# Aluminum and Aluminum Alloys

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## Overview

Aluminum and aluminum alloys have many outstanding attributes that lead to a wide range of applications, including good corrosion and oxidation resistance, high electrical and thermal conductivities, low density, high reflectivity, high ductility and reasonably high strength, and relatively low cost.

Aluminum is a lightweight material with a density of 2.7 g/cm$^3$ (0.1 lb/in.$^3$). Pure aluminum and its alloys have the face-centered cubic (fcc) structure, which is stable up to its melting point at 657 °C (1215 °F). Because the fcc structure contains multiple slip planes, this crystalline structure greatly contributes to the excellent formability of aluminum alloys.

Aluminum alloys display a good combination of strength and ductility. Aluminum alloys are among the easiest of all metals to form and machine. The precipitation hardening alloys can be formed in a relatively soft state and then heat treated to much higher strength levels after forming operations are complete. In addition, aluminum and its alloys are nontoxic and among the easiest to recycle of any of the structural materials.

Aluminum is the most abundant metal in the Earth's crust, but it was not until the 1800s that elemental aluminum was successfully extracted. Even the first processes developed were inefficient and extremely expensive. It is rumored that the French Emperor Napoleon III used sterling silver and gold tableware for routine dinner guests, reserving his highly prized aluminum tableware for only the most honored guests on special occasions. The situation changed in 1886 to 1888 with the nearly simultaneous development of the Hall-Héroult process for electrolytic reduction and the Bayer process for inexpensive production of alumina ($Al_2O_3$) from bauxite ore. These breakthroughs allowed the widespread production and use of aluminum and aluminum alloys. Charles Hall, the developer of the Hall-Héroult process, went on to form the Aluminum Company of America (Alcoa).

### Types of Aluminum Alloys

Aluminum alloys are normally classified into one of three groups: wrought non-heat-treatable alloys, wrought heat treatable alloys, and casting alloys.

**Wrought non-heat-treatable alloys** cannot be strengthened by precipitation hardening; they are hardened primarily by cold working. The wrought non-heat-treatable alloys include the commercially pure aluminum series (1*xxx*), the aluminum-manganese series (3*xxx*), the aluminum-silicon series (4*xxx*), and the aluminum-magnesium series (5*xxx*). While some of the 4*xxx* alloys can be hardened by heat treatment, others can only be hardened by cold working.

**Wrought heat treatable alloys** can be precipitation hardened to develop quite high strength levels. These alloys include the 2*xxx* series (Al-Cu and Al-Cu-Mg), the 6*xxx* series (Al-Mg-Si), the 7*xxx* series (Al-Zn-Mg and Al-Zn-Mg-Cu), and the aluminum-lithium alloys of the 8*xxx* alloy series. The 2*xxx* and 7*xxx* alloys, which develop the highest strength levels, are the main alloys used for metallic aircraft structure.

**Casting alloys** include both non-heat-treatable and heat treatable alloys. The major categories include the 2*xx.x* series (Al-Cu), the 3*xx.x* series (Al-Si + Cu or Mg), the 4*xx.x* series (Al-Si), the 5*xx.x* series (Al-Mg), the 7*xx.x* series (Al-Zn), and the 8*xx.x* series (Al-Sn). The 2*xx.x*, 3*xx.x*, 7*xx.x*, and 8*xx.x* alloys can be strengthened by precipitation hardening, but the properties obtained are not as high as for the wrought heat treatable alloys.

