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The Practical Reference Guide to

Welding Aluminum



Commercial Applications



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THE PRACTICAL REFERENCE GUIDE to WELDING ALUMINUM in COMMERCIAL APPLICATIONS

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AUTHOR NOTES

Ultimately, I would like to thank Bob Schneider, who is an old friend of mine, for making this book happen. A couple of years ago, I was asked by Debrah Weir of AWS to review a similar book that Bob had written titled "The Practical Guide for Welding Aluminum: High Quality Fusion Welding." My review concluded that, while Bob's book captured his long and varied experience in the aerospace industry, it didn't include practices common in other, higher production volume industries. The next thing I knew, Bob and Debrah suggested that I cover those industries in a separate volume, which became this book. With additional encouragement and support from Debrah, who is Corporate Director of New Product Development for AWS, and Lee Kvidahl, an AWS past president and the current chair of the AWS Product Development Committee, this book has become a reality. Thank you both for your patience and help.

I would also like to thank Dr. Toby Pearlstein of Bain & Co., Mr. Paul Sullivan, formerly of the Massachusetts Highway Department, and Mr. Randy Kissell of the TGB Group for their help in reviewing and suggesting constructive changes to this guide. Although neither had direct involvement with this guide, I would be remiss if I didn't acknowledge the long-time contributions of two other people: Paul Dickerson, formerly of Alcoa, and Paul Miller, formerly of MK Industries. Paul Dickerson was my mentor for many years and taught me most of what I know about welding aluminum. Paul Miller has been a friend for a long time, has been tireless in promoting the use of proper techniques and proper equipment in the welding of aluminum alloys, and has been a great help to me on many occasions.

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TABLE OF CONTENTS

	Page No.
Basic Safety Precautions	vi
Introduction.....	1
Welding Aluminum vs. Welding Steel	1
Aluminum Alloy and Temper Designations	1
Effect of Welding on Mechanical Properties of Aluminum Alloys	4
Filler Metal Selection.....	5
Preparing for Welding.....	8
Gas Tungsten Arc Welding (GTAW)	10
Gas Metal Arc Welding (GMAW).....	15
Shielded Metal Arc Welding (SMAW).....	26
Weld Defects—Causes and Cures	26
Solving Problems in Qualifying Weld Procedures	29
Other Publications Available from AWS.....	33

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LIST OF TABLES

Figure		Page No.
1	Destination system for wrought alloys	2
2	Designation system for cast alloys.....	2
3	Chemical composition of wrought aluminum filler metals.....	6
4a	Guide to the selection of filler metal for general purpose welding	7
4b	Guide to the selection of filler metal for general purpose welding	7
5	Comparison of filler metals 4043 and 5356.....	8
6	Current ratings for tungsten electrodes for AC GTAW welding with argon shielding.....	14
7	Typical procedures for manual gas tungsten arc welding of butt joints in aluminum with AC and argon shielding	16
8	Typical procedures for manual gas tungsten arc welding of fillet welds in aluminum with AC and argon shielding	16
9	Current carrying capacities of various diameter 2% thoriated electrodes in DC electrode negative welding (DCEN).....	17
10	Typical procedures for manual GTAW of butt joints in aluminum with DCEN and helium shielding in flat position	17
11	Typical procedures for manual GTAW of fillet welds in aluminum with DCEN and helium shielding	17
12	Approximate transition currents for various wire diameters.....	19
13	Typical procedures for gas metal arc welding of groove welds in aluminum alloys with argon shielding.....	25
14	Typical procedures for gas metal arc welding of fillet welds in aluminum alloys with argon shielding.....	25

