Corrosion of Aluminum and Aluminum Alloys

Edited by
J.R. Davis

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Preface

Corrosion problems associated with aluminum and its alloys are as varied as the products made from them. For example, stress-corrosion cracking or corrosion fatigue of critical aircraft components, such as aluminum alloy landing gear parts, can lead to catastrophic failure. In the packaging industry, only minute amounts of pitting corrosion can be tolerated in aluminum beverage cans because of the long periods of exposure, the effect of corrosion on the beverage packaged, and the thinness of the container. In addition, even water staining corrosion can render the can stock sheet worthless.

Methods of preventing corrosion in these industries are equally diverse. The essential elements of an aircraft corrosion prevention and control program are proper material selection, an adequate finish specification, and a thorough plan for effective maintenance, monitoring, inspection, and repair. For protection of beverage cans, corrosion control may be as simple as applying lacquer to prevent pitting, or proper storage and shipment procedures to minimize water staining.

This book was designed for use by practicing engineers, as well as maintenance and operating personnel, who are concerned with the problem of corrosion of aluminum in their day-to-day job functions. It is not intended for those who are looking for advanced electrochemical theories and techniques. Instead, emphasis was placed on the forms of corrosion that affect aluminum, test methods for determining susceptibility to the various types of corrosion, and steps that can be taken to prevent corrosion.

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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	$2.655 \times 10^{-8}\ \Omega \cdot$ 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

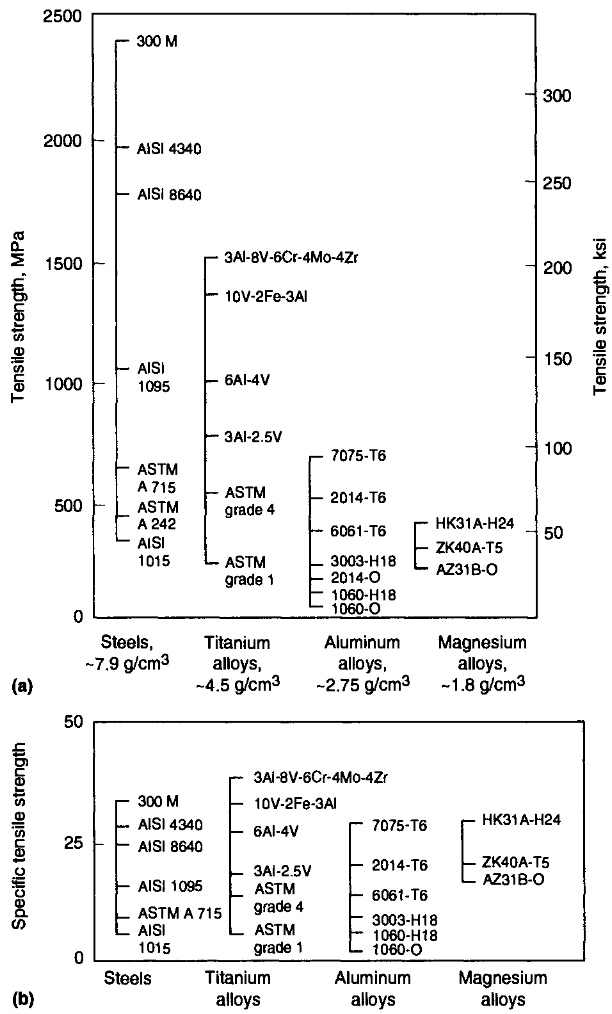

Fig. 1 Comparison of aluminum alloys with competing structural alloys on the basis of (a) tensile strength and (b) specific tensile strength (tensile strength, in ksi, divided by density, in g/cm^3)

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	Weldability(b) Arc	Weldability(b) 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

