CHAPTER 1

Introduction and Uses of Lightweight Materials

DURING THE INDUSTRIAL REVOLUTION of the 18th and 19th centuries, the basic materials of construction were sparse. There was wood, stone, brick and mortar, and iron and steel. However, the irons and steels of that day were vastly inferior to the ones used today. In 1709, Abraham Darby established a coke-fired blast furnace to produce cast iron, and by the end of the 18th century, cast iron began to replace wrought iron, because it was cheaper. The ensuing availability of inexpensive iron was one of the factors leading to the Industrial Revolution. In the late 1850s, Henry Bessemer invented a new steelmaking process, involving blowing air through molten pig iron, to produce mild steel. This made steel much more economical.

With the advent of the 20th century, improved lightweight materials such as aluminum, magnesium, beryllium, titanium, titanium aluminides, engineering plastics, structural ceramics, and composites with polymer, metal, and ceramic matrices began to appear.

Aluminum. Before the Hall-Héroult process was developed in the late 1880s, aluminum was exceedingly difficult to extract from its various ores. This made pure aluminum more valuable than gold. Napoleon III, Emperor of France, is reputed to have given a banquet where the most honored guests were given aluminum utensils, while the others made do with gold. Charles Martin Hall of Ohio in the United States and Paul Héroult of France independently developed the Hall-Héroult electrolytic process that made extracting aluminum from minerals cheaper and is now the principal method used worldwide. In 1888, Hall founded the Pittsburgh Reduction Company, today known as Alcoa.

The next breakthrough in aluminum came in 1901 when Alfred Wilm, while working in a military research center in Germany, accidentally discovered age hardening, in particular age hardening of aluminum alloys.

He made this discovery after hardness measurements on aluminum-copper alloy specimens were found to increase in hardness at room temperature. The increase in hardness was identified after Wilm's measurements were interrupted by a weekend, and when resumed on Monday, the hardness had increased. The economical production of aluminum and the discovery of age hardening allowed the rapid replacement of aluminum for wood and fabric in airplanes.

Magnesium. Magnesium was one of the main aerospace construction materials used for German military aircraft as early as World War I and extensively for German aircraft in World War II. The extraction of magnesium from seawater was pioneered in the United States by Dow. Their magnesium plant became operational in 1941, marking the first time that man had mined the ocean for a metal. After the Japanese attack on Pearl Harbor, the U.S. government asked Dow to increase its magnesium production, so a second plant was constructed. Today, Dow's Texas Operations spreads across more than 5000 acres with more than 75 individual production plants.

Beryllium. The first pure samples of beryllium were produced in 1898. However, it took until World War I (1914 to 1918) before significant amounts of beryllium were produced. Large-scale production started in the early 1930s and rapidly increased during World War II, due to the rising demand for the hard beryllium-copper alloys.

Titanium. The large-scale production and use of titanium was a result of the Cold War. In the 1950s and 1960s, the Soviet Union pioneered titanium use in military and submarine applications. Starting in the early 1950s, titanium began to be used extensively for military aviation purposes, particularly in high-performance jets, the most notable being the Black Bird supersonic spy plane. The Department of Defense realized the strategic importance of the metal and supported early efforts of commercialization. Throughout the Cold War, titanium was considered a strategic material by the U.S. government, and a large stockpile of titanium sponge was maintained by the Defense National Stockpile Center. Today, the world's largest producer, Russian-based VSMPO-Avisma, accounts for an estimated 29% of the world market share.

Engineering Plastics. The first plastic based on a synthetic polymer was phenolic, made from phenol and formaldehyde. In 1907, Leo Baekeland was trying to develop an insulating shellac to coat wires in electric motors and generators. He found that mixtures of phenol and formaldehyde formed a sticky mass when mixed together, and when heated, the mass became an extremely hard solid. After World War I, improvements in chemical technology led to an explosion in new forms of plastics. Among the earliest examples of new plastics were polystyrene and polyvinyl chloride. The real star of the plastics industry in the 1930s was polyamide, far better known by its trade name nylon. Nylon was the first purely synthetic fiber, introduced by DuPont Corporation at the 1939 World's Fair in New York City.