LIST OF FIGURES

Figure		Page No.
1	The relationship of yield strength, amount of cold work, and alloy content.....	3
2	The “H” temper designations for strain-hardened alloys.....	3
3	Hardness vs. distance for 6061 T4 and T6 in the as-welded (AW) and postweld-aged (PWA) conditions	4
4	Correct pneumatic chisel geometry for backgouging aluminum	11
5	Gas tungsten arc welding equipment arrangement.....	11
6	GTAW showing the proper addition of welding filler rod	15
7	Diagram of gas metal arc welding equipment.....	18
8	Volt/ampere relationship for a constant-current (CC) power supply	19
9	Volt/ampere relationship for a constant-potential (CP) power supply	20
10	The “push” part of a push-pull feeder	21
11	A “pull” gun for a push-pull feeder	22
12	Add-on pull welding gun	22
13	One-pound spool gun for feeding aluminum.....	22
14	Drive rolls and wire guides for feeding aluminum	23
15	Radiograph showing a crater crack.....	26
16	Radiograph showing a longitudinal weld crack	27
17	Radiograph of a weld showing incomplete penetration.....	27
18	Cross section of a weld with incomplete fusion	28
19	Cross section of a weld with excessive porosity.....	28
20	Radiograph showing tungsten contamination	28
21	Radiograph showing copper contamination.....	29
22	Bent test requirements from AWS D1.2 using plunger type tester.....	30
23	Bent test requirements for wraparound bend test fixture.....	31
24	Typical joint geometries for arc welding of aluminum (not to scale).....	32

BASIC SAFETY PRECAUTIONS

Burn Protection. Molten metal, sparks, slag, and hot work surfaces are produced by welding, cutting, and allied processes. These can cause burns if precautionary measures are not used. Workers should wear protective clothing made of fire-resistant material. Pant cuffs, open pockets, or other places on clothing that can catch and retain molten metal or sparks should not be worn. High-top shoes or leather leggings and fire-resistant gloves should be worn. Pant legs should be worn over the outside of high-top shoes. Helmets or hand shields that provide protection for the face, neck, and ears, and a head covering to protect the head should be used. In addition, appropriate eye protection should be used.

Electrical Hazards. Electric shock can kill. However, it can be avoided. Live electrical parts should not be touched. The manufacturer's instructions and recommended safe practices should be read and understood. Faulty installation, improper grounding, and incorrect operation and maintenance of electrical equipment are all sources of danger.

All electrical equipment and the workpiece should be grounded. The workpiece lead is not a ground lead. It is used only to complete the welding circuit. A separate connection is required to ground the workpiece. The workpiece should not be mistaken for a ground connection.

Fumes and Gases. Many welding, cutting, and allied processes produce fumes and gases which may be harmful to health. Avoid breathing the air in the fume plume directly above the arc. Do not weld in a confined area without a ventilation system. Use point-of-welding fume removal when welding galvanized steel, zinc, lead, cadmium, chromium, manganese, brass, or bronze. Do not weld on piping or containers that have held hazardous materials unless the containers have been inerted properly.

Compressed Gas Cylinders. Keep caps on cylinders when not in use. Make sure that gas cylinders are chained to a wall or other structural support. Do not weld on cylinders.

Radiation. Arc welding may produce ultraviolet, infrared, or light radiation. Always wear protective clothing and eye protection to protect the skin and eyes from radiation. Shield others from light radiation from your welding operation.

Special Precautions. In the following conditions when welding aluminum alloys:

- (1) High levels of fumes are produced when using the 5XXX (magnesium-bearing) aluminum filler metals.
- (2) The use of argon-based shielding gas blends results in the production of ozone, especially with 4XXX filler metals.

The use of filtering masks or airline respirators will be required if it is determined that personnel are being exposed to excessive pollutants.

Caution must also be observed in the reaction between aluminum and certain solvents and cleaners. Consult information provided by manufacturers for the necessary safe practices in the use of their products.

AWS also recommends a personal copy of "Arc Welding Safely," "Fire Safety in Welding and Cutting," and "Safety in Welding, Cutting, and Allied Processes."

