Chapter 1

Introduction

ALUMINUM became an economic competitor in engineering applications toward the end of the 19th century. The reason aluminum was not used earlier was the difficulty of extracting it from its ore. When the electrolytic reduction of aluminum oxide (Al_2O_3) dissolved in molten cryolite was independently developed by Charles Martin Hall in the United States and Paul T. Héroult in France, the aluminum industry was born.

The emergence of three important industrial developments in the late 1800s and early 1900s would, by demanding material characteristics consistent with the unique qualities of aluminum and its alloys, greatly benefit growth in the production and use of the new metal. The first of these was the introduction of the first internal-combustion-engine-powered vehicles. Aluminum would play a role as an automotive material of increasing engineering value. Secondly, electrification would require immense quantities of lightweight conductive metal for long-distance transmission and for construction of the towers needed to support the overhead network of cables that deliver electrical energy from sites of power generation. Within a few decades, a third important application area was made possible by the invention of the airplane by the Wright brothers. This gave birth to an entirely new industry which grew in partnership with the aluminum industry development of structurally reliable, strong, and fracture-resistant parts for airframes, engines, and ultimately, for missile bodies, fuel cells, and satellite components.

However, the aluminum industry growth was not limited to these developments. The first commercial applications of aluminum were novelty items such as mirror frames, house (address) numbers, and serving trays. Cooking utensils were also a major early market. In time, aluminum applications grew in diversity to the extent that virtually every aspect of modern life would be directly or indirectly affected by use. Today, aluminum is surpassed only by steel in its use as a structural material.

Key Characteristics of Aluminum

Aluminum offers a wide range of properties that can be engineered precisely to the demands of specific applications through the choice of alloy, temper, and fabrication process. The properties of aluminum and its alloys which give rise to their widespread usage include the following:

- Aluminum is light; its density is only one-third that of steel.
- Aluminum and aluminum alloys are available in a wide range of strength values—from highly ductile low-strength commercially pure aluminum to very tough high-strength alloys with ultimate tensile strengths approaching 690 MPa (100 ksi).
- Aluminum alloys have a high strength-to-weight ratio.
- Aluminum retains its strength at low temperatures and is often used for cryogenic applications.
- Aluminum has high resistance to corrosion under the majority of service conditions, and no colored salts are formed to stain adjacent surfaces or discolor products with which it comes into contact.
- Aluminum is an excellent conductor of heat and electricity.
- Aluminum is highly reflective.
- Aluminum is nonferromagnetic, a property of importance in the electrical and electronics industries.
- Aluminum is nonpyrophoric, which is important in applications involving inflammable or explosive materials handling or exposure.
- Aluminum is nontoxic and is routinely used in containers for food and beverages.

- Aluminum 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.
- Aluminum is recyclable. Aluminum has substantial scrap value and a well-established market for recycling, providing both economic and environmental benefits.
- Aluminum is easily fabricated. Aluminum can be formed and fabricated by all common metalworking and joining methods.

Table 1 lists the important physical properties of pure aluminum. Table 2 shows the characteristics of aluminum and their importance for different end uses.

Low Density. Aluminum has a density of only 2.7 g/cm^3, approximately 35% that of steel (7.83 g/cm^3) and 30% of copper (8.93 g/cm^3) or brass (8.53 g/cm^3). One cubic foot of steel weighs about 222 kg (490 lb); a cubic foot of aluminum weighs only about 77 kg (170 lb).

Table 1 Summary of the important physical properties of high-purity (≥99.95% Al) aluminum

Property	Value
Thermal neutron cross section	0.232 ± 0.003 barns
Lattice constant (length of unit cube)	4.0496×10^{-10} m at 298 K
Density (solid)	2699 kg/m^3 (theoretical density based on lattice spacing) 2697–2699 kg/m^3 (polycrystalline material)
Density (liquid)	2357 kg/m^3 at 973 K 2304 kg/m^3 at 1173 K
Coefficient of expansion	23×10^{-6}/K at 293 K
Thermal conductivity	2.37 W/cm · K at 298 K
Volume resistivity	2.655×10^{-8} Ω · m
Magnetic susceptibility	16×10^{-3}/m^3 g/atom at 298 K
Surface tension	868 dyne/cm at the melting point
Viscosity	0.012 poise at the melting point
Melting point	933.5 K
Boiling point	2767 K
Heat of fusion	397 J/g
Heat of vaporation	1.08×10^{-4} J/g · K
Heat capacity	0.90 J/g · K

Strength. Commercially pure aluminum has a tensile strength of about 90 MPa (13 ksi). Thus its usefulness as a structural material in this form is somewhat limited. By working the metal, as by cold rolling, its strength can be approximately doubled. Much larger increases in strength can be obtained by alloying aluminum with small percentages of one or more other elements such as manganese, silicon, copper, magnesium, or zinc. Like pure aluminum, the alloys are also made stronger by cold working. Some of the alloys are further strengthened and hardened by heat treatments. Figure 1 shows the range of strength levels of representative aluminum and aluminum alloys.

