Antimony is present in trace amounts (0.01 to 0.1 ppm) primary in commercial-grade aluminum. Antimony has a very small solid solubility in aluminum (<0.01%). Some bearing alloys contain up to 4 to 6% Sb. Antimony can be used instead of bismuth to counteract hot cracking in aluminum-magnesium alloys.

Arsenic. The compound AsAl is a semiconductor. Arsenic is very toxic (as AsO3) and must be controlled to very low limits where aluminum is used as foil for food packaging.

Beryllium is used in aluminum alloys containing magnesium to reduce oxidation at elevated temperatures. Up to 0.1% Be is used in aluminizing baths for steel to improve adhesion of the aluminum film and restrict the formation of the deleterious iron-aluminum complex.

Bismuth. The low-melting-point metals such as bismuth, lead, tin, and cadmium are added to aluminum to make free-machining alloys. These elements have a restricted solubility in solid aluminum and form a soft, low-melting phase that promotes chip
breaking and helps to lubricate the cutting tool. An advantage of bismuth is that its expansion on solidification compensates for the shrinkage of lead. A 1-to-1 lead-bismuth ratio is used in the aluminum-copper alloy, 2011, and in the aluminum-Mg-Si alloy, 6262. Small additions of bismuth (20 to 200 ppm) can be added to aluminum-magnesium alloys to counteract the detrimental effect of sodium on hot cracking.

**Boron** is used in aluminum and its alloys as a grain refiner and to improve conductivity by precipitating vanadium, titanium, chromium, and molybdenum. Boron can be used alone (at levels of 0.005 to 0.1%) as a grain refiner during solidification, but becomes more effective when used with an excess of titanium. Commercial grain refiners commonly contain titanium and boron in a 5-to-1 ratio.

**Cadmium** is a relatively low-melting element that finds limited use in aluminum. Up to 0.3% Cd may be added to aluminum-copper alloys to accelerate the rate of age hardening, increase strength, and increase corrosion resistance. At levels of 0.005 to 0.5%, it has been used to reduce the time of aging of aluminum-zinc-magnesium alloys.

**Calcium** has very low solubility in aluminum and forms the intermetallic CaAl<sub>4</sub>. An interesting group of alloys containing about 5% Ca and 5% Zn have superplastic properties. Calcium combines with silicon to form CaSi<sub>2</sub>, which is almost insoluble in aluminum and therefore will increase the conductivity of commercial-grade metal slightly. In aluminum-magnesium-silicon alloys, calcium will decrease age hardening. Its effect on aluminum-silicon alloys is to increase strength and decrease elongation, but it does not make these alloys heat treatable.

**Carbon** may occur infrequently as an addition in aluminum in the form of oxycarbides and carbides, of which the most common is A14C3, but carbide formation with other impurities such as titanium is possible. A14C3 decomposes in the presence of water and water vapor, and this may lead to surface pitting.

**Cerium**, mostly in the form of mischmetal (rare earths with 50 to 60% Ce), has been added experimentally to casting alloys to increase fluidity and reduce die sticking.

**Chromium** occurs as a minor impurity in commercial-purity aluminum (5 to 50 ppm). It has a large effect on electrical resistivity. Chromium is a common addition to many alloys of the aluminum-magnesium, aluminum-magnesium-silicon, and aluminum-magnesium-zinc groups, in which it is added in amounts generally not exceeding 0.35%. In excess of these limits, it tends to form very coarse constituents with other impurities or additions such as manganese, iron, and titanium. Chromium has a slow diffusion rate and forms fine dispersed phases in wrought products. These dispersed phases inhibit nucleation and grain growth. Chromium is used 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 hot working or heat treatment.

**Cobalt** is not a common addition to aluminum alloys. It has been added to some aluminum-silicon alloys containing iron, where it transforms the acicular β (aluminum-iron-silicon) into a more rounded aluminum-cobalt-iron phase, thus improving strength and elongation. Aluminum-zinc-magnesium-copper alloys containing 0.2 to 1.9% Co are produced by powder metallurgy.