Plastics came of age during World War II. Traditional materials were in short supply due to the war effort and the Pacific supply of rubber was cut off. Plastics became an acceptable substitute for many traditional materials. By 1950, the largest plastic part made was a 19 kg (42 lb) Admiral television. In 1952, engineering plastics came into use, and a door liner for an Admiral refrigerator was produced using injection molding. Since 1976, plastics have become the most used material in the world. The plastics industry in the United States has grown an average of 7.7% per year for the past 40 years. In 1979, the production of plastics in the United States exceeded that of steel. By 2000, the plastics industry was the fourth largest manufacturing segment in the United States, following only transportation, electronics, and the chemical industries.

Structural Ceramics. Ceramics are one of mankind's most ancient materials. Once humans discovered that clay could be dug up and formed into objects by mixing it with water and firing it, the industry was born. As early as 24,000 B.C., animal and human figurines were made from clay and other materials and then fired in kilns partially dug into the ground. Almost 10,000 years later, as settled communities were established, tiles were manufactured in Mesopotamia and India. The first use of functional pottery vessels for storing water and food is thought to be around 9,000 or 10,000 B.C. Fired clay-based products were the only ceramics available until approximately 100 years ago. At that point, new classes of starting materials, such as silicon carbide for abrasives, began to be used. Until the 1950s, the most important ceramic materials were (1) pottery, bricks and tiles, (2) cements, and (3) glass.

The development of structural ceramics has been partially motivated by U.S. government sponsorship of programs during the 1970s and 1980s to develop ceramics for engine applications. Improvements in processing and properties have continued. For engines and more demanding applications, compositions are being developed that are based either on two or more phases of particulates or on matrices reinforced with whiskers or fibers.

Composites. The first known fiberglass-reinforced composite product was a boat hull manufactured in the mid-1930s. Fiberglass-reinforced composites applications have revolutionized the aerospace, sporting goods, marine, electrical, corrosion resistance, and transportation industries. Fiberglass-reinforced composite materials date back to the early 1940s in the defense industry, particularly for use in aerospace and naval applications. The U.S. Air Force and Navy capitalized on their high strength-to-weight ratio and inherent resistance to weather and the corrosive effects of salt air and sea. By 1945, over 7 million pounds of fiberglass were used in military applications. Fiberglass pipe was first introduced in 1948 and was widely used within the corrosion market and the oil industry.

In 1959 and 1962, two processes for manufacturing high-strength and high-modulus carbon fibers from rayon and polyacrylonitrile precursor fibers were invented simultaneously. In 1963, high-modulus carbon fibers made from pitch were invented. High-performance carbon-fiber composites were first used in military aircraft. By the early 1980s, the AV-B Harrier vertical take-off and landing jet contained 28% composites in its airframe. These early successes with composites helped Boeing and Airbus succeed in incorporating advanced composites on commercial aircraft. In 2011, the first Boeing Dreamliner with a 50% composite airframe was introduced into service.

1.1 Today's Lightweight Materials

The distinguishing feature of the materials covered in this book is that they all have low densities. Densities range from as low as 0.80 g/cm^3 (0.030 lb/in.^{3}) for unfilled polymers to as high as 4.5 g/cm^3 (0.160 lb/in.^{3}) for titanium. While the density of titanium is high compared to unfilled polymers, it is significantly lighter than the metals it usually competes with—alloy steel at 7.86 g/cm^3 (0.283 lb/in.^{3}) and superalloys with densities that range from 7.8 to 9.4 g/cm^3 (0.282 to 0.340 lb/in.^{3}). In addition, unfilled polymers have rather low tensile strengths that range from 34 to 103 MPa (5 to 15 ksi), while unidirectional carbon/epoxy can attain tensile strengths as high as 2410 MPa (350 ksi). Some of the lightweight materials can only be used to approximately 66 °C (150 °F), while others maintain useful properties to over 1370 °C (2500 °F). Therefore, as shown in Table 1.1, the lightweight materials covered in this book cover a wide range of properties and, as a result, fulfill a wide range of applications.

1.2 Aluminum Alloys

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
- Relatively low cost

Potential limitations of aluminum alloys are:

- Moderate modulus of elasticity
- Fatigue strength sometimes much lower than static strength
- High-strength 2*xxx* and 7*xxx* alloys can be difficult to weld.

