Aluminium Alloys

Aluminium is the third most plentiful element on earth (next to oxygen and silicon), but, until the late 1800s, was expensive and difficult to produce.

General Properties and Uses of Aluminium: Aluminium has a density of (**2.70 g/cm3**), or one-third the density of steel, and a modulus of elasticity of **(10 ×10^6 psi)**. Although aluminium alloys have lower tensile properties compared with those of steel, their specific strength (or strength-to-weight ratio) is excellent. The Wright brothers used an Al-Cu alloy for their engine for this very reason. Aluminium can be formed easily, it has high thermal and electrical conductivity, and does not show a ductile-to-brittle transition at low temperatures. It is nontoxic and can be recycled with only about 5% of the energy that was needed to make it from alumina (Al_2O_3). This is why the recycling of aluminium is so successful. **Aluminum's' beneficial physical properties** include nonmagnetic behavior and its resistance to oxidation and corrosion. However, aluminium does not display a true endurance limit, so failure by fatigue eventually may occur, even at low stresses. Because of its low-melting temperature, aluminium does not perform well at elevated temperatures. Finally, Aluminium alloys have low hardness, leading to poor wear resistance. Aluminium responds readily to strengthening mechanisms. Table 1 compares the strength of pure annealed aluminium with that of alloys strengthened by various techniques. The alloys may be 30 times stronger than pure aluminium.

Table.1 The effect of strengthening mechanisms in aluminium and aluminium alloys.

Material	Tensile Strength (psi)	Yield Strength (psi)	% Elongation	Ratio of Alloy-to-Metal Yield Strengths
Pure Al	6,500	2,500	60	1
Commercially pure Al (at least 99% pure)	13,000	5,000	45	2.0
Solid-solution-strengthened Al alloy	16,000	6,000	35	2.4
Cold-worked Al	24,000	22,000	15	8.8
Dispersion-strengthened Al alloy	42,000	22,000	35	8.8
Age-hardened Al alloy	83,000	73,000	11	29.2

About 25% of the aluminium produced today is used in the transportation industry, another 25% is used for the manufacture of beverage cans and other packaging, about 15% is used in construction, 15% in electrical applications, and 20% in other applications. Aluminum reacts with oxygen, even at room temperature, to produce an extremely (very) thin aluminium-oxide layer that protects the underlying metal from many corrosive environments. We should be careful, though, not to generalize this behavior. For example, aluminium powder (because it has a high surface area), when present in the form of an oxidizer, such as ammonium perchlorate and iron oxide as catalysts, serves as the fuel for solid rocket boosters (SRBs). These boosters use ~200,000 lbs. of atomized aluminium powder every time the space shuttle takes off and can generate enough force for the shuttle to reach a speed of ~3000 miles per hour. New developments related to aluminium include the development of aluminium alloys containing higher Mg concentrations for use in making automobiles.

Designation: Aluminium alloys can be divided into two major groups: **wrought** and **casting alloys**, depending on their method of fabrication. Wrought alloys, which are shaped by plastic deformation, have compositions and microstructures significantly different from casting alloys, reflecting the different requirements of the manufacturing process. Within each major group we can divide the alloys into two subgroups: **heat-treatable** and **non-heat treatable alloys**. Aluminum alloys are designated by the numbering system shown in figure 1. The first number specifies the principle alloying elements, and the remaining numbers refer to the specific composition of the alloy.

Aluminium Alloy Designation System (CEN)

		Major alloying element	Atoms in solution	Work hardening	Precipitation hardening	
WROUGHT ALLOYS*) EN AW-	1XXX	None (min. 99.00% Al)		X		Non-heat treatable alloys
	3XXX	Mn	X	X		
	4XXX	Si	X	X		
	5XXX	Mg	X	X		
	2XXX	Cu	X	(X)	X	Heat treatable alloys
	6XXX	Mg + Si	X	(X)	X	
	7XXX	Zn	X	(X)	X	
	8XXX	Other	X	(X)	X	

CASTING ALLOYS*) EN AB- EN AC- EN AM-		
	1XXX0	None (min. 99.00% Al)
	2XXX0	Cu
	4XXX0	Si
	5XXX0	Mg
	7XXX0	Zn
	8XXX0	Sn
	9XXX0	Master Alloys

*) letters preceding the alloy numbers have the following meaning
EN = European Standard
A = Aluminium
B = Ingot
C = Cast Alloy
M = Master Alloy
W = Wrought Alloy

Sources: according to EN 573; prEN 1780

Figure 1. Aluminium Alloy Designations.