### Melting and Primary Fabrication

To produce pure aluminum, alumina ($Al_2O_3$) is first extracted from the mineral bauxite, which contains approximately 50% $Al_2O_3$. In the Bayer process, a sodium hydroxide solution is used to precipitate aluminum hydroxide, which is then calcined to form alumina. Alumina is then converted to pure aluminum by electrolysis using the Hall-Héroult process (Fig. 1). The cell is lined with carbon cathodes, and consumable electrodes are gradually fed into the top of the cell. The electrolyte is cryolite ($Na_3AlF_6$) with 8 to 10 wt% $Al_2O_3$ dissolved in it. The cell operates at temperatures in the range of 955 to 1010 °C (1750 to 1850 °F) with a power rating of 10 to 12 kWh/kg aluminum. Pure aluminum (~99 wt%) is reduced at the cathode and forms a molten pool in the bottom of the cell, which is drained from the bottom and cast into aluminum ingots. Because the production of aluminum takes a lot of electrical energy and recycling aluminum takes much less energy, a large portion of general-purpose aluminum is currently made from recycled material.

The semicontinuous direct chill process (Fig. 2) is the most widely used process for casting commercial ingots that will receive fur-

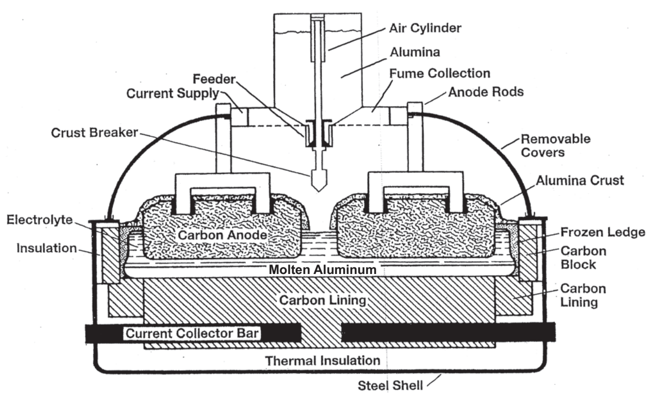


**Fig. 1 Electrolytic cell used to produce aluminum. Source: Ref 1**

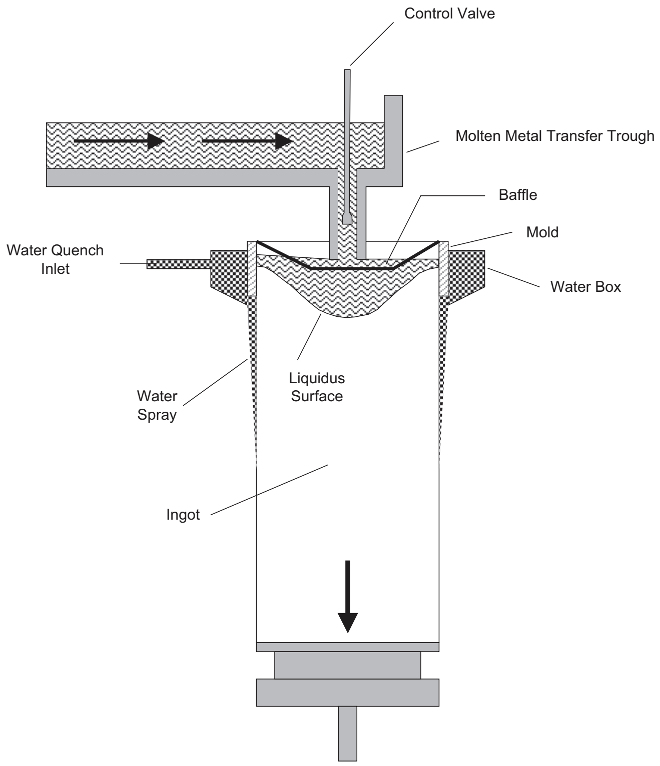


**Fig. 2 Semicontinuous direct chill casting. Source: Ref 1**

ther processing, such as rolling, extrusion, or forging. It produces fine-grained ingots at high production rates. In this process, molten aluminum is poured into a shallow, water-cooled mold of the required shape. When the metal begins to freeze, the false bottom in the mold is lowered at a controlled rate, and water is sprayed on the freshly solidified metal as it exits the mold. A water box or spray rings are placed around the ingot to rapidly cool the ingot. One of the main advantages of direct chill continuous casting is that it helps to eliminate the segregation that occurs in high-strength alloys produced by the older tilt casting procedures. These alloys, when produced by tilt casting, are highly segregated because of the broad solidification temperature ranges and the shape of the freezing front. Direct chill casting eliminates most of this type of segregation because the liquid metal freezing front is almost horizontal, and the liquid metal freezes from the bottom to the top of the ingot.