High Strength-to-Weight Ratio. The strength-to-weight ratio of aluminum is much higher than that of many common grades of constructional steels—often double or more (Fig. 1). This property permits design and construction of strong, lightweight structures that are particularly advantageous for anything that moves—space vehicles and aircraft as well as all types of land- and water-borne vehicles.

Corrosion Resistance. When aluminum surfaces are exposed to the atmosphere, a thin invisible oxide skin forms immediately, which protects the metal from further oxidation. This self-protecting characteristic gives aluminum its high resistance to corrosion. Unless exposed to some substance or condition that destroys this protective oxide coating, the metal remains fully protected against corrosion. Aluminum is highly resistant to weathering, even in industrial atmospheres that often corrode other metals. It is also corrosion resistant to many acids. Alkalis are among the few substances that attack the oxide skin and therefore are corrosive to aluminum. Although the metal can safely be used in the presence of certain mild alkalis with the aid of inhibitors, in general, direct contact with alkaline substances should be avoided.

The high thermal conductivity of aluminum (about 50 to 60% that of copper) came prominently into play in the very first large-scale commercial application of the metal in cooking utensils. This characteristic is important whenever the transfer of thermal energy from one medium to another is involved, either heating or cooling. Thus aluminum heat exchangers are

Table 2 Property combinations important for the use of aluminum in various application areas

	Characteristics				Type of semifabricated products					
Field of use	Lightness	Good heat and electrical conductivity	Resistance to corrosion	Decorative aspects (with or without surface treatment)	Castings or forgings	Formed sheet	Impact extrusions	Extruded sections	Wire and cable	Foil
Transport	1	...	2	2	2	2	...	2	...	...
Building	2	...	2	1	...	2	...	2	...	...
Packaging	3	3	1	1	...	...	2	...	...	2
Electrical	3	1	2	...	...	...	2	2	2	2
Household	2	1	1	2	...	2	...	...	...	2
Machines, appliances	1	2	2	2	2	2	...	2	...	...
Chemicals and food	2	2	1	2	3	2	...	2	...	2

1, very important; 2, important; 3, desirable commonly used in the food, chemical, petroleum, aircraft, and other industries.

High Electrical Conductivity. Aluminum is one of the two common metals having an electrical conductivity high enough for use as an electric conductor. The conductivity of electric conductor grade (1350) is about 62% that of the International Annealed Copper Standard (IACS). Because aluminum has less than one-third the specific gravity of copper, however, a pound of aluminum will go about twice as far as a pound of copper when used for this purpose.

Reflectivity. Smooth aluminum is highly reflective of the electromagnetic spectrum, from radio waves through visible light and on into the infrared and thermal range. It bounces away about 80% of the visible light and 90% of the radiant heat striking its surface. The high reflectivity gives aluminum a decorative appearance; it also makes aluminum a very effective barrier against thermal radiation, suitable for such applications as automotive heat shields.

Nontoxic Characteristics. The fact that aluminum is nontoxic was discovered in the early days of the industry. It is this characteristic that permits the metal to be used in cooking utensils without any harmful effect on the body. Today a great deal of aluminum equipment is used in the food processing industry. Nontoxicity permits aluminum foil wrapping to be used safely in direct contact with food products.

Finishability. For the majority of applications, aluminum needs no protective coating. Mechanical finishes such as polishing, sand blasting, or wire brushing meet the majority of needs. In many instances, the surface