The degree of strengthening is given by the **temper designation T** or **H**, depending on whether the alloy is heat-treated or strain-hardened (Table 3). Other designations indicate whether the alloy is annealed (O), solution-treated (W), or used in the as-fabricated condition (F). The numbers following the **T** or **H** indicate the amount of strain hardening, the exact type of heat treatment, or other special aspects of the processing of the alloy.

Wrought Alloys The **1xxx**, **3xxx**, **5xxx**, and most of the **4xxx** wrought alloys are not age-hardenable. The **1xxx** and **3xxx** alloys are single-phase alloys except for the presence of small amounts of inclusions or intermetallic compounds. Their properties are controlled by strain hardening, solid-solution strengthening, and grainsize control. However, because the solubilities of the alloying elements in aluminium are small at room temperature, the degree of solid-solution strengthening is limited. The 5xxx alloys contain two phases at room temperature (α, a solid solution of magnesium in aluminium, and $\mathbf{Mg_2Al_3}$, a hard, brittle intermetallic compound) as shown in figure 2. The Aluminium-Magnesium (**Al-Mg**) alloys are strengthened by a fine dispersion of Mg_2Al_3, as well as by strain hardening, solid-solution strengthening, and grain-size control. However, because $\mathbf{Mg_2Al_3}$ is not coherent, age-hardening treatments are not possible. The 4xxx series alloys also contain two phases (**α** and nearly pure silicon, **β**). Alloys that contain both silicon and magnesium can be age hardened by permitting $\mathbf{Mg_2Si}$ to precipitate. The 2xxx, 6xxx, and 7xxx alloys are age-hardenable alloys. Although excellent specific strengths are obtained for these alloys, the amount of precipitate that can form is limited. In addition, they cannot be used at temperatures above approximately **(175°C)** in the aged condition. The most widely used aircraft aluminium alloy is 2024. There is also an interest in the development of precipitation hardened (**Al-Li**) alloys due to their high Young′s modulus and low density. However, high-processing costs, anisotropic properties, and lower fracture toughness have proved to be limiting factors. Al-Li alloys are used to make space shuttle fuel tanks.

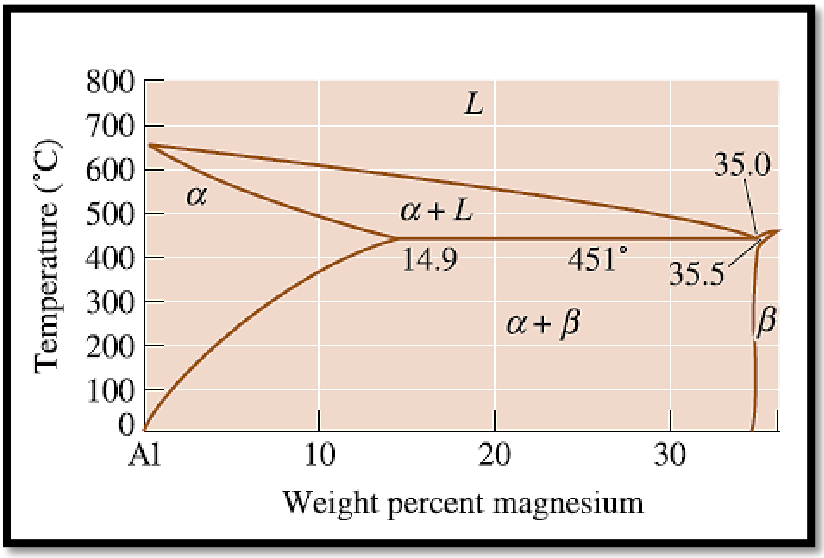

Figure 2. Portion of the Aluminum-Magnesium phase diagram.

Table 3. Temper designations for Aluminium alloys.