Table 1.1 Comparison of lightweight materials

Material	Density		Tensile strength		Modulus of elasticity		Elongation, %	Continuous-use temperature		Relative cost(a)
	g/cm^3	lb/in.^{3}	MPa	ksi	GPa	10^6 psi		°C	°F	
Aluminum alloys	2.77	0.100	207–552	30–80	69–76	10–11	10–30	480	250	3
Magnesium alloys	1.74	0.063	138–345	20–50	45	6.5	3–10	390	200	4
Beryllium alloys	1.85	0.067	345–483	50–70	303	44.0	1–3	2010	1100	8
Titanium alloys	4.43	0.160	827–1241	120–180	103–110	15–16	10–30	1290–2010	700–1100	6
Titanium aluminide alloys	4.21	0.152	448–827	65–120	145–172	21–25	1–4	3000	1650	9
Engineering plastics	0.83–13.8	0.03–0.50	35–103	5–15	2.0–9.0	0.3–1.3	2–700	300–390	150–200	1–4
Polymer-matrix composites										
Discontinuous fibers(b)	1.38	0.050	172	25	9.0	1.3	4	480	250	2
Continuous fibers(c)	1.58	0.057	2413	350	172	25	2	480	250	6
Metal-matrix composites										
Discontinuous fibers(d)	2.93	0.106	276–345	40–50	93–114	13.5–16.5	0.5–1.5	660	350	5
Continuous fibers(e)	3.96	0.144	1379	200	186	27	0.85	2550	1400	8
Structural ceramics	2.49–5.5	0.09–0.2	140–448	20–65	207–414	30–60	<1	3180–4620	1750–2550	5
Ceramic-matrix composites										
Discontinuous fibers(f)	3.60	0.130	903(g)	131(g)	103	15	…	3630	2000	7
Continuous fibers(h)	3.46	0.125	214	31	138	20	<1	4710w	2600	10

(a) 1 is lowest cost; 10 is highest cost. (b) Nylon with 30% glass. (c) Unidirectional carbon/epoxy. (d) Die-cast SiC particles/aluminum. (e) SCS-6 silicon carbide fiber/titanium. (f) Alumina reinforced with 25% SiC whiskers. (g) Bend strength. (h) Woven SiC/SiC

Aluminum is an industrial and 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. As a result of a naturally occurring tenacious surface oxide film (Al_2O_3), a great number of aluminum alloys have exceptional corrosion resistance in many atmospheric and chemical environments. Its corrosion and oxidation resistance is especially important in architectural and transportation applications. On an equal weight and cost basis, aluminum is a better electrical 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. Wrought 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 not toxic and among the easiest to recycle of any of the structural materials.

Aluminum has a density that is one-third the density of steel. Although aluminum alloys have lower tensile properties than steel, their specific strength (strength/density) is excellent. Aluminum is easily formed, 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 approximately 5% of the energy needed to make it from alumina, which is why the recycling of aluminum is so successful. The beneficial physical properties of aluminum include its nonferromagnetic behavior and resistance to oxidation and corrosion. However, aluminum does not display a true endurance limit, so failure by fatigue may eventually occur, even at relatively low stresses. Because of its low melting temperature, aluminum does not perform well at elevated temperatures. Finally, aluminum has low hardness, leading to poor wear resistance. Aluminum responds readily to strengthening mechanisms; alloys may be 30 times stronger than pure aluminum. The attractiveness of aluminum is that it is a relatively low-cost, lightweight metal that can be heat treated to fairly high strength levels, and it is one of the most easily fabricated of the high-performance materials, which usually correlates directly with lower costs.

Approximately 25% of the aluminum produced today is used in the transportation industry, another 25% in the manufacture of beverage cans and other packaging, about 15% in construction, 15% in electrical applications, and 20% in other applications.

The dominance of steel in the automotive industry is being challenged by plastics and aluminum. In 2010, approximately 90 kg (200 lb) of aluminum was used in an average car made in the United States. The long-term goal of the aluminum community is an all-aluminum chassis, known as a “body in white.” The most notable example of an aluminum chassis is the high-end Audi A8 luxury sedan, which uses a spaceframe construction. This method uses complex hollow extruded sections joined by welding to form a rigid framework. A weight savings of 140 kg (310 lb) relative to a steel body is achieved by covering the spaceframe with prestressed aluminum body panels. The question remains whether car manufacturers and buyers are willing to accept a more expensive, if lighter, product. The present consensus appears to be that except for certain niche products, steel remains the low-cost material of choice. Much will depend on the future price structure for the individual materials, developments in materials processing, and the impetus for further weight-saving in relation to fuel efficiency. In the meantime, the use of higher-strength steels at thinner gage for panels will continue to expand, taking advantage of the very efficient monocoque steel sheet body structure and the high production rates possible with this system, and with increased use of coatings to provide corrosion protection.