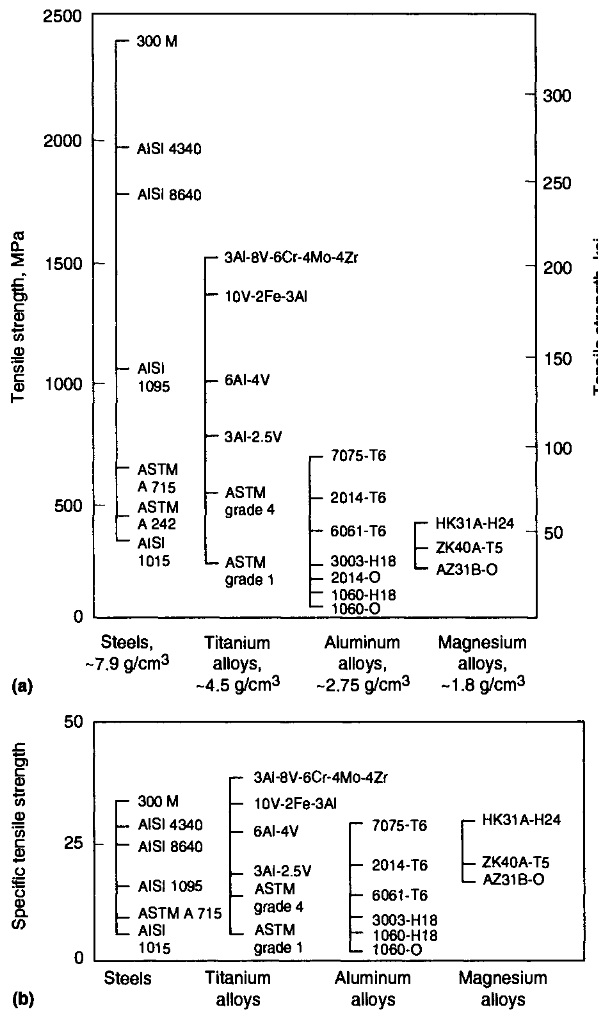

Fig. 1 Comparison of aluminum alloys with competing structural alloys on the basis of (a) tensile strength and (b) specific tensile strength (tensile strength, in ksi, divided by density, in g/cm^3)

finish supplied is entirely adequate without further finishing. Where the plain aluminum surface does not suffice or where additional protection is required, any of a wide variety of surface finishes may be applied. Chemical, electrochemical, and paint finishes are all used. Many colors are available in both chemical and electrochemical finishes. If paint, lacquer, or enamel is used, any color possible with these finishes can be applied. Vitreous enamels have been developed for aluminum, and the metal can also be electroplated.

Ease of Fabrication. The ease with which aluminum can be fabricated into any form is one of its most important assets. Often it can compete successfully with cheaper materials having a lower degree of workability. The metal can be cast by any method known to foundrymen. It can be rolled to any desired thickness down to foil thinner than paper; aluminum sheet can be stamped, drawn, spun or roll-formed. The metal also can be hammered or forged. Aluminum wire, drawn from rolled rod, may be stranded into cable or any desired size and type. There is almost no limit to the different profiles (shapes) in which the metal can be extruded.

The ease and speed with which aluminum can be machined is one of the important factors contributing to the low cost of finished aluminum parts. The metal can be turned, milled, bored, or machined in other manners at the maximum speeds of which most machines are capable. Another advantage of its flexible machining characteristics is that aluminum rod and bar can readily be employed in the high-speed manufacture of parts by automatic screw machines.

Almost any method of joining is applicable to aluminum: riveting, welding, brazing, or soldering. A wide variety of mechanical aluminum fasteners simplifies the assembly of many products. Adhesive bonding of aluminum parts is widely employed, particularly in joining aircraft components.

Table 3 lists fabrication characteristics of commonly used wrought aluminum and aluminum alloys.

Property Combinations Needed for Specific End Uses. In most applications, two or more key characteristics of aluminum come prominently into play—for example, light weight combined with strength in airplanes, railroad cars, trucks, and other transportation equipment. High resistance to corrosion and high thermal conductivity are important in equipment for the chemical and petroleum industries; these properties combine with nontoxicity for food processing equipment.

Attractive appearance together with high resistance to weathering and low maintenance requirements have led to extensive use in buildings of all types. High reflectivity, excellent weathering characteristics, and light weight are all important in roofing materials. Light weight contributes to low handling and shipping costs, whatever the application. Table 2 reviews the material characteristics required for different markets and applications. Additional information can also be found in the section "Applications" in this chapter.

Competing Metals for Lightweight Construction. The light (low density) metals and alloys of commercial importance are based on aluminum, magnesium, and titanium. Each of these metals has distinct qualities that make them suitable or preferred for certain applications.

With a density of 1.8 g/cm^3, magnesium alloys are among the lightest known structural alloys. This is their chief advantage when compared with aluminum and titanium. However, a low yield strength and modulus of elasticity combined with poor thermal and electrical conductivity limit their range of application. Figure 1 compares the properties of magnesium and aluminum alloys.

The combination of low density (~4.5 g/cm^3), outstanding corrosion resistance, and high strength make titanium and titanium alloys popular in the aerospace, chemical processing, and medical (prostheses) industries. However, its high price (due to processing difficulties) has limited the use of titanium to niche markets. Figure 1 compares the properties of titanium and aluminum alloys.

The Aluminum Industry

Primary Aluminum Production

Occurrence. Aluminum comprises about 8% of the earth's crust, making it second only to silicon (~28%). Iron is third at about 5%. The principal ore of aluminum, bauxite, usually consists of mixtures of hydrated aluminum oxide, either AlO(OH) or $Al(OH)_3$. Besides these compounds, bauxite contains iron oxide (which gives it a reddish-brown color), as well as silicates (clay and quartz), and titanium oxide. The bauxites used for the production of aluminum typically contain 35 to 60% total aluminum oxide.

Extraction or Refining Methods. The most widely used technology for producing aluminum involves two steps: extraction and purification of aluminum oxide (alumina) from ores (primarily bauxite although alternate raw materials can be used), and electrolysis of the oxide after it has been dissolved in fused cryolite.