F	As-fabricated (hot-worked, forged, cast, etc.)
O	Annealed (in the softest possible condition)
H	Cold-worked
	H1x—cold-worked only. (x refers to the amount of cold work and strengthening.)
	H12—cold work that gives a tensile strength midway between the O and H14 tempers.
	H14—cold work that gives a tensile strength midway between the O and H18 tempers.
	H16—cold work that gives a tensile strength midway between the H14 and H18 tempers.
	H18—cold work that gives about 75% reduction.
	H19—cold work that gives a tensile strength greater than 2000 psi of that obtained by the H18 temper.
	H2x—cold-worked and partly annealed.
	H3x—cold-worked and stabilized at a low temperature to prevent age hardening of the structure.
W	Solution-treated
T	Age-hardened
	T1—cooled from the fabrication temperature and naturally aged.
	T2—cooled from the fabrication temperature, cold-worked, and naturally aged.
	T3—solution-treated, cold-worked, and naturally aged.
	T4—solution-treated and naturally aged.
	T5—cooled from the fabrication temperature and artificially aged.
	T6—solution-treated and artificially aged.
	T7—solution-treated and stabilized by overaging.
	T8—solution-treated, cold-worked, and artificially aged.
	T9—solution-treated, artificially aged, and cold-worked.
	T10—cooled from the fabrication temperature, cold-worked, and artificially aged.

Casting Alloys: Many of the common aluminium casting alloys contain enough silicon to cause the eutectic reaction, giving the alloys low melting points, good fluidity, and good castability. **Fluidity** is the ability of the liquid metal to low through a mold without prematurely solidifying, and **castability** refers to the ease with which a good casting can be made from the alloy.

The properties of the aluminum-silicon (Al-Si) alloys are controlled by solid-solution strengthening of an aluminum matrix, dispersion strengthening by the β phase, and solidification, which controls the primary grain size and shape as well as the nature of the eutectic micro-constituent. Fast cooling obtained in die casting or permanent mold casting increases strength by refining grain size and the eutectic micro-constituent. Grain refinement using **Boron** and **Titanium** additions, modification using **Sodium** or **Strontium** to change the eutectic structure, and hardening with **Phosphorus** to refine the primary silicon are all done in certain alloys to improve the microstructure and, thus, the degree of dispersion strengthening. Many alloys also contain copper, magnesium, or zinc, thus permitting age hardening.

EXAMPLE.1

A steel cable (**0.5 in**). in diameter has a yield strength of (**70,000 psi**). The density of steel is about (**7.87 g/cm^3**). Determine (a) the maximum load that the steel cable can support, (b) the diameter of a cold worked aluminium-manganese alloy (3004-H 18, yield strength= 36,000 psi) required to support the same load as the steel, and (c) the weight per foot of the steel cable versus the aluminium alloy cable.

SOLUTION

a. $\text{Load} = F = (\sigma_y \times A) = 70{,}000\left(\frac{\pi}{4}\right)(0.5 \text{ in.})^2 = 13{,}744 \text{ lb}$

b. The yield strength of the aluminum alloy is 36,000 psi. Thus:

$$A = \frac{\pi}{4}d^2 = \frac{F}{\sigma_y} = \frac{13{,}744}{36{,}000} = 0.38 \text{ in.}^2$$

$$\therefore d = 0.697 \text{ in.}$$

c. $\text{Density of steel} = \rho = 7.87 \text{ g/cm}^3 = 0.284 \text{ lb/in.}^3$

$\text{Density of aluminum} = \rho = 2.70 \text{ g/cm}^3 = 0.097 \text{ lb/in.}^3$

$\text{Weight of steel} = Al\rho = \frac{\pi}{4}(0.5 \text{ in.})^2(12)(0.284) = 0.669 \text{ lb/ft}$

$\text{Weight of aluminum} = Al\rho = \frac{\pi}{4}(0.697)^2(12)(0.097) = 0.444 \text{ lb/ft}$

Although the yield strength of the aluminum alloy is lower than that of the steel and the cable must be larger in diameter, the aluminum alloy cable weighs only about half as much as the steel cable. When comparing materials, a proper factor-of-safety should also be included during design.

Copper Alloys

Copper occurs in nature as sulfides and also as elemental copper. Copper is typically produced by a pyro-metallurgical (high-temperature) process. The copper ore containing high-sulfur contents is concentrated, then converted into a molten immiscible liquid containing copper sulfide-iron sulfide and is known as a copper matte. This is done in a flash smelter. In a separate reactor, known as a copper converter, oxygen introduced to the matte, converts the iron sulfide to iron oxide and the copper sulfide to an impure copper called blister copper, which is then purified electrolytically. Other methods for copper extraction include leaching copper from low-sulfur ores with an acid, then electrolytically extracting the copper from the solution.