Rolled aluminum is the most common of the wrought aluminum product forms. Sheet is defined as rolled aluminum in the range of 0.15 to 6.35 mm (0.006 to 0.250 in.) thick. If the thickness is greater than 6.35 mm (0.250 in.), then it is called plate. Foil refers to aluminum product that is less than 0.15 mm (0.006 in.) thick. Aluminum foil, sheet, and plate are produced from aluminum ingots using the following steps:

1. Scalping of the ingot
2. Preheating and homogenizing the ingot
3. Reheating the ingot, if required, to the hot rolling temperature
4. Hot rolling to form a slab
5. Intermediate annealing
6. Cold rolling along with intermediate anneals to form foil and sheet product forms

## Fabrication

**Heat Treatment.** Aluminum alloys are commonly annealed to soften them and increase ductility, or the heat treatable alloys are strengthened by precipitation hardening.

Annealing, a process that reduces strength and hardness while increasing ductility, can also be used for both the non-heat-treatable and heat treatable grades of wrought and cast alloys. Annealing treatments are used during complex cold forming operations to allow further forming without the danger of sheet cracking. The softest, most ductile, and most formable condition for aluminum alloys is produced by full annealing to the O condition. If cold-worked aluminum alloys are heated to a sufficiently high temperature for a sufficiently long time, annealing will occur in three stages: recovery, recrystallization, and grain growth. During recovery, the internal stresses due to cold work are reduced, with some loss of strength and a recovery of some ductility. During recrystallization, new unstrained nuclei form and grow until they impinge on each other to form a new recrystallized grain structure. Heating for longer times or at higher temperatures will generally result in grain growth, which is normally undesirable.

In precipitation hardening, an alloy is heated to a high enough temperature to take a significant amount of an alloying element into solid solution (Fig. 3). It is then rapidly cooled (quenched) to room temperature, trapping the alloying elements in solution. On reheating to an intermediate temperature, the host metal rejects the alloying element in the form of an extremely fine precipitate only several angstroms in diameter (1 Å = $10^{-9}$ m). The fine precipitate creates matrix strains in the lattice that act as barriers to the motion of dislocations and provide resistance to slip, thereby increasing the strength and hardness (Fig. 4). Precipitation hardening consists of three steps:

1. Solution heat treating
2. Rapidly quenching to a lower temperature
3. Aging

In solution heat treating, the alloy is heated to a temperature that is high enough to put the soluble alloying elements in solution. After holding at the solution treating temperature for long enough for diffusion of solute atoms into the solvent matrix to occur, it