The Bayer process is almost universally employed for the purification of bauxite. In this process, which was developed by Austrian Karl Joseph Bayer in 1892, the crushed and ground bauxite is digested with caustic soda solution, at elevated temperature and under pressure, and the alumina is dissolved out as a solution of sodium aluminate. The residue, known as "red mud," contains the oxides of iron, silicon, and titanium and is separated by settling and filtration. Aluminum hydrate is separated from the solution of sodium aluminate by seeding and precipitation and is converted to the oxide, Al_2O_3, by calcination.

Present practice for aluminum electrolysis involves the use of the Hall-Héroult cell as pictured in Fig. 2. The cell is lined with carbon, which acts as the cathode; steel bars are embedded in the cathode lining to provide a path for current flow. The anodes are also of

Table 3 Comparative fabrication characteristics of wrought aluminum alloys

Alloy	Temper	Cold workability(a)	Machinability(a)	Weldability(b) Gas	Weldability(b) Arc	Weldability(b) Resistance spot and seam	Brazeability(b)	Solderability(c)
1050	O	A	E	A	A	B	A	A
	H12	A	E	A	A	A	A	A
	H14	A	D	A	A	A	A	A
	H16	B	D	A	A	A	A	A
	H18	B	D	A	A	A	A	A
1060	O	A	E	A	A	B	A	A
	H12	A	E	A	A	A	A	A
	H14	A	D	A	A	A	A	A
	H16	B	D	A	A	A	A	A
	H18	B	D	A	A	A	A	A
1100	O	A	E	A	A	B	A	A
	H12	A	E	A	A	A	A	A
	H14	A	D	A	A	A	A	A
	H16	B	D	A	A	A	A	A
	H18	C	D	A	A	A	A	A
1145	O	A	E	A	A	B	A	A
	H12	A	E	A	A	A	A	A
	H14	A	D	A	A	A	A	A
	H16	B	D	A	A	A	A	A
	H18	B	D	A	A	A	A	A
1199	O	A	E	A	A	B	A	A
	H12	A	E	A	A	A	A	A
	H14	A	D	A	A	A	A	A
	H16	B	D	A	A	A	A	A
	H18	B	D	A	A	A	A	A
1350	O	A	E	A	A	B	A	A
	H12, H111	A	E	A	A	A	A	A
	H14, H24	A	D	A	A	A	A	A
	H16, H26	B	D	A	A	A	A	A
	H18	B	D	A	A	A	A	A
2011	T3	C	A	D	D	D	D	C
	T4, T451	B	A	D	D	D	D	C
	T8	D	A	D	D	D	D	C
2014	O	...	D	D	D	B	D	C
	T3, T4, T451	C	B	D	B	B	D	C
	T6, T651, T6510, T6511	D	B	D	B	B	D	C
2024	O	...	D	D	D	D	D	C
	T4, T3, T351, T3510, T3511	C	B	C	B	B	D	C
	T361	D	B	D	C	B	D	C
	T6	C	B	D	C	B	D	C
	T861, T81, T851, T8510, T8511	D	B	D	C	B	D	C
	T72	...	B	...	...	...	...	...
2036	T4	B	C	...	B	B	D	...
2124	T851	D	B	D	C	B	D	C
2218	T61	...	...	...	...	C	...	C
	T72	...	B	D	C	B	D	C
2219	O	...	...	D	A	B	D	...
	T31, T351, T3510, T3511	C	B	A	A	A	D	NA
	T37	D	B	A	A	A	D	...
	T81, T851, T8510, T8511	D	B	A	A	A	D	...
	T87	D	B	A	A	A	D	...
2618	T61	...	B	D	C	B	D	NA
3003	O	A	E	A	A	B	A	A
	H12	A	E	A	A	A	A	A
	H14	B	D	A	A	A	A	A
	H16	C	D	A	A	A	A	A
	H18	C	D	A	A	A	A	A
	H25	B	D	A	A	A	A	A

(continued)

(a) Ratings A through D for cold workability and A through E for machinability are relative ratings in decreasing order of merit. (b) Ratings A through D for weldability and brazeability are relative ratings defined as follows: A, generally weldable by all commercial procedures and methods; B, weldable with special techniques or for specific applications and requiring preliminary trials or testing to develop welding procedure and weld performance; C, limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties; D, no commonly used welding methods have been developed. (c) Ratings A through D and NA for solderability are relative ratings defined as follows: A, excellent; B, good; C, fair; D, poor; NA, not applicable

Table 3 (continued)