Copper-based alloys have higher densities than that for steels. Although the yield strength of some alloys is high, their specific strength is typically less than that of aluminium or magnesium alloys. These alloys have better resistance to fatigue, creep, and wear than the lightweight aluminum and magnesium alloys. Many of these alloys have excellent ductility, corrosion resistance, electrical and thermal conductivity, and most can easily be joined or fabricated into useful shapes. **Applications for copper-based alloys** include electrical components (such as wire), pumps, valves, and plumbing parts, where these properties are used to advantage.

Copper alloys are also unusual in that they may be selected to produce an appropriate decorative color. Pure copper is red; zinc additions produce a yellow color, and nickel produces a silver color. Copper can corrode easily; forming a basic copper sulfate ($CuSO_4.3Cu(OH)_2$). This is a green compound that is insoluble in water (but soluble in acids). This green patina provides an attractive finish for many applications. The statue of Liberty is green because of the green patina of the oxidized copper skin that covers the steel structure.

Table 1. Properties of typical copper alloys obtained by different strengthening mechanisms.

Material	Tensile Strength (psi)	Yield Strength (psi)	% Elongation	Strengthening Mechanism
Pure Cu, annealed	30,300	4,800	60	None
Commercially pure Cu, annealed to coarse grain size	32,000	10,000	55	Solid solution
Commercially pure Cu, annealed to fine grain size	34,000	11,000	55	Grain size
Commercially pure Cu, cold-worked 70%	57,000	53,000	4	Strain hardening
Annealed Cu-35% Zn	47,000	15,000	62	Solid solution
Annealed Cu-10% Sn	66,000	28,000	68	Solid solution
Cold-worked Cu-35% Zn	98,000	63,000	3	Solid solution + strain hardening
Age-hardened Cu-2% Be	190,000	175,000	4	Age hardening
Quenched and tempered Cu-Al	110,000	60,000	5	Martensitic reaction
Cast manganese bronze	71,000	28,000	30	Eutectoid reaction

The wide variety of copper-based alloys take advantage of all of the strengthening mechanisms that we have discussed. The effects of these strengthening mechanisms on the mechanical properties are summarized in Table 1. Copper containing less than **(0.1%)** impurities is used for electrical and microelectronics applications. Small amounts of **Cadmium**, **Silver**, and **Al_2O_3** improve their hardness without significantly impairing conductivity. The single-phase copper alloys are strengthened by cold working. Examples of this effect are shown in Table 1. The FCC structure of copper provides for excellent ductility and a high strain-hardening coefficient.

Solid-Solution-Strengthened Alloys: A number of copper-based alloys contain large quantities of alloying elements, yet remain single phase. Important binary phase diagrams are shown in figure 1. The Copper-Zinc (Cu-Zn), or **Brass**, alloys with less than **40% Zn** form single-phase solid solutions of zinc in copper. The **Mechanical Properties** even elongation increase as the zinc content increases. These alloys can be cold formed into rather complicated yet corrosion-resistant components. **Bronzes** are alloys of copper containing tin (**Cu-Sn**) and can certainly contain other elements. Manganese bronze (**Cu-Mg**) is a particularly high-strength alloy containing manganese as well as zinc for solid-solution strengthening.

Tin bronzes (**Cu-Sn**), often called phosphor bronzes, may contain up to **10% Sn** and remain single phase. The phase diagram predicts that the alloy will contain the **Cu_3Sn** (**ε**) compound. However, the kinetics of the reaction are so slow that the precipitate particles often do not form.

Alloys containing less than about 9% Al or less than 3% Si are also single phase. These aluminum bronzes and silicon bronzes have good forming characteristics and are often selected for their good strength and excellent toughness.