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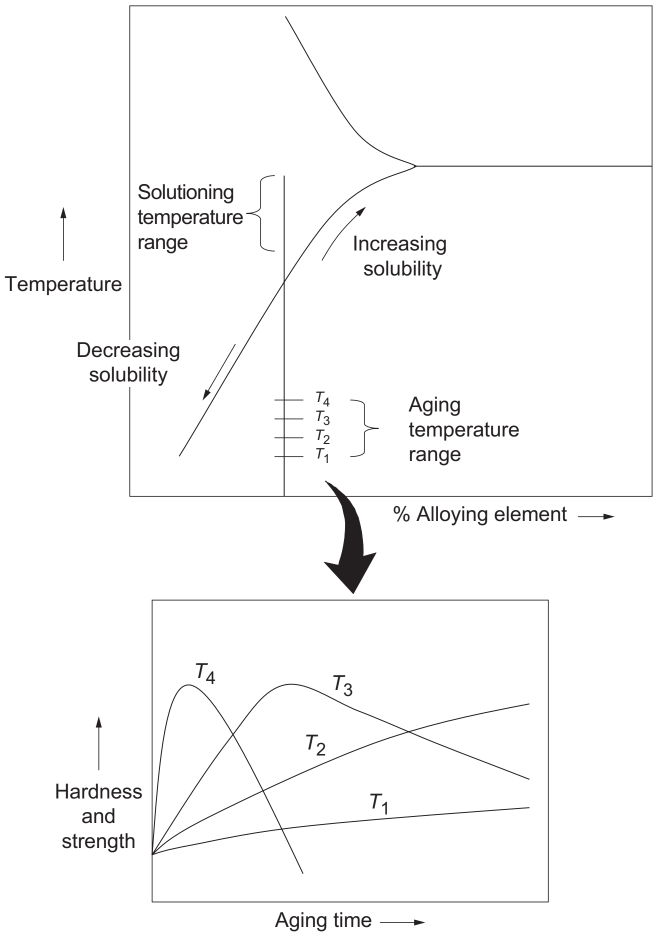


**Fig. 3 Typical precipitation hardening heat treatment. Source: Ref 1**

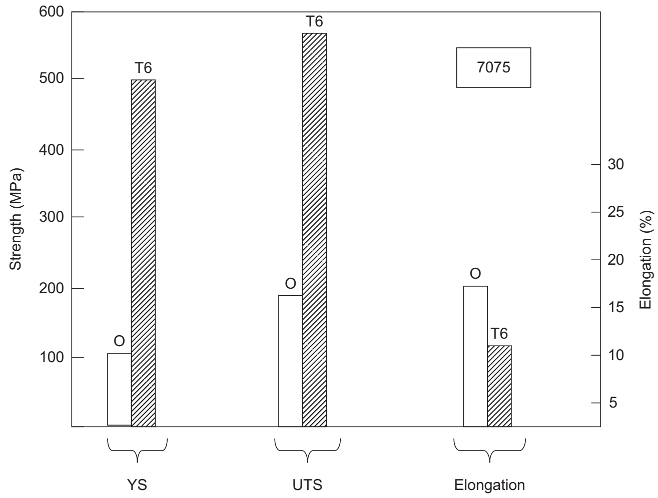


**Fig. 4 Effects of heat treatment on 7075 aluminum alloy. Source: Ref 1**

is quenched to a lower temperature (e.g., room temperature) to keep the alloying elements trapped in solution. During aging, the alloying elements trapped in solution precipitate to form a uniform distribution of very fine particles. Some aluminum alloys will harden after a few days at room temperature—a process called natural aging—while others are artificially aged by heating to an intermediate temperature. If this alloy is aged at room temperature, it is designated as being in the T4 condition (solution heat treated and naturally aged), while if it is aged by reheating to an intermediate temperature, it is designated as T6 (solution heat treated and artificially aged). Cold working during heat treating will improve the properties of certain alloys and includes the T3 condition (solution heat treated, cold worked, and then naturally aged), the T8 condition (solution heat treated, cold worked, and then artificially aged), and the T9 condition (solution heat treated, artificially aged, and then cold worked). The T7 condition (solution heat treated and overaged), in which the alloy is intentionally aged past its peak strength by aging at a higher temperature, is used with some high-strength alloys to improve fracture toughness and corrosion resistance. As an example of the aforementioned designations, the designation 2024-T3 would indicate that alloy 24 (which defines the specific chemistry) belongs to the 2*xxx* series of wrought alloys and is strengthened by solution heating, cold working, and then naturally aging.