Introduction

The use of aluminum as a structural material is a fairly recent development. Originally, aluminum was considered to be a precious metal. In fact, when the Washington Monument was completed in December, 1884, it was capped with a 100-ounce pyramid of pure aluminum. The problem that initially impeded the use of aluminum as a structural material was the fact that aluminum is a reactive metal. It is never found in its elemental state in nature, but is always tightly bound with oxygen as aluminum oxide, Al_2O_3 .

Aluminum oxide, found as bauxite ore, was always plentiful; however, no direct reduction method, such as that used to make steel, was found to produce aluminum from bauxite until 1886, when the American, Charles M. Hall, and the Frenchman, Paul Heroult, almost simultaneously, yet independently, discovered electrolytic processes for obtaining pure aluminum from aluminum oxide. As a result, aluminum became available in commercial quantities. These processes, with some modifications, are still used today.

Since that time, aluminum has found wide use in numerous applications:

- It conducts electricity and heat almost as well as copper.
- It is widely used in electrical bus bars and other conductors, heat exchangers, and cookware.
- It does not become brittle with decreasing temperature, but instead becomes stronger, so it has found wide application in cryogenic equipment at temperatures as low as -452°F .
- It is very corrosion resistant in most environments, so it has found wide applications in marine and chemical environments.

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

Welding Aluminum vs. Welding Steel

Most industrial welders start out by learning how to weld steel; a minority later move on to welding aluminum. Since most welding equipment is designed to weld steel, the welding of aluminum alloys is frequently just an afterthought. However, this attitude is changing.

The welding of aluminum is often approached as though aluminum were just shiny steel. However, there are definite differences between the welding of steel and aluminum. This guide will discuss these differences and how to overcome the problems that arise when the welding of aluminum is considered to be the same as the welding of steel. Three common fallacies are as follows:

(1) *If you take enough care almost all steels are weldable.*

Fabricators regularly fall into this trap. There are some aluminum alloys—especially the stronger ones—that are just not arc weldable.

(2) *All steels are heat treatable.*

Some aluminum alloys are heat treatable, but some aren't. Even for the heat-treatable aluminum alloys, the heat treatments are totally different from those used for steel. In fact, if you heat some alloys and then quench them, they become softer, not harder. Be aware of the differences and act accordingly.

(3) *When welding steels, you can almost always make a weld that is as strong as the parent material.*

In aluminum alloys, the weld will rarely be as strong as the parent material. This is usually true for welds in both heat-treatable and nonheat-treatable alloys. The strength difference between the weld or heat-affected zone (HAZ) and the parent is significant, often 30% or more.

Aluminum Alloy and Temper Designations

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

Wrought Alloys

Wrought alloy designations use a four-digit number, plus a temper designation. All aluminum alloys have been divided into eight “families” depending on the main alloying elements. The aluminum alloy families are shown in Table 1, along with their heat treatability.

For example, if you have a piece of 6061, according to Table 1, the 6061 is a wrought alloy (4 digits) that is heat treatable, and contains magnesium and silicon. The second digit shows whether the alloy is the first such alloy registered (in which case the second digit will be “0,” as in 5054). Digits other than “0” indicate that the alloy is a modification of a registered alloy, i.e., 5154 is the first modification of 5054, and 5754 is the seventh modification. The last two digits are assigned arbitrarily by the Aluminum Association when the alloy is registered. Note there is no indication of alloy or weld strength given by the material designation.

Cast Alloys

The designation system for cast alloys is shown in Table 2. The specific families are somewhat different from the designations for wrought alloys—these designations have only three digits, followed by a decimal point and another digit. For cast alloys the first digit shows the alloy family. The next two

Table 2. Designation system for cast alloys.

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

digits are arbitrarily assigned. Alloy modifications are shown by a letter prefix; therefore, 356 is the original version of an alloy and A356 is the first modification, B356 is the second modification, etc. The number following the decimal point designates whether the alloy is produced as a casting of final form or is produced as an ingot for re-melting.

Temper Designations

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

(1) **“O” Temper** (not the number zero). When an alloy is given this designation, the supplier has annealed the alloy (typically at 650–750°F), and the alloy is as soft and weak as possible.