Alloy	Temper	Cold workability(a)	Machinability(a)	Weldability(b) Gas	Weldability(b) Arc	Weldability(b) Resistance spot and seam	Brazeability(b)	Solderability(c)
3004	O	A	D	B	A	B	B	B
	H32	B	D	B	A	A	B	B
	H34	B	C	B	A	A	B	B
	H36	C	C	B	A	A	B	B
	H38	C	C	B	A	A	B	B
3105	O	A	E	B	A	B	B	B
	H12	B	E	B	A	B	B	B
	H14	B	D	B	A	A	B	B
	H16	C	D	B	A	A	B	B
	H18	C	D	B	A	A	B	B
	H25	B	D	B	A	A	B	B
4032	T6	...	B	D	B	C	D	NA
4043	...	NA	C	NA	NA	NA	NA	NA
5005	O	A	E	A	A	B	B	B
	H12	A	E	A	A	A	B	B
	H14	B	D	A	A	A	B	B
	H16	C	D	A	A	A	B	B
	H18	C	D	A	A	A	B	B
	H32	B	E	A	A	A	B	B
	H34	C	D	A	A	A	B	B
	H36	C	D	A	A	A	B	B
	H38	...	D	A	A	A	B	B
5050	O	A	E	A	A	B	B	C
	H32	A	D	A	A	A	B	C
	H34	B	D	A	A	A	B	C
	H36	C	C	A	A	A	B	C
	H38	C	C	A	A	A	B	C
5052	O	A	D	A	A	B	C	D
	H32	B	D	A	A	A	C	D
	H34	B	C	A	A	A	C	D
	H36	C	C	A	A	A	C	D
	H38	C	C	A	A	A	C	D
5056	O	A	D	C	A	B	D	D
	H111	A	D	C	A	A	D	D
	H12, H32	B	D	C	A	A	D	D
	H14, H34	B	C	C	A	A	D	D
	H18, H38	C	C	C	A	A	D	D
	H192	D	B	C	A	A	D	D
	H392	D	B	C	A	A	D	D
5083	O	B	D	C	A	B	D	D
	H321, H116	C	D	C	A	A	D	D
	H111	C	D	C	A	A	D	D
5086	O	A	D	C	A	B	D	D
	H32, H1116	B	D	C	A	A	D	D
	H34	B	C	C	A	A	D	D
	H36	C	C	C	A	A	D	D
	H38	C	C	C	A	A	D	D
	H111	B	D	C	A	A	D	D
5154	O	A	D	C	A	B	D	D
	H32	B	D	C	A	A	D	D
	H34	B	C	C	A	A	D	D
	H36	C	C	C	A	A	D	D
	H38	C	C	C	A	A	D	D
5182	O	A	D	C	A	B	D	D
	H19	D	B	C	A	A	D	D
5252	H24	B	D	A	A	A	C	D
	H25	B	C	A	A	A	C	D
	H28	C	C	A	A	A	C	D
5254	O	A	D	C	A	B	D	D
	H32	B	D	C	A	A	D	D
	H34	B	C	C	A	A	D	D
	H36	C	C	C	A	A	D	D
	H38	C	C	C	A	A	D	D
5356	...	NA	B	NA	NA	NA	NA	NA
5454	O	A	D	C	A	B	D	...

(continued)

Table 3 (continued)

Alloy	Temper	Cold workability(a)	Machinability(a)	Weldability(b) Gas	Arc	Resistance spot and seam	Brazeability(b)	Solderability(c)
5454 (continued)								
	H32	B	D	C	A	A	D	...
	H34	B	C	C	A	A	D	NA
	H111	B	D	C	A	A	D	...
5456	O	B	D	C	A	B	D	...
	H111	C	D	C	A	A	D	...
	H321, H115	C	D	C	A	A	D	NA
5457	O	A	E	A	A	B	B	B
5652	O	A	D	A	A	B	C	D
	H32	B	D	A	A	A	C	D
	H34	B	C	A	A	A	C	D
	H36	C	C	A	A	A	C	D
	H38	C	C	A	A	A	C	D
5657	H241	A	D	A	A	A	B	...
	H25	B	D	A	A	A	B	NA
	H26	B	D	A	A	A	B	...
	H28	C	D	A	A	A	B	...
6005	T5	C	C	A	A	A	A	NA
6009	T4	A	C	A	A	A	A	B
6010	T4	B	C	A	A	A	A	B
6061	O	A	D	A	A	B	A	B
	T4, T451, T4510, T4511	B	C	A	A	A	A	B
	T6, T651, T652, T6510, T6511	C	C	A	A	A	A	B
6063	T1	B	D	A	A	A	A	B
	T4	B	D	A	A	A	A	B
	T5, T52	B	C	A	A	A	A	B
	T6	C	C	A	A	A	A	B
	T83, T831, T832	C	C	A	A	A	A	B
6066	O	B	D	D	B	B	D	...
	T4, T4510, T4511	C	C	D	B	B	D	NA
	T6, T6510, T6511	C	B	D	B	B	D	...
6070	T4, T4511	B	C	A	A	A	B	NA
	T6	C	C	A	A	A	B	...
6101	T6, T63	C	C	A	A	A	A	NA
	T61, T64	B	D	A	A	A	A	...
6151	T6, T652	...	...	...	...	...	...	B
6201	T81	...	C	A	A	A	A	NA
6262	T6, T651, T6510, T6511	C	B	A	A	A	A	NA
	T9	D	B	A	A	A	A	...
6351	T5, T6	C	C	A	A	A	A	B
6463	T1	B	D	A	A	A	A	...
	T5	B	C	A	A	A	A	NA
	T6	C	C	A	A	A	A	...
7005	T53	C	A	B	B	B	B	B
7049	T73, T7351, T7352	D	B	D	C	B	D	D
	T76, T7651	D	B	D	C	B	D	D
7050	T74, T7451, T7452	D	B	D	C	B	D	D
	T76, T761	D	B	D	C	B	D	D
7072	...	A	D	A	A	A	A	A
7075	O	...	D	D	C	B	D	D
	T6, T651, T652, T6510, T6511	D	B	D	C	B	D	D
	T73, T7351	D	B	D	C	B	D	D
7175	T74, T7452	D	B	D	C	B	D	D
7178	O	...	...	D	C	B	D	D
	T6, T651, T6510, T6511	D	B	D	C	B	D	D
7475	T6, T651	D	B	D	C	B	D	D
	T73, T7351, T7352	D	B	D	C	B	D	D
	T76, T7651	D	B	D	C	B	D	D