Aluminum alloys can be divided into two major groups: wrought and casting alloys (Table 1.2). Wrought alloys, which are shaped by plastic deformation, have compositions and microstructures significantly different

Table 1.2 Designations for aluminum alloys

Series	Aluminum content or main alloying element
Wrought alloys	
1*xxx*	99.00% min
2*xxx*	Copper
3*xxx*	Manganese
4*xxx*	Silicon
5*xxx*	Magnesium
6*xxx*	Magnesium and silicon
7*xxx*	Zinc
8*xxx*	Others
9*xxx*	Unused
Cast alloys	
1*xx*.0	99.00% min
2*xx*.0	Copper
3*xx*.0	Silicon with copper and/or magnesium
4*xx*.0	Silicon
5*xx*.0	Magnesium
6*xx*.0	Unused
7*xx*.0	Zinc
8*xx*.0	Tin
9*xx*.0	Other

from casting alloys, reflecting the different requirements of the manufacturing process. Within each major group, the alloys can be divided into two subgroups: heat-treatable and non-heat-treatable alloys.

The 1*xxx*, 3*xxx*, 5*xxx*, and most of the 4*xxx* wrought alloys cannot be strengthened by heat treatment. The 1*xxx*, 3*xxx*, and 5*xxx* alloys are strengthened by strain hardening, solid-solution strengthening, and grain-size control. The primary uses of the 1*xxx* series are in applications that require a combination of extremely high corrosion resistance and formability (e.g., foil and strip for packaging, chemical equipment, tank car or truck bodies, spun hollowware, and elaborate sheet metal work). In the 3*xxx* alloy series, alloy 3004 and its modification 3104 are the principals for drawn and ironed bodies for beverage cans for beer and soft drinks (Fig. 1.1). As a result, they are among the most-used individual alloys in the aluminum system, in excess of 1.6 billion kg (3.5 billion lb) per year. The 5*xxx* series of alloys has an outstanding combination of strength, toughness, weldability, and corrosion resistance in saltwater. As a result, they find wide application in building and construction; highway structures including bridges, storage tanks, and pressure vessels; cryogenic tankage and systems for temperatures as low as –270 °C (–455 °F) or near absolute zero; and marine applications. A large welded 5*xxx* aluminum substructure for a high-speed single-hull ship is shown in Fig. 1.2.

The 2*xxx*, 6*xxx*, and 7*xxx* alloys can be strengthened by precipitation hardening heat treatments. The greatest usage for the high-strength precipitation-hardened 2*xxx* and 7*xxx* alloys is in aircraft and spacecraft applications. As shown in Fig. 1.3, 2*xxx* alloys are used for fuselage

