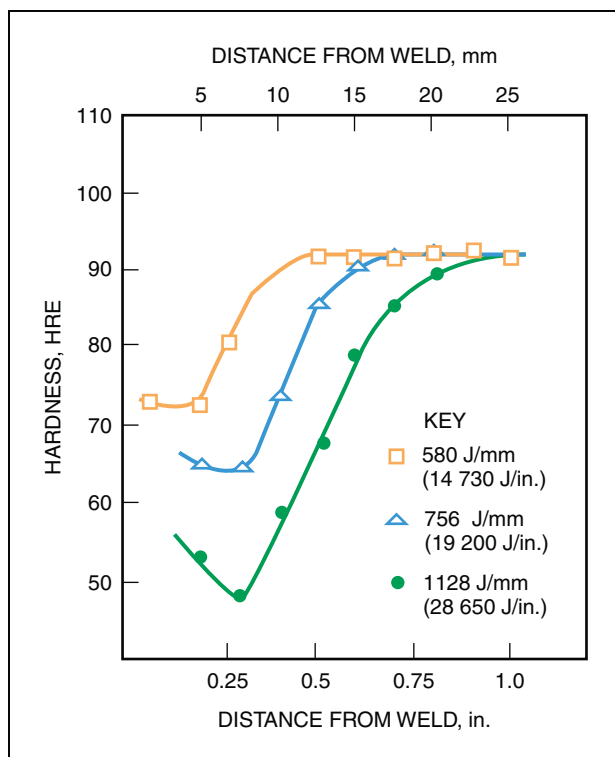


Figure 1.4—Rockwell Hardness E Scale Profiles of the Heat-Affected Zone of Gas Tungsten Arc Welds on 6061-T6 Using Varied Heat Input

Heat-Treatable Alloys. The heat-treatable alloys contain alloying elements that exhibit a noticeable change in solubility with a change in temperature. The high strengths of these alloys are induced by the controlled-solution heat-treatment and precipitation hardening (aging) of some of the microconstituents. The heat-treatable alloys typically are welded in the aged condition, during which a controlled amount of hardening microconstituents are precipitated from solid solution. The heat of welding causes resolution of the hardening microconstituents in the HAZ, followed by an uncontrolled precipitation of the microconstituents in the HAZ on cooling. This overaging in the HAZ lowers the base-metal strength adjacent to the weld.

The response of heat-treatable alloys to welding is much more complex than that of the nonheat-treatable alloys because response depends on the peak temperature and the time at temperature to which the metal is exposed (refer to Figure 1.4). Thus, variations in the metallurgical structure will change with distance from the weld interface, as illustrated in Figure 1.6 and Figure 1.7. To completely soften these alloys, the annealing temperature must be maintained for several hours. In the HAZ, the annealing temperature is exceeded for a short period of time. The welding process, technique, preheat and interpass temperatures, and the rate of cooling greatly influence the degree of microstructural changes, which influences the sensitivity to hot cracking and the amount of softening that occurs.

Table 1.25
Mechanical Properties of Gas-Shielded
Arc Welded Butt Joints in Nonheat-Treatable Aluminum Alloys

Base Alloy	Filler Alloy	Average Ultimate Tensile Strength		Minimum Ultimate Tensile Strength		Minimum Tensile Yield Strength*		Tensile Elongation % in 50.8 mm (2 in.)	Free Bend Elongation %
		MPa	ksi	MPa	ksi	MPa	ksi		
1060	1188	69	10	55	8	17	2.5	29	63
1100	1100	90	13	76	11	31	4.5	29	54
1350	1188	69	10	55	8	17	2.5	29	63
3003	1100	110	16	97	14	48	7	24	58
5005	5356	110	16	97	14	48	7	15	32
5050	5356	158	23	124	18	55	8	18	36
5052	5356	193	28	172	25	90	13	19	39
5083	5183	296	43	276	40	165	24	16	34
5086	5356	269	39	241	35	117	17	17	38
5154	5654	228	33	207	30	103	15	17	39
5454	5554	241	35	214	31	110	16	17	40
5456	5556	317	46	290	42	179	26	14	28

*0.2% offset in a 254 mm (10 in.) gauge length across a butt joint.