(a) Ratings A through D for cold workability and A through E for machinability are relative ratings in decreasing order of merit. (b) Ratings A through D for weldability and brazeability are relative ratings defined as follows: A, generally weldable by all commercial procedures and methods; B, weldable with special techniques or for specific applications and requiring preliminary trials or testing to develop welding procedure and weld performance; C, limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties; D, no commonly used welding methods have been developed. (c) Ratings A through D and NA for solderability are relative ratings defined as follows: A, excellent; B, good; C, fair; D, poor; NA, not applicable carbon and are gradually fed into the top of the cell because the anodes are continually consumed during electrolysis. A group of cells are connected in series to obtain the voltage required by the particular direct current power source that is being used.

For aluminum, the electrolyte used is cryolite (Na_3AlF_6) with 8 to 10% Al_2O_3 dissolved in it. Other additives, such as CaF_2 and AlF_3, are added to obtain desirable physical properties. The melting point of the electrolyte is approximately 940 °C (1725 °F), and the Hall-Héroult cell operates at temperatures of approximately 960 to 1000 °C (1760 to 1830 °F).

At the cathode of the aluminum cell, aluminum is reduced from an ionic state to a metallic state—for example:

$$Al^{3+} + 3e^- = Al_{(l)}$$

This is a very simplified representation of the complex reactions that take place at the cathode. However, it does represent the overall production of molten aluminum, which forms a molten pool in the bottom of the cell. Periodically, the molten pool of aluminum metal is drained or siphoned from the bottom of the cell and cast.

At the anode, oxygen is oxidized from its ionic state to oxygen gas. The oxygen gas in turn reacts with the carbon anode to form carbon dioxide gas, which gradually consumes the anode material. Two types of anodes are in use: prebaked and self-baking. Prebaked anodes are individual carbon blocks that are replaced one after another as they are consumed. Self-baking anodes, as shown in Fig. 2, are made up of carbon paste that is fed into a steel frame above the cell. As the anode descends in the cell, it hardens, and new carbon paste is fed continually into the top of the steel frame.

Impurities in the Al_2O_3 raw material which are more noble than aluminum are reduced at the cathode along with the aluminum. Examples of two common metals associated with aluminum ores that fit this description are iron and silicon. It is, therefore, very important that raw materials be as free of these metal oxides as possible. By careful control of raw materials, aluminum with a purity of 99% or higher may be produced. Generally, the purity of aluminum as it comes from the electrolysis cell (i.e., up to 99.9%) is adequate. High-purity aluminum of at least 99.97% Al content is necessary for certain special purposes (e.g., reflectors or electrolytic capacitors). For such applications, second-stage refining operations (Hoopes cell electrolysis) are necessary. Aluminum produced in this way is 99.99% pure. Higher purities of up to 99.9999% ("six-nines" aluminum) can be obtained with zone-refining operations.

Secondary Aluminum Production

Advantages. Aluminum recovered from scrap (secondary aluminum) has been an important contributor to the total metal supply since the 1950s. The economics of recycling, together with improved techniques of scrap preparation and melting, which provide higher yields, led to the development of the secondary aluminum industry. The increased concern with, and economic implications of, energy supply in recent years have focused even more attention on recycling of aluminum because of its energy-intensive nature. The energy required to remelt secondary aluminum preparatory to fabrication for reuse is only 5% of that required to produce new (primary) aluminum. Today secondary aluminum accounts for about 35% of the aluminum supply in both the United States and Europe.