**Forming.** Both cold and hot extrusion methods are used to produce extruded aluminum shapes. Cold or impact extrusions are made by a single sharp blow of a punch into a die cavity that contains a blank or slug of the correct size and shape. Almost all aluminum alloys can be formed by impact extrusion. The slugs are annealed and then generally impact extruded at room temperature. Direct hot extrusion is used to make structural shapes. In the direct extrusion process, the cylindrical ingot is preheated and then extruded in the temperature range of 343 to 510 °C (650 to 950 °F), depending on the specific alloy. The preheated ingot is placed in a hydraulic press and squeezed at high pressure through a steel die to produce the desired shape. The 6*xxx* series of alloys, because of their easy extrudability, are the most popular alloys for producing shapes. Aluminum alloys are forged using hammers, mechanical presses, and hydraulic presses. Forging is conducted in the range of 360 to 471 °C (680 to 880 °F), depending on the specific alloy.

As a result of their fcc crystalline structure and their relatively low rates of work hardening, aluminum alloys are readily formable at room temperature. During cold working, the number of dislocations in the matrix dramatically increase, which act as barriers to slip. Thus, cold working increases the strength while reducing the ductility (Fig. 5). Cold-worked aluminum is designated by various grades of the H temper, with higher second digits indicating increasing amounts of cold work (for example, the H1 temper is stronger and harder than the H2 temper). The choice of temper

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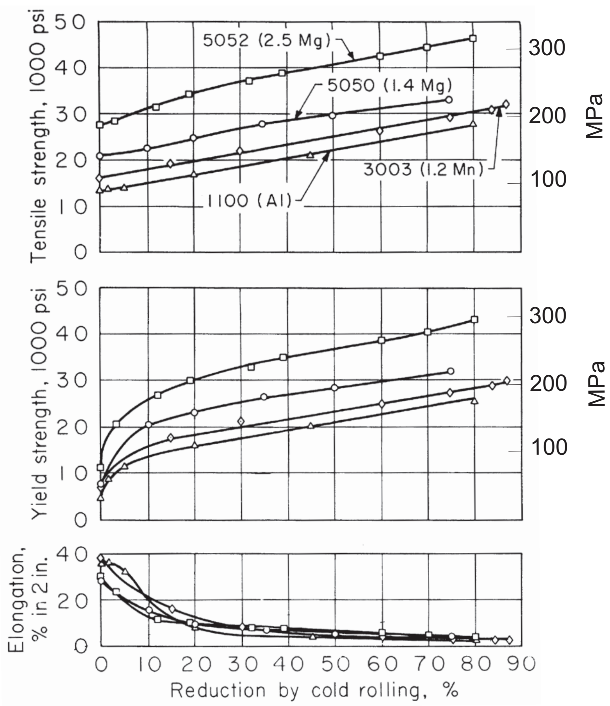


**Fig. 5 Work-hardening curves for wrought non-heat-treatable aluminum alloys. Source: Ref 1**

for forming depends on the severity of the forming operation and the alloy being formed. Aluminum alloys can be readily formed at room temperature in either the annealed (O condition) or the solution heat treated condition (W temper). For alloys formed in the W temper, it is normal practice to refrigerate the solution heat treated material to prevent natural aging before forming.

Aluminum castings can offer significant cost-savings by reducing the number of components and the associated assembly cost. Three types of casting processes are used extensively for aluminum alloys: sand casting for small numbers of large pieces, permanent mold casting for small and medium part sizes, and die castings for small parts where a large quantity can justify the cost of the die casting tooling. The 3*xx.x* alloys are the workhorses of the aluminum casting industry, accounting for more than 95% of all die castings and 80% of all sand and permanent mold castings produced. The 3*xx.x* alloys contain appreciable amounts of silicon, which is by far the most important alloying element in aluminum casting alloys. Silicon greatly improves the fluidity of molten aluminum, especially when the amount approaches the eutectic. Silicon increases fluidity, reduces cracking, and improves feeding to minimize shrinkage porosity. The order of the alloy series in decreasing castability is 3*xx.x*, 4*xx.x*, 5*xx.x*, 2*xx.x*, and 7*xx.x*.