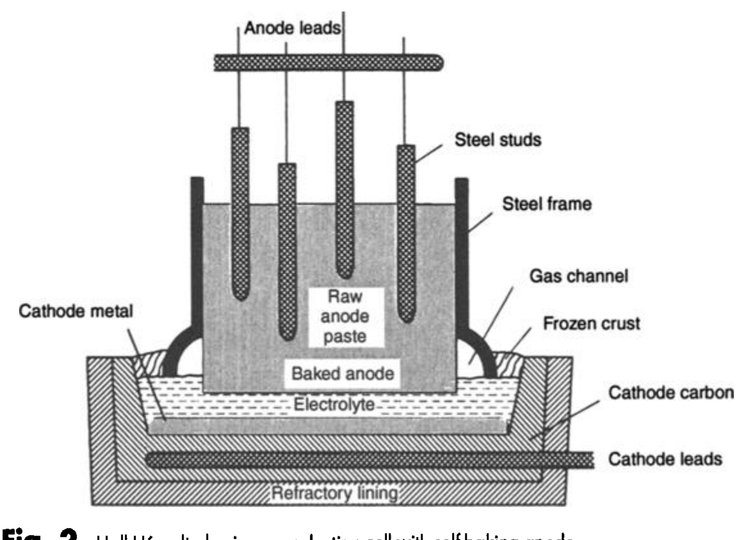

Fig. 2 Hall-Héroult aluminum production cell with self-baking anode

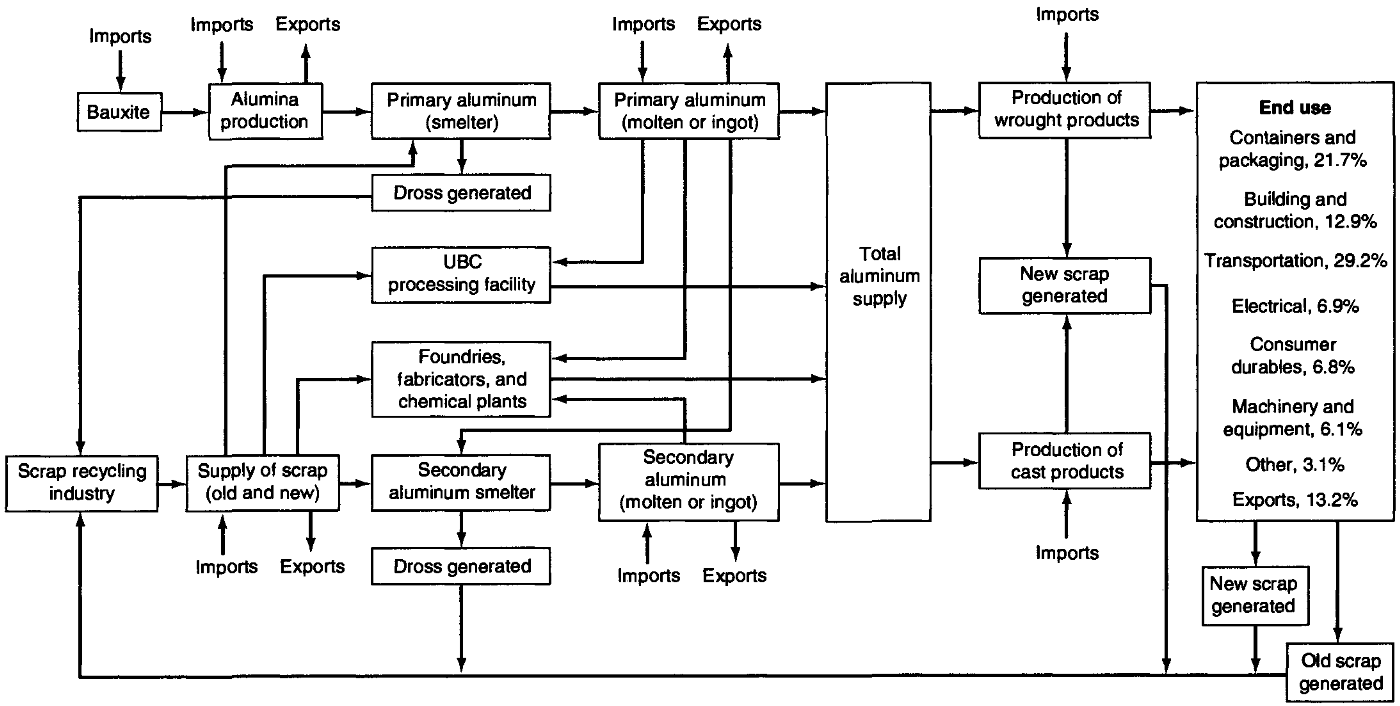

Fig. 3 Flow diagram for aluminum in the United States, showing the role of recycling in the industry. Scrap recycling (lower left) includes scrap collectors, processors, dealers and brokers, sweat furnace operators, and dross reclaimers.

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

specified), used in aircraft structural components and other high-strength applications. The 7*xxx* series are the strongest aluminum alloys, with yield strengths ≥500 MPa (≥73 ksi) possible.

- 8*xxx*: Alloys characterizing miscellaneous compositions. The 8*xxx* series alloys can contain appreciable amounts of tin, lithium, and/or iron.
- 9*xxx*: Reserved for future use

A comprehensive listing of composition limits for wrought aluminum and aluminum alloys can be found in Appendix 1 to this book.

Cast Alloy Families. Casting compositions are described by a three-digit system followed by a decimal value. The decimal .0 in all cases pertains to casting alloy limits. Decimals .1 and .2 concern ingot compositions, which, after melting and processing, should result in chemistries conforming to casting specifications requirements. Alloy families for casting compositions include the following:

- 1*xx.x*: Controlled unalloyed (pure) compositions, especially for rotor manufacture
- 2*xx.x*: Alloys in which copper is the principal alloying element. Other alloying elements may be specified.
- 3*xx.x*: Alloys in which silicon is the principal alloying element. The other alloying elements such as copper and magnesium are specified. The 3*xx.x* series comprises nearly 90% of all shaped castings produced.
- 4*xx.x*: Alloys in which silicon is the principal alloying element
- 5*xx.x*: Alloys in which magnesium is the principal alloying element
- 6*xx.x*: Unused
- 7*xx.x*: Alloys in which zinc is the principal alloying element. Other alloying elements such as copper and magnesium may be specified.
- 8*xx.x*: Alloys in which tin is the principal alloying element
- 9*xx.x*: Unused