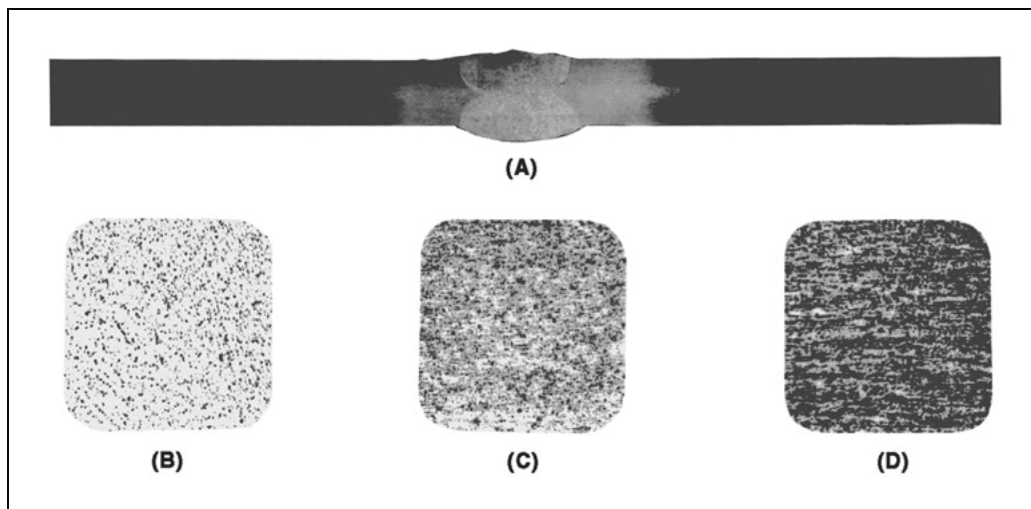


Figure 1.5—Cross Section of (A) Gas Metal Arc Weld in 5456-H321 Plate, 9.5 mm (0.375 in.) Thick (Magnified 2X), Showing (B) Weld Metal, (C) Heat-Affected Zone, and (D) Unaffected Zone (Magnified 100X)

The base metal immediately adjacent to the fusion zone (B) is heated to a temperature sufficient to rapidly re-dissolve any precipitates. This solid-solution zone (C) will attain an intermediate strength and will be quite ductile. Adjoining the solid-solution area is a zone (D) that has been subjected to temperatures higher than the precipitation-hardening temperature but lower than the solution-heat-treatment temperature. This zone exhibits varying degrees of over-aging and softening, depending on the temperature and time held at the over-aging temperature. The portion of overaged (or partially annealed) metal (D) closest to the solid-solution zone generally possesses the lowest strength. Postweld aging treatments have little effect on the strength of this zone. The entire weldment must be solution heat-treated and aged to reproduce the previous properties of the base material. It is best to weld the heat-treated alloys with a fast procedure that rapidly dissipates the heat to minimize the degree of over-aging and reduction of strength that can occur in the heat-affected zone (HAZ).

Complete heat treatment (solution treating followed by age hardening) of weldments may be practical in some cases. When this is not the case, only postweld aging can be used to improve the strength of the solid-solution zones, but this method should not be expected to strengthen the already overaged material. If the base metal is welded in the solution-heat-treated (-T4) condition, postweld aging can be very effectively employed to improve as-welded strength. This procedure is most

effective for low-heat-input welding processes or techniques that avoid excessive precipitation aging. Typical calculations of this improvement in strength of welds in butt joints in heat-treated aluminum alloys are shown in Table 1.26. Table 1.27 shows the effect of welding conditions on the strength of groove joints in Alloy 6061 with filler metal ER4043.

TENSILE STRENGTH AND DUCTILITY

The tensile strength and ductility of aluminum-base alloys are affected by the heat of welding and by applied heat treatments. The effects on nonheat-treatable alloys and heat-treatable alloys are presented in this section.

Nonheat-Treatable Alloys

The heat of welding causes nonheat-treatable alloys to lose the effects of strain hardening in the HAZ. This zone (adjacent to the weld) reaches the annealed condition, which is characterized by decreased strength and increased ductility. Because the metal is annealed by the initial welding operation, repeated welding during a repair operation does not further reduce the strength, except as influenced by a possibly wider HAZ. For this reason, the minimum annealed tensile strength of the base metal is generally considered as the minimum strength of butt joints in the nonheat-treatable alloys.