**Fabrication.** Aluminum alloys are extremely easy to machine. Cutting speeds as high as 305 m/min (1000 ft/min) are common. The implementation of high-speed machining during the 1990s allowed even higher metal-removal rates; three times greater metal-removal rates are typical.

As a metal class, aluminum alloys are rather difficult to weld but can be welded by gas metal arc welding, gas tungsten arc welding, and resistance welding. The 2*xxx* and copper-containing 7*xxx* alloys are either very difficult to weld or unweldable by conventional arc welding methods. However, a relative new process called friction stir welding, which is a solid-state welding process (the weld joint never becomes a liquid), is capable of welding even the most difficult of the aluminum alloys.

**Finishing.** The naturally forming alumina ($Al_2O_3$) coating is thin (0.005 to 0.015 mm, or 0.0002 to 0.0006 in., thick) and a poor base for paint. Two types of coatings, chemical conversion coatings and anodizing, are used to form a more uniform and thicker oxide for enhanced corrosion protection. Chemical conversion coatings produce a porous and absorptive oxide (0.051 to 0.076 mm, or 0.002 to 0.003 in., thick) that is very uniform and morphologically tailored to bond well with paint primers. The oxides are chromate or phosphate based, which further aids in corrosion protection.

To further enhance corrosion resistance, finished parts are frequently anodized before being placed in service, to increase the thickness of the $Al_2O_3$ layer on the surface. Anodizing is an electrolytic process that produces thicker (0.051 to 0.13 mm, or 0.002 to 0.005 in.) and more durable oxides than those produced by conversion coatings; therefore, it provides better corrosion resistance. Both sulfuric and chromic acid baths are used along with an electrical current to deposit a porous oxide layer on the surfaces.

## Properties

Among the most striking characteristics of aluminum is its versatility. More than 300 alloy compositions are commonly recognized, and many additional variations have been developed internationally and in supplier/consumer relationships. The properties of aluminum that make this metal and its alloys the most economical and attractive for a wide variety of uses are appearance, light weight, fabricability, physical properties, mechanical properties, and corrosion resistance.

Aluminum can display excellent corrosion resistance in most environments, including atmosphere, water (including salt water), petrochemicals, and many chemical systems. Some of the wrought high-strength alloys that are prone to corrosion can be supplied as Alclad, in which thin layers of a corrosion-resistant aluminum alloy are diffusion bonded to both surfaces of the alloy during the hot rolling operations at the mill.

Aluminum surfaces can be highly reflective. Radiant energy, visible light, radiant heat, and electromagnetic waves are efficiently reflected, while anodized and dark anodized surfaces can be reflective or absorbent. The reflectance of polished aluminum,

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over a broad range of wavelengths, leads to its selection for a variety of decorative and functional uses.

Aluminum is nonferromagnetic, a property of importance in the electrical and electronics industries. It is nonpyrophoric, which is important in applications involving inflammable or explosive materials handling or exposure. Aluminum is also nontoxic and is routinely used in containers for foods and beverages. It has an attractive appearance in its natural finish, which can be soft and lustrous or bright and shiny. It can be virtually any color or texture.

**Thermal and Electrical Properties.** Aluminum typically displays excellent electrical and thermal conductivity, but specific alloys have been developed with high degrees of electrical resistivity. These alloys are useful, for example, in high-torque electric motors. Aluminum is often selected for its electrical conductivity, which is nearly twice that of copper on an equivalent weight basis. The requirements of high conductivity and mechanical strength can be met by use of long-line, high-voltage, aluminum steel-cored reinforced transmission cable. The thermal conductivity of aluminum alloys, approximately 50 to 60% that of copper, is advantageous in heat exchangers, evaporators, electrically heated appliances and utensils, and automotive cylinder heads and radiators.