(2) **“F” Temper**. An alloy supplied in this temper is supplied “as fabricated.” The supplier guarantees that the chemistry of the material meets the chemical requirements for the specified alloy, but there are no claims regarding the mechanical properties of the alloy. This temper is often specified by fabricators who subsequently forge or form the supplied material and establish mechanical properties by heat treatment after forming.

Table 1. Destination system for wrought alloys.

Alloy Family	Main Alloying Elements	Heat Treatable
1XXX	Pure Aluminum	No
2XXX	Copper (sometimes with magnesium)	Yes
3XXX	Manganese (sometimes with magnesium)	No
4XXX	Silicon	No
5XXX	Magnesium	No
6XXX	Magnesium plus silicon	Yes
7XXX	Zinc (sometimes with magnesium and copper)	Yes
8XXX	All others	Normally Yes
NOTE: The designation 2XXX, etc. is an industry standard abbreviation used to mean “all the alloys in the 2000 series.”		

Nonheat-Treatable Alloys—Strain-Hardened Designations

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

- (1) The more an alloy is deformed, the stronger it becomes. At some point, the alloy will have no ductility left and will fracture.
- (2) The higher the alloy content, the more an alloy will gain strength by being deformed.

Both of these phenomena are shown in Figure 1.

The temper designation for strain-hardened alloys is usually made up of two digits as shown in Figure 2.

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

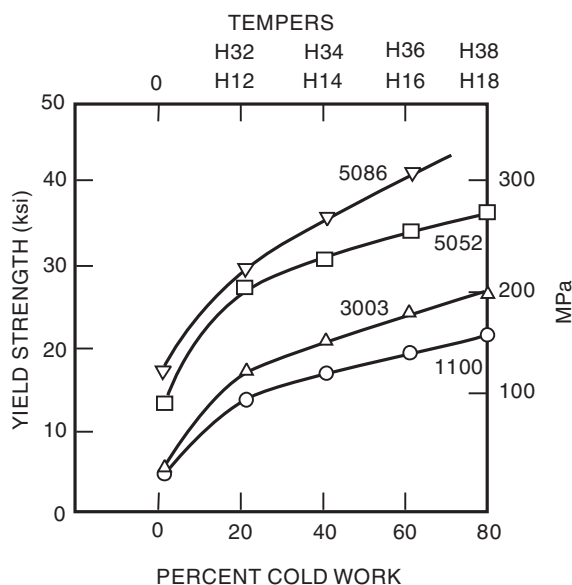


Figure 1. The relationship of yield strength, amount of cold work, and alloy content.

The first digit indicates basic operations:

- H1—strain hardened only.
- H2—strain hardened and partially annealed.
- H3—strain hardened and stabilized.

The second digit indicates degree of strain hardening:

- HX2—quarter hard.
- HX4—half hard.
- HX6—three-quarters hard.
- HX8—full hard.
- HX9—extra hard.

The third digit indicates a variation of a two-digit temper.

Figure 2. The “H” temper designations for strain-hardened alloys.

Heat-Treatable Alloys

The strain-hardened H tempers are not used for heat-treatable alloys. Instead, a series of T tempers indicating the heat treatment state are used. A total of 10 tempers exist, T1 through T10. However, the tempers commonly seen are T4 and T6.

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

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

The tensile and yield strengths of T4 material will increase for several weeks after the heat treatment and, in some alloys, will increase significantly. However, once past this initial period, the T4 alloy is stable indefinitely. The user normally is unaware

of this initial strength increase, because the aluminum producer doesn't ship the alloy until the strength has stabilized.

The T4 temper, while stable, does not give maximum strength to the alloy. Most alloys are sold in a maximum strength T6 temper. To get from T4 to T6 temper, put the material in a furnace at a temperature of 325–400°F and allow it to age from 1–5 hours. The dissolved alloying elements will form submicroscopic pre-precipitates in the material and produce maximum strength. If this aging heat treatment is carried out at high temperatures for an extended period, the precipitates will get too large—resulting in a lower strength “overaged” condition.