The Recycling Loop. The reclamation of aluminum scrap is a complex interactive process involving collection centers, primary producers, secondary smelters, metal processors and consumers. Figure 3 depicts the flow of

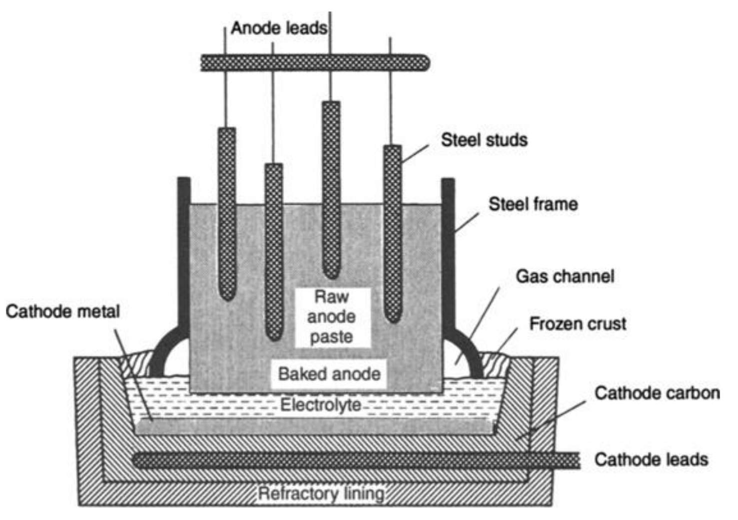

Fig. 2 Hall-Héroult aluminum production cell with self-baking anode

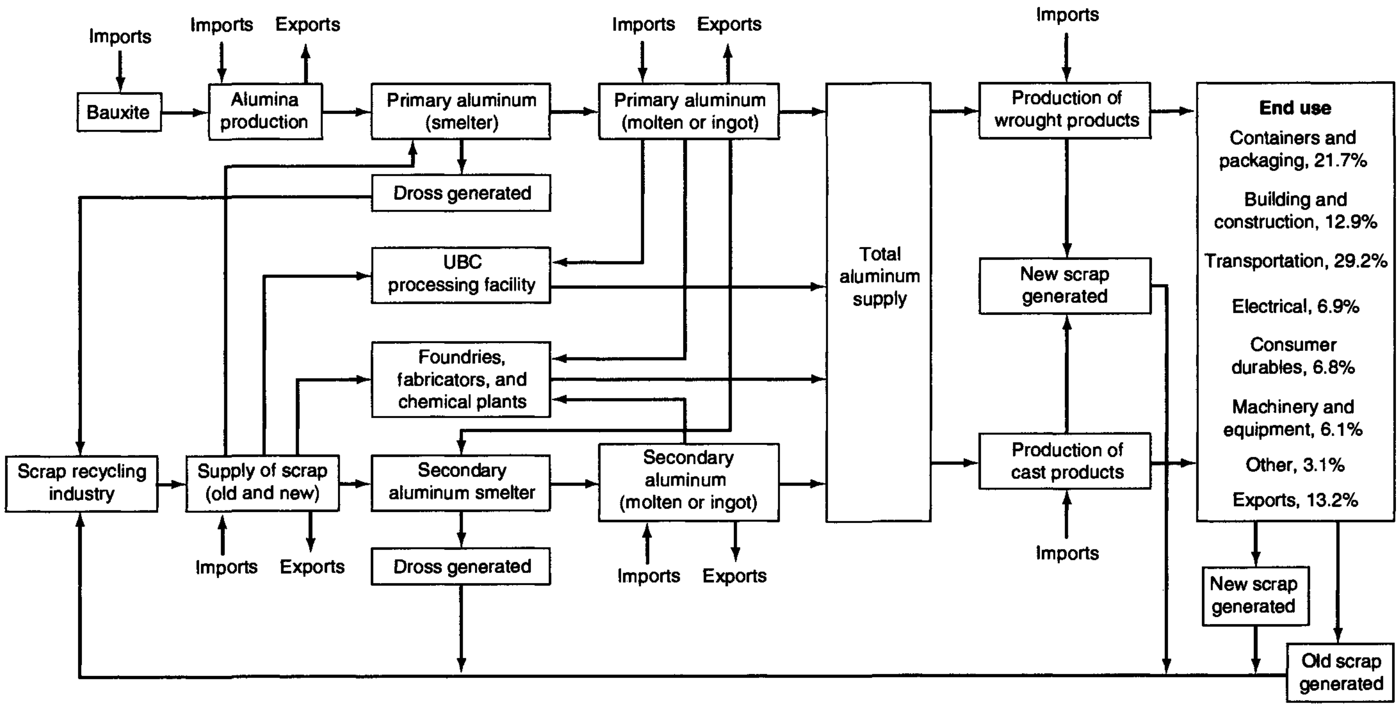

Fig. 3 Flow diagram for aluminum in the United States, showing the role of recycling in the industry. Scrap recycling (lower left) includes scrap collectors, processors, dealers and brokers, sweat furnace operators, and dross reclaimers.

metal originating in primary smelting operations through various recycling activities. The initial reprocessing of scrap takes place in the facilities of primary producers. In-process scrap, generated both in casting and fabricating, is reprocessed by melting and recasting. Increasingly, primary producers are purchasing scrap to supplement primary metal supply; an example of such activity is the purchase of toll conversion of used beverage cans (UBC) by primary producers engaged in the production of rigid container stock.