**Mechanical Properties.** Some aluminum alloys exceed structural steel in strength. However, pure aluminum and certain aluminum alloys are noted for extremely low strength and hardness. The tensile yield strength of superpurity aluminum in its softest annealed state is approximately 10 MPa (1.5 ksi), whereas that of some heat treated commercial high-strength alloys exceeds 550 MPa (80 ksi). Higher strengths, up to a yield strength of 690 MPa (100 ksi) and over, may be readily produced, but the fracture toughness of such alloys does not meet levels considered essential for aircraft or other critical-structure applications. The density of aluminum and its alloys is approximately 7 GPa (10 msi), which is lower than titanium (10 GPa, or 15 msi) and steel (21 GPa, or 30 msi) alloys. However, when measured on a stiffness-to-density basis, aluminum alloys are weight-competitive with the heavier titanium and steel alloys. One rather disappointing property of high-strength aluminum alloys is their fatigue performance; the fatigue limit of most high-strength alloys falls within the 137 to 172 MPa (20 to 25 ksi) range.

Work hardening raises the strength of aluminum quite substantially. Commercial-purity aluminum (99.60% pure) has a yield strength of 27 MPa (3.9 ksi) when fully annealed, but if cold worked by swaging or rolling to 75% reduction in area, the yield strength increases to 125 MPa (18 ksi).

As with most metals with the fcc crystalline structure, there is no ductile-to-brittle transition; aluminum remains ductile at cryogenic temperatures, with tensile elongation actually increasing somewhat below −200 °C (−328 °F). Although aluminum alloys can achieve high strength at room temperature, tensile and creep strength decline sharply above 200 °C (392 °F).

## Applications

Aluminum is a consumer metal of great importance. Aluminum and its alloys are used for foil, beverage cans, cooking and food processing utensils, architectural and electrical applications, and structures for boats, aircraft, and other transportation vehicles. Alloy 3004, which is used for beverage cans, has the highest single usage of any aluminum alloy, accounting for approximately ¼ of the total usage of aluminum.

As a result of a naturally occurring tenacious surface oxide film ($Al_2O_3$), a great number of aluminum alloys provide exceptional resistance to corrosion in many atmospheric and chemical environments. Its corrosion and oxidation resistance is especially important in architectural and transportation applications. With a yield strength comparable to that of mild steel, 6061 is one of the most widely used of all aluminum alloys for general construction.

The 5*xxx* alloys are used extensively in the transportation industries for boat and ship hulls; dump truck bodies; large tanks for carrying gasoline, milk, and grain; and pressure vessels, especially where cryogenic storage is required. The weldability of these alloys is excellent, and they have excellent corrosion resistance.

On an equal weight and cost basis, aluminum is a better conductor than copper. Its high thermal conductivity leads to applications such as radiators and cooking utensils. Its low density is important for hand tools and all forms of transportation, especially aircraft.

The high-strength 2*xxx* and 7*xxx* alloys are competitive on a strength-to-weight ratio with the higher-strength but heavier titanium and steel alloys and thus have traditionally been the dominant structural material in both commercial and military aircraft. In addition, aluminum alloys are not embrittled at low temperatures and become even stronger as the temperature is decreased without significant ductility losses, making them ideal for cryogenic fuel tanks for rockets and launch vehicles. Aluminum-lithium alloys are attractive for aerospace applications because the addition of lithium increases the modulus of aluminum and reduces the density (each 1 wt% of lithium increases the modulus by approximately 6% while decreasing the density approximately 3%).

## REFERENCE

1. F.C. Campbell, Ed., Elements of Metallurgy and Engineering Alloys, ASM International, 2008

## SELECTED REFERENCES

- *Heat Treating,* Vol 4, *ASM Handbook,* ASM International, 1991
- *Metals Handbook Desk Edition,* 2nd ed., ASM International, 1998
- *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* ASM International, 1990