Note: This final aging heat treatment is carried out at 400°F maximum. The welding heat, which can heat the surrounding material to well over this temperature, can significantly degrade the strength of the weld HAZ.

Effect of Welding on Mechanical Properties of Aluminum Alloys

The effects of welding on the mechanical properties of aluminum weldments can be best understood by discussing nonheat-treatable alloys and heat-treatable alloys separately.

Nonheat-Treatable Alloys

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

Since the HAZ can never become softer than the “O” temper, any excess welding heat input will not make the HAZ softer. It can, however, make the HAZ wider. Normally, this will not further reduce

the strength of the welded joint, although other problems can arise due to excessive heat input.

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

Heat-Treatable Alloys

There is no blanket statement that can be made about the welded strength of heat-treatable alloys. As previously mentioned, the weld will generally be weaker than the parent material. However, the welded properties will strongly depend on the temper of the material before welding and also on heat treatments performed after welding.

Figure 3 shows a microhardness trace across a weld, starting at the center of the weld. The graph shows four curves that represent material in the T4 and T6 tempers in the as-welded (AW) and postweld-aged (PWA) conditions. The following can be noted:

(1) The HAZ is shown to be about 1/2 in. wide. However, the actual width will depend on several variables, including the welding process used and the thickness of the material. HAZ widths of 1 in. are not uncommon in thin materials.

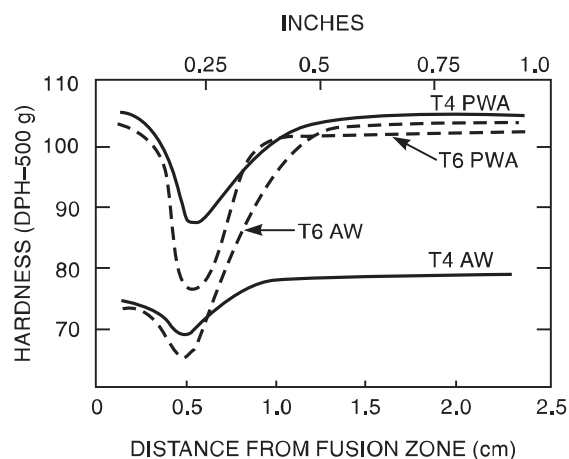


Figure 3. Hardness vs. distance for 6061 T4 and T6 in the as-welded (AW) and postweld-aged (PWA) conditions.

(2) The hardness and strength of the weldment is typically lowest in the HAZ. Because of this, strength of the welding filler alloy is not a primary concern when making butt welds. A weld will most often fail in the HAZ.

(3) Unlike the nonheat-treatable alloys, the hardness (and therefore strength) in the HAZ is not always the same. It depends on the material temper prior to welding and on whether the weld is postweld-aged:

(a) The weakest HAZ occurs when the material is welded in the T6 temper and used as-welded.

(b) The HAZ, and therefore the weldment, will actually be slightly stronger if the material is used in the T4 temper and used as-welded.

(c) If the weldment in either T4 or T6 material is postweld-aged, the strength of the HAZ can increase significantly. The exact postweld heat-treatment varies with the alloy, but is usually aged at approximately 400°F for one hour.

The fabricator has some options that are unavailable when fabricating the nonheat-treatable alloys in terms of recovering some of the strength lost during welding. For example, since the 6XXX alloys bend more easily around a smaller radius in the T4 temper than in the T6 temper, these alloys can be bought in the T4 temper, formed easily, welded, and then aged. The resulting mechanical properties will be significantly higher than if the material was purchased in the T6 temper.

Finally, if the right filler alloy is chosen, the finished weldment can be completely heat treated and the T6 properties restored. This requires a re-solution heat-treatment, quench, and re-aging. This procedure is often practical for small structures, but not for large ones. For example, aluminum bicycle frames are often fabricated in this way.