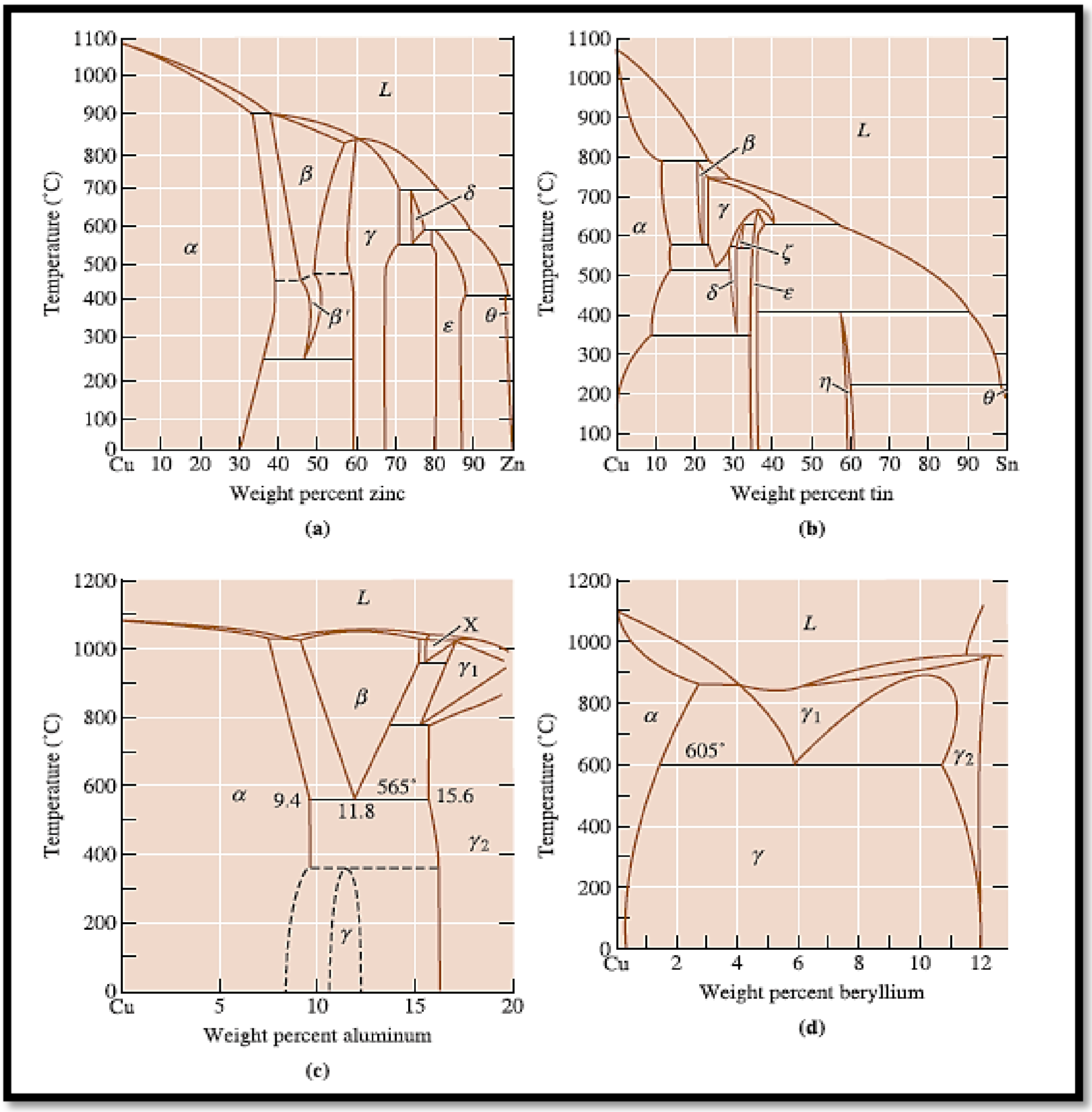

Figure 1. Binary phase diagrams for the (a) Copper-Zinc, (b) Copper-Tin, (c) Copper-Aluminum, and (d) Copper-Beryllium systems.

Age-Hardenable Alloys A number of copper-base alloys display an age-hardening response, including zirconium-copper, chromium-copper, and beryllium-copper. The **Copper-Beryllium alloys** are used for their high strength, their high stiffness (making them useful as springs and fine wires), and their non-sparking qualities (making them useful for tools to be used near flammable gases and liquids).

Phase Transformations Aluminium bronzes that contain over **9% Al** can form b phase on heating above 565°C, the eutectoid temperature. On subsequent cooling, the eutectoid reaction produces a lamellar structure (like pearlite) that contains a brittle **γ2** compound. The low temperature peritectoid reaction, a **γ2**! g, normally does not occur. The eutectoid product is relatively weak and brittle, but we can rapidly quench the b to produce martensite, or b_0, which has high strength and low ductility. When b_0 is subsequently tempered, a combination of high strength, good ductility, and excellent toughness is obtained as fine platelets of a precipitate from the b_0.

Leaded-Copper Alloys Virtually any of the wrought alloys may contain up to 4.5% Pb. The lead forms a monotectic reaction with copper and produces tiny lead spheres as the last liquid to solidify. The lead improves machining characteristics. Use of leaded-copper alloys, however, has a major environmental impact and, consequently, new alloys that are lead free have been developed. The following two examples illustrate the use of copper-based alloys.