**Copper.** Aluminum-copper alloys containing 2 to 10% Cu, generally with other additions, form important families of alloys. Both cast and wrought aluminum-copper alloys respond to solution heat treatment and subsequent aging with an increase in strength and hardness and a decrease in elongation. The strengthening is maximum between 4 and 6% Cu, depending upon the influence of other constituents present.

**Copper-magnesium.** The main benefit of adding magnesium to aluminum-copper quenching, in wrought material of certain alloys of this type, an increase in strength accompanied by high ductility occurs on aging at room temperature. On artificial aging, a further increase in strength, especially in yield strength can be obtained, but at a substantial sacrifice in tensile elongation.

**Copper-magnesium plus other elements.** The cast aluminum-copper-magnesium alloys containing iron are characterized by dimensional stability and improved bearing characteristics, as well as by high strength and hardness at elevated temperatures. However, in a wrought Al-4%Cu-0.5%Mg alloy, iron in concentrations as low as 0.5% lowers the tensile properties in the heat-treated condition, if the silicon content is less than that required to tie up the iron as the aFeSi constituent.

**Gallium** is an addition in aluminum and is usually present at levels of 0.001 to 0.02%. At these levels its effect on mechanical properties is quite small. At the 0.2% level, gallium has been found to affect the corrosion characteristics and the response to etching and brightening of some alloys.

**Hydrogen** has a higher solubility in the liquid state at the melting point than in the solid at the same temperature. Because of this, gas porosity can form during solidification. Hydrogen is produced by the reduction of water vapor in the atmosphere by aluminum and by the decomposition of hydrocarbons. In addition to causing primary porosity in casting, hydrogen causes secondary porosity, blistering, and high-temperature deterioration (advanced internal gas precipitation) during heat treating. It probably plays a role in grain-boundary decohesion during stress-corrosion cracking. Its level in melts is controlled by fluxing with hydrogen-free gases or by vacuum degassing.

**Indium.** Small amounts (0.05 to 0.2%) of indium have a marked influence on the age hardening of aluminum-copper alloys, particularly at low copper contents (2 to 3% Cu).

**Iron** is the most common addition found in aluminum. It has a high solubility in molten aluminum and is therefore easily dissolved at all molten stages of production. The solubility of iron in the solid state is very low (−0.04%) and therefore, most of the
iron present in aluminum over this amount appears as an intermetallic second phase in combination with aluminum and often other elements.

**Lead.** Normally present only as a trace element in commercial-purity aluminum, lead is added at about the 0.5% level with the same amount as bismuth in some alloys (2011 and 6262) to improve machinability.

**Lithium.** The impurity level of lithium is of the order of a few ppm, but at a level of less than 5 ppm it can promote the discoloration (blue corrosion) of aluminum foil under humid conditions. Traces of lithium greatly increase the oxidation rate of molten aluminum and alter the surface characteristics of wrought products.

**Magnesium** is the major alloying element in the 5xxx series of alloys. Its maximum solid solubility in aluminum is 17.4%, but the magnesium content in current wrought alloys does not exceed 5.5%. The addition of magnesium markedly increases the strength of aluminum without unduly decreasing the ductility. Corrosion resistance and

**Magnesium-Manganese.** In wrought alloys, this system has high strength in the work-hardened condition, high resistance to corrosion, and good welding characteristics. Increasing amounts of either magnesium or manganese intensify the difficulty of fabrication and increase the tendency toward cracking during hot rolling, particularly if traces of sodium are present.

**Magnesium-Silicon.** Wrought alloys of the 6xxx group contain up to 1.5% each of magnesium and silicon in the approximate ratio to form Mg2Si, that is, 1.73:1. The maximum solubility of Mg2Si is 1.85%, and this decreases with temperature. Precipitation upon age hardening occurs by formation of Guinier-Preston zones and a very fine precipitate. Both confer an increase in strength to these alloys, though not as great as in the case of the 2xxx or the 7xxx alloys.