A comprehensive listing of composition limits for cast aluminum and aluminum alloys can be found in Appendix 2 to this book.

Temper Designations. The temper designation system adopted by the Aluminum Association and used in the United States is used for all product forms (both wrought and cast), with the exception of ingot. The system is based on the sequences of mechanical or thermal treatments, or both, used to produce the various tempers. The temper designation follows the alloy designation and is separated from it by a hyphen.

Aluminum alloys are hardened and strengthened by either deformation at room temperature, referred to as strain hardening and designation by the letter H, or by an aging heat treatment designated by the letter T. If a wrought alloy has been annealed to attain its softest condition, the letter O is used in the temper designation. If the product has been shaped without any attempt to control the amount of hardening, the letter F (as-fabricated) is used for the temper designation. The strain-hardened and heat-treated conditions are further subdivided according to the degree of strain hardening and the type of heat treating. Major subdivisions of basic tempers (i.e., H, T, O, and F) are indicated by one or more digits following the letter. A more complete description of the temper designation system for aluminum and aluminum alloys can be found in Appendix 3 to this book.

Effects of Alloying Additions

A brief summary of the effects of the principal alloying additions on aluminum is given here. Emphasis is placed on their influence on strength and response to heat treatment . The effects of alloying elements on the corrosion resistance of aluminum alloys is discussed in Chapter 2, "Understanding the Corrosion Behavior of Aluminum," as well as in other chapters in this book that deal with specific forms of corrosion (e.g., stress-corrosion cracking).

Copper is one of the most important additions to aluminum. It has appreciable solubility and a substantial strengthening effect through the age-hardening characteristics it imparts to aluminum. Many alloys contain copper either as the major addition (2*xxx* or 2*xx.x* series) or as an additional alloying element, in concentrations of 1 to 10%.