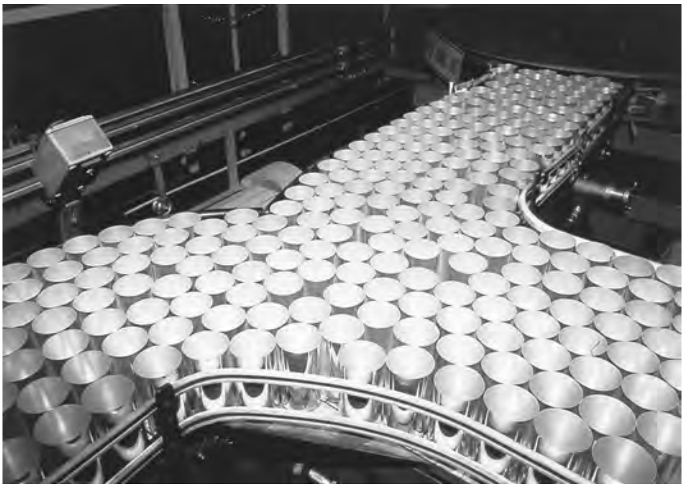
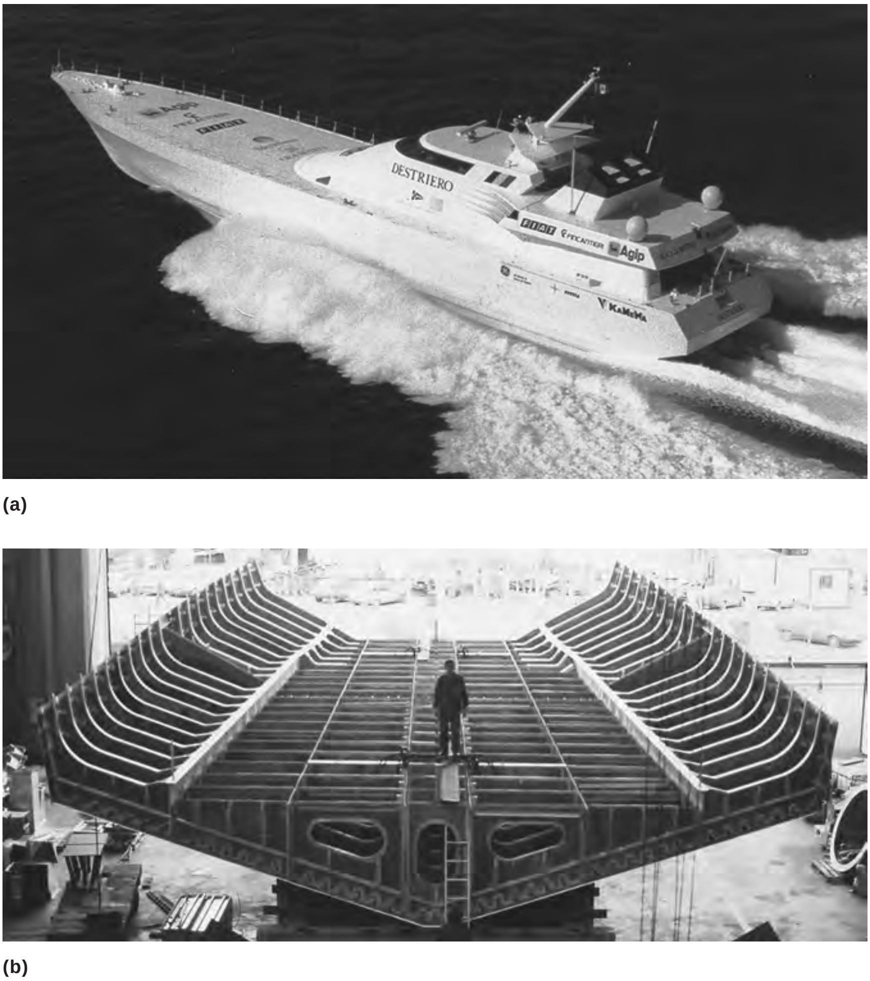


Fig. 1.1 The bodies of beverage cans are alloys 3004 or 3104, making it the largest-volume alloy consumed in the industry. Source: Ref 1.1

construction and 7*xxx* alloys for wing structures. A unique feature of the 6*xxx* alloys is their great extrudability, making it possible to produce in single shapes relatively complex architectural forms, as shown in Fig. 1.4. They can be heat treated to moderate strength levels and have good corrosion resistance.

The highest-usage casting alloys contain enough silicon that the alloys have low melting points, good fluidity, and good castability. Fluidity is the ability of the liquid metal to flow through a mold without prematurely solidifying, and castability refers to the ease with which a good casting can be made from the alloy. Quite intricate structural castings (Fig. 1.5) can be produced using a wide range of casting processes.

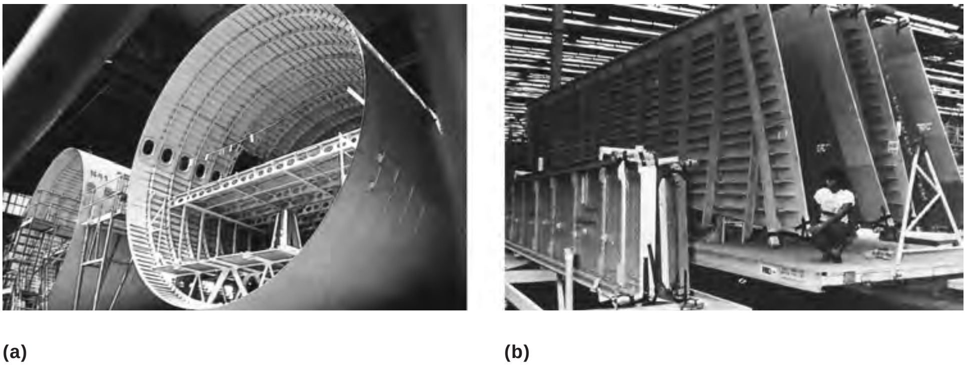
Improvements in aluminum manufacturing technology include high-speed machining and friction stir welding. Although higher metal-removal rates are an immediate benefit of high-speed machining, an additional cost-saving is the ability to machine extremely thin walls and webs. This allows the design of weight-competitive high-speed machined assemblies, in which sheet metal parts that were formally assembled with mechanical fasteners can now be machined from a single, or several blocks of, aluminum plate (Fig. 1.6). Another recent development, called friction stir welding, is a new solid-state joining process that has the ability to weld the difficult, or impossible, to fusion weld 2*xxx* and 7*xxx* alloys with less distortion, fewer defects, and better durability than achievable using conventional welding techniques.