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

Filler Metal Selection

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

Several characteristics that determine the best filler metal choice for a given base material, or combination of base materials, are:

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

There are a number of filler metal selection charts that take these factors into account and give good overall recommendations for filler metal selection. A composite of these charts covering most alloy combinations is shown in Table 4.

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

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

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

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

(4) **4XXX Alloys.** These alloys are usually found as welding or brazing fillers. If encountered as parent

Table 3. Chemical composition of wrought aluminum filler metals.

Filler Alloy	Elements, wt. % ^a								Other Elements		Al
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Each	Total	
1100	Note b	Note b	0.05–0.20	0.05	—	—	0.10	—	0.05 ^c	0.15	99.0 min.
1188	0.06	0.06	0.005	0.01	0.01	—	0.03	0.01	0.01 ^c	—	99.88 min.
2319	0.20	0.03	5.8–6.8	0.20–0.40	0.02	—	0.10	0.10–0.20	0.05 ^c	0.15	Remainder
4009 ^d	4.5–5.5	0.20	1.0–1.5	0.10	0.45–0.6	—	0.10	0.10–0.20	0.05 ^c	0.15	Remainder
4010 ^e	6.5–7.5	0.20	0.20	0.10	0.30–0.45	—	0.10	0.20	0.05 ^c	0.15	Remainder
4011 ^f	6.5–7.5	0.20	0.20	0.10	0.45–0.7	—	0.10	0.04–0.20	0.05 ^f	0.15	Remainder
4043	4.5–6.0	0.8	0.30	0.05	0.05	—	0.10	0.20	0.05 ^c	0.15	Remainder
4047	11.0–13.0	0.8	0.30	0.15	0.10	—	0.20	—	0.05 ^c	0.15	Remainder
4145	9.3–10.7	0.8	3.3–4.7	0.15	0.15	0.15	0.20	—	0.05 ^c	0.15	Remainder
4643	3.6–4.6	0.8	0.10	0.05	0.10–0.30	—	0.10	0.15	0.05 ^c	0.15	Remainder
5183	0.40	0.40	0.10	0.50–1.0	4.3–5.2	0.05–0.25	0.25	0.15	0.05 ^c	0.15	Remainder
5356	0.25	0.40	0.10	0.05–0.20	4.5–5.5	0.05–0.20	0.10	0.06–0.20	0.05 ^c	0.15	Remainder
5554	0.25	0.40	0.10	0.50–1.0	2.4–3.0	0.05–0.20	0.25	0.05–0.20	0.05 ^c	0.15	Remainder
5556	0.25	0.40	0.10	0.50–1.0	4.7–5.5	0.05–0.20	0.25	0.05–0.20	0.05 ^c	0.15	Remainder
5654	Note g	Note g	0.05	0.01	3.1–3.9	0.15–0.35	0.20	0.05–0.15	0.05 ^c	0.15	Remainder

a. Single values are maximum, except where otherwise specified.
 b. Silicon plus iron shall not exceed 0.95%.
 c. Beryllium shall not exceed 0.0008%.
 d. Same composition as C355.0 cast alloy.
 e. Same composition as A356.0 cast alloy.
 f. Beryllium content is 0.04 to 0.07%. Same composition as A357.0 cast alloy. Used for GTAW rod only.
 g. Silicon plus iron shall not exceed 0.45%.

materials, 4047 is usually the best choice as a filler metal.

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

(a) **5052.** This alloy has just the right amount of Mg content to exhibit a relatively high crack sensi-

tivity. If it is welded with 5052 filler alloy, it will often crack. To avoid the tendency to crack, 5052 is usually welded with a filler alloy of much higher Mg content, such as 5356. The resulting weld metal, an alloy of the 5356 and 5052, has a Mg content high enough to be crack-resistant. Additionally, the Mg content of 5052 is low enough so that it can be successfully welded using 4043.

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

(c) **5454.** This alloy is a lower Mg alloy specifically developed to be immune to the stress corrosion cracking already noted. Filler alloy 5554 is