Manganese has limited solid solubility in aluminum but in concentrations of about 1% forms an important series of non-heat-treatable wrought aluminum alloys (3*xxx* series). It is employed widely as a supplementary addition in both heat treatable and non-heat-treatable alloys and provides substantial strengthening.

Silicon lowers the melting point and increases the fluidity (improves casting characteristics) of aluminum. A moderate increase in strength is also provided by silicon additions.

Magnesium provides substantial strengthening and improvement of the work-hardening characteristics of aluminum. It has a relatively high solubility in solid aluminum, but Al-Mg alloys containing less than 7% Mg (5*xxx* series) do not show appreciable heat treatment characteristics. Magnesium is also added in combination with other elements, notably copper and zinc, for even greater improvements in strength.

Zinc is employed in casting alloys and in conjunction with magnesium in wrought alloys to produce heat treatable alloys (7*xxx* series) having the highest strength among aluminum alloys.

Copper and silicon are used together in the commonly used 3*xx.x* series casting alloys. Desirable ranges of characteristics and properties are obtained in both heat treatable and non-heat-treatable alloys.

Magnesium and silicon are added in appropriate proportions to form Mg_2Si, which is a basis for age hardening in both wrought and (6*xxx* series) and casting (3*xx.x* series) alloys.

Tin improves the antifriction characteristic of aluminum, and cast Al-Sn alloys (8*xx.x* series) are used for bearings.

Lithium is added to some alloys in concentrations approaching 3 wt% to decrease density and increase the elastic modulus. Examples include Al-Cu-Li alloys (e.g., 2091) containing 1.7 to 2.3% Li and Al-Li-Cu-Mg alloys (e.g., 8090) containing 2.2 to 2.7% Li.

Properties of Wrought Alloys

Non-heat-treatable wrought aluminum alloys are those that derive their strength from solid-solution or dispersion hardening and are further strengthened by strain hardening. They include 1*xxx*, 3*xxx*, 4*xxx*, 5*xxx*, and some 8*xxx* (Al-Fe and Al-Fe-Ni) alloys. Heat treatable alloys are strengthened by solution heat treatment and controlled aging and include the 2*xxx*, 6*xxx*, 7*xxx*, and some 8*xxx* (Al-Li-Cu-Mg) alloys. The strength ranges attainable with various classes of wrought alloys are given in Table 4.

Mechanical Properties. Typical mechanical (tensile) properties of some commonly used wrought aluminum alloys are shown in Tables 5 and 6. In Table 5, mechanical properties are shown for several representative non-heat-treatable alloys in the annealed, half hard and full hard tempers; values for high-purity aluminum (99.99%) are included for comparison. Although pure aluminum can be substantially strain hardened, a mere 1% alloying addition produces a comparable tensile strength to that of fully hardened pure aluminum with much greater ductility in the alloy. The alloys can then be substantially strain hardened to produce even greater strengths.

While strain hardening increases both tensile and yield strengths, the effect is more pronounced for the yield strength so that it approaches the tensile strength, and they are nearly equal in the fully hard temper. Ductility and workability are reduced as the material is

Table 4 Strength ranges of various wrought aluminum alloys

Aluminum Association series	Type of alloy composition	Strengthening method	Tensile strength range MPa	ksi
1*xxx*	Al	Cold work	70–175	10–25
2*xxx*	Al-Cu-Mg (1–2.5% Cu)	Heat treat	170–310	25–45
2*xxx*	Al-Cu-Mg-Si (3–6% Cu)	Heat treat	380–520	55–75
3*xxx*	Al-Mn-Mg	Cold work	140–280	20–40
4*xxx*	Al-Si	Cold work (some heat treat)(a)	105–350	15–50
5*xxx*	Al-Mg (1–2.5% Mg)	Cold work	140–280	20–40
5*xxx*	Al-Mg-Mn (3-6% Mg)	Cold work	280–380	40–55
6*xxx*	Al-Mg-Si	Heat treat	150–380	22–55
7*xxx*	Al-Zn-Mg	Heat treat	380–520	55–75
7*xxx*	Al-Zn-Mg-Cu	Heat treat	520–620	75–90
8*xxx*	Al-Li-Cu-Mg	Heat treat	280–560	40–80

(a) Alloy 4032 is heat treatable.