Scrap incurred in the processing or fabrication of semifabricated aluminum products represents an additional source of recyclable aluminum. Traditionally, this form of new scrap has been returned to the supplier for recycling, or it has been disposed of through sale on the basis of competitive bidding by metal traders, primary producers and secondary smelters.

Finished aluminum products, which include such items as consumer durable and nondurable goods; automotive, aerospace, and military products; machinery; miscellaneous transportation parts; and building and construction materials, have finite lives. In time, discarded aluminum becomes available for collection and recovery. So-called old scrap (metal product that has been discarded after use) can be segregated into classifications that facilitate recycling and recovery.

Process Technologies. Scrapped aluminum products are broken into small pieces and separated from dirt and foreign materials so as to yield feedstock suitable for remelting. This is done using breakers, shredders, magnetic, and settlement/flotation separators. Such scrap typically contains alloys of many types, all mixed together. A more sophisticated kind of recycling was developed in the 1970s and 1980s for process scrap and UBCs. By selectively collecting scrap in targeted alloy categories, the goal was to recycle the material back into products similar to those from which it originated. Thus, the casthouses of extrusion plants produce extrusion billets from process scrap and from recycled scrap extrusions. Similarly, the high rate of recovery of UBCs from the consumer enables a large proportion of canstock coils to be made from UBCs. Recovery of UBCs has multiplied repeatedly since the early 1970s. In 1997, some 2,052 million pounds of UBCs were collected in the United States. This constitutes 66.8% of can shipments. In some countries, for example Sweden, recycling rates exceeding 80% are achieved.

Aluminum Alloys

The mechanical, physical, and chemical properties of aluminum alloys depend on composition and microstructure. The addition of selected elements to pure aluminum greatly enhances its properties and usefulness. Because of this, most applications for aluminum utilize alloys having one or more elemental additions. The major alloying additions used with aluminum are copper, manganese, silicon, magnesium, and zinc; other elements are also added in smaller amounts for grain refinement and to develop special properties. The total amount of these elements can constitute up to 10% of the alloy composition (percentages given in weight percent unless otherwise noted). Impurity elements are also present, but their total percentage is usually less than 0.15% in aluminum alloys.

Classifications and Designations

It is convenient to divide aluminum alloys into two major categories: wrought composition and cast compositions. A further differentiation for each category is based on the primary mechanism of property development. Many alloys respond to thermal treatment based on phase solubilities. These treatments include solution heat treatment, quenching, and precipitation (or age) hardening. For either casting or wrought alloys, such alloys are described as heat treatable. A large number of other wrought compositions rely instead on work hardening through mechanical reduction, usually in combination with various annealing procedures for property development. These alloys are referred to as work hardening or non-heat-treatable. Some casting alloys are essentially not heat treatable and are used only in as-cast or in thermally modified conditions unrelated to solutions or precipitation effects.

Cast and wrought alloy nomenclatures have been developed. The Aluminum Association system is most widely recognized in the United States. Their alloy identification system employs different nomenclatures for wrought and cast alloys but divides alloys into families for simplification.

Wrought Alloy Families. For wrought alloys, a four-digit system is used to produce a list of wrought composition families as follows:

- 1*xxx*: Controlled unalloyed (pure) composition, used primarily in the electrical and chemical industries
- 2*xxx*: Alloys in which copper is the principal alloying element, although other elements, notably magnesium, can be specified. 2*xxx* series alloys are widely used in aircraft where their high strengths (yield strengths as high as 455 MPa, or 66 ksi) are valued.
- 3*xxx*: Alloys in which manganese is the principal alloying element, used as general-purpose alloys for architectural applications and various products
- 4*xxx*: Alloys in which silicon is the principal alloying element, used in welding rods and brazing sheet
- 5*xxx*: Alloys in which magnesium is the principal alloying element, used in boat hulls, gangplanks, and other products exposed to marine environments
- 6*xxx*: Alloys in which magnesium and silicon are the principal alloying elements, commonly used for architectural extrusions.
- 7*xxx*: Alloys in which zinc is the principal alloying element (although other elements, such as copper, magnesium, chromium, and zirconium, can be