**Manganese** is a common addition in primary aluminum, in which its concentration normally ranges from 5 to 50 ppm. It decreases resistivity. Manganese increases strength either in solid solution or as a finely precipitated intermetallic phase. It has no adverse effect on corrosion resistance. Manganese has a very limited solid solubility in aluminum in the presence of normal impurities but remains in solution when chill cast so that most of the manganese added is substantially retained in solution, even in large ingots.

**Mercury** has been used at the level of 0.05% in sacrificial anodes used to protect steel structures. Other than for this use, mercury in aluminum or in contact with it as a metal or a salt will cause rapid corrosion of most aluminum alloys.

**Molybdenum** is a very low level (0.1 to 1.0 ppm) impurity in aluminum. It has been used at a concentration of 0.3% as a grain refiner, because the aluminum end of the equilibrium diagram is peritectic, and also as a modifier for the iron constituents, but it is not in current use for these purposes.
Nickel. The solid solubility of nickel in aluminum does not exceed 0.04%. Over this amount, it is present as an insoluble intermetallic, usually in combination with iron. Nickel (up to 2%) increases the strength of high-purity aluminum but reduces ductility. Binary aluminum-nickel alloys are no longer in use but nickel is added to aluminum-copper and to aluminum-silicon alloys to improve hardness and strength at elevated temperatures and to reduce the coefficient of expansion.

Niobium. As with other elements forming a peritectic reaction, niobium would be expected to have a grain refining effect on casting. It has been used for this purpose, but the effect is not marked.

Phosphorus is a minor impurity (1 to 10 ppm) in commercial-grade aluminum. Its solubility in molten aluminum is very low (~0.01% at 660°C) and considerably smaller in the solid.

Silicon, after iron, is the highest addition level in electrolytic commercial aluminum to produce Mg2Si in the 6xxx series of heat-treatable alloys.

Vanadium. There is usually 10 to 200 ppm V in commercial-grade aluminum, and because it lowers conductivity, it generally is precipitated from electrical conductor alloys with boron.

Zinc. The aluminum-zinc alloys have been known for many years, but hot cracking of the casting alloys and the susceptibility to stress-corrosion cracking of the wrought alloys curtailed their use. Aluminum-zinc alloys containing other elements offer the highest combination of tensile properties in wrought aluminum alloys.

Zinc-Magnesium. The addition of magnesium to the aluminum-zinc alloys develops the strength potential of this alloy system, especially in the range of 3 to 7.5% Zn. Magnesium and zinc form MgZn2, which produces a far greater response to heat treatment than occurs in the binary aluminum-zinc system. The strength of the wrought aluminum-zinc alloys also is substantially improved by the addition of magnesium. Increasing the MgZn2 concentration from 0.5 to 12% in cold-water quenched 1.6 mm sheet continuously increases the tensile and yield strengths. The addition of magnesium in excess (100 and 200%) of that required to form MgZn2 further increases tensile strength.

Zinc-Magnesium-Copper. The addition of copper to the aluminum-zinc-magnesium system, together with small but important amounts of chromium and manganese, results in the highest-strength aluminum-base alloys commercially available. In this alloy system, zinc and magnesium control the aging process. The effect of copper is to increase the aging rate by increasing the degree of supersaturation and perhaps through nucleation of the CuMgAl2 phase. Copper also increases quench sensitivity upon heat treatment. In general, copper reduces the resistance to general corrosion of aluminum-zinc-magnesium alloys, but increases the resistance to stress corrosion. The minor alloy additions, such as chromium and zirconium, have a marked effect on mechanical properties and corrosion resistance.
Zirconium additions in the range 0.1 to 0.3% are used to form a fine intermetallic precipitate that inhibits recovery and recrystallization. An increasing number of alloys, particularly in the aluminum-zinc-magnesium family, use zirconium additions to increase the recrystallization temperature and to control the grain structure in wrought products.