(a)

(b)

Fig. 1.2 Aluminum alloy usage in the marine industry. (a) High-speed single-hull ship. (b) 5*xxx* aluminum alloy internal hull stiffener structure. Source: Ref 1.1



(a) (b)

Fig. 1.3 Aluminum alloys used for commercial aircraft. (a) 2*xxx* alloys for fuselage. (b) 7*xxx* alloys for wings. Source: Ref 1.1

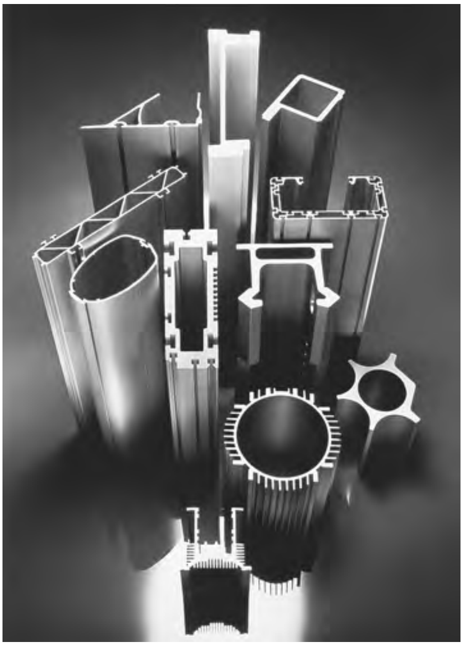
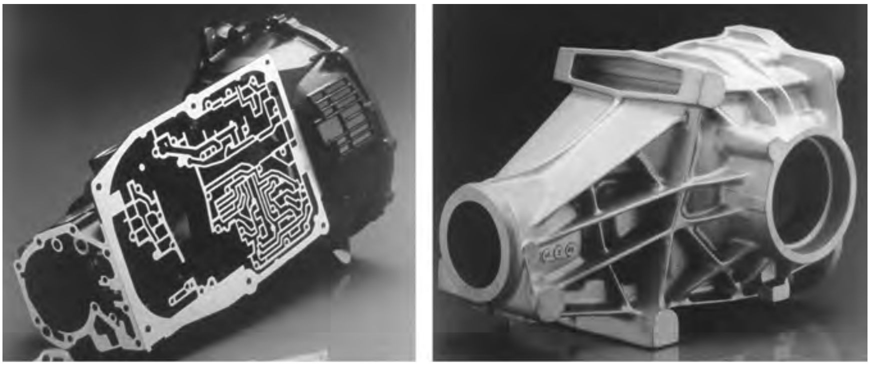


Fig. 1.4 6*xxx* aluminum alloy structural extrusions. Source: Ref 1.1



(a)

(b)

Fig. 1.5 Aluminum alloy cast products. (a) Aluminum alloy 380.0 gearbox casting for passenger car. (b) Aluminum alloy 380.0 rear axle casting. Source: Ref 1.1

1.3 Magnesium Alloys

Magnesium alloys usually compete with aluminum alloys for structural applications. Compared to high-strength aluminum alloys, magnesium alloys are not as strong (tensile strength of 138 to 345 versus 275 to 550 MPa, or 20 to 50 versus 40 to 80 ksi) and have a lower modulus of elasticity (45 versus 69 GPa, or 6.5 versus 10 to 11 × 10^6 psi). However, magnesium is significantly lighter (1.74 versus 2.77 g/cm^3, or 0.063 versus 0.100 lb/in.^{3})