Table 5 Typical mechanical properties of representative non-heat-treatable aluminum alloys

Alloy	Nominal composition	Temper	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.), %	Hardness(a), HB
1199	99.99+% Al	O	45	6.5	10	1.5	50	...
		H18	117	17	110	16	5	...
1100	99+% Al	O	90	13	34	5	35	23
		H14	124	18	117	17	9	32
		H18	165	24	152	22	5	44
3003	1.2% Mn	O	110	16	41	6	30	28
		H14	152	22	145	21	8	40
		H18	200	29	186	27	4	55
3004	1.2% Mn, 1.0% Mg	O	179	26	69	10	20	45
		H34	241	35	200	29	9	63
		H38	283	41	248	36	5	77
5005	0.8% Mg	O	124	18	41	6	25	28
		H34	159	23	138	20	8	41
		H38	200	29	186	27	5	55
5052	2.5 Mg	O	193	28	90	13	25	47
		H34	262	38	214	31	10	68
		H38	290	42	255	37	7	77
5456	5.1% Mg, 0.8% Mn	O	310	45	159	23	24	...
		H116	352	51	255	37	16	90

(a) 500 kg load on 10 mm ball

strain hardened, and most alloys have limited formability in the fully hard tempers.

The effect of alloying additions on the strength of annealed aluminum is dramatically depicted in Fig. 4 The pseudolinear relationship between yield strength and percent alloying addition extends to the strongest non-heat-treatable commercial alloy, 5456, with approximately 6% Mg plus Mn (minor alloying elements have not been figured into the percent alloying additions). This relationship does not hold for the heat treatable 2*xxx* and 7*xxx* series alloys.

Table 6 lists typical mechanical properties and nominal compositions of some representative heat treatable aluminum alloys. The strengthening effect of the alloying additions in these alloys is not reflected in the annealed condition to the same extent as that in the non-heat-treatable alloys (see Fig. 4), but the full value of the additions can be seen in the aged conditions. Aged heat treatable alloys are significantly stronger than full hard non-heat-treatable alloys and generally retain more ductility. The range of strengths available with commonly used aluminum alloys is shown in Table 4 and Fig. 5.

Mechanical Properties at Low Temperatures. Aluminum alloys represent a very important class of structural metals for subzero-temperature applications and are used for structural parts operating at temperatures as low as –270 °C (–450 °F). Below zero, most aluminum alloys show little change in properties. Yield and tensile strengths can increase (Fig. 6), and elongation can decrease slightly. Impact strength remains approximately constant. Consequently, alumi-

Table 6 Typical mechanical properties of representative heat-treatable aluminum alloys

Alloy	Nominal composition	Temper	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation in 50 mm (2 in.), %	Hardness(a), HB
2219	6.3% Cu,	O	172	25	69	10	18	...
	0.3% Mn	T37	393	57	317	46	11	117
		T87	476	69	393	57	10	130
2024	4.4% Cu,	O	186	27	76	11	20	47
	1.5% Mg,	T4	469	68	324	47	20	120
	0.6% Mn	T861	517	75	490	71	6	135
4032	12.2% Si	T6	379	55	317	46	9	120
6061	1.0% Mg,	O	124	18	55	8	25	30
	0.6% Si	T4	241	35	145	21	22	65
		T6	310	45	276	40	12	95
7005	4.6% Zn,	O	193	28	83	12	20	...
	1.4% Mg	T6	352	51	290	42	13	...
7075	5.6% Zn,	O	228	33	103	15	17	60
	2.4% Mg,	T6	572	83	503	73	11	150
	1.6% Cu	T73	503	73	434	63	13	...

(a) 500 kg load on 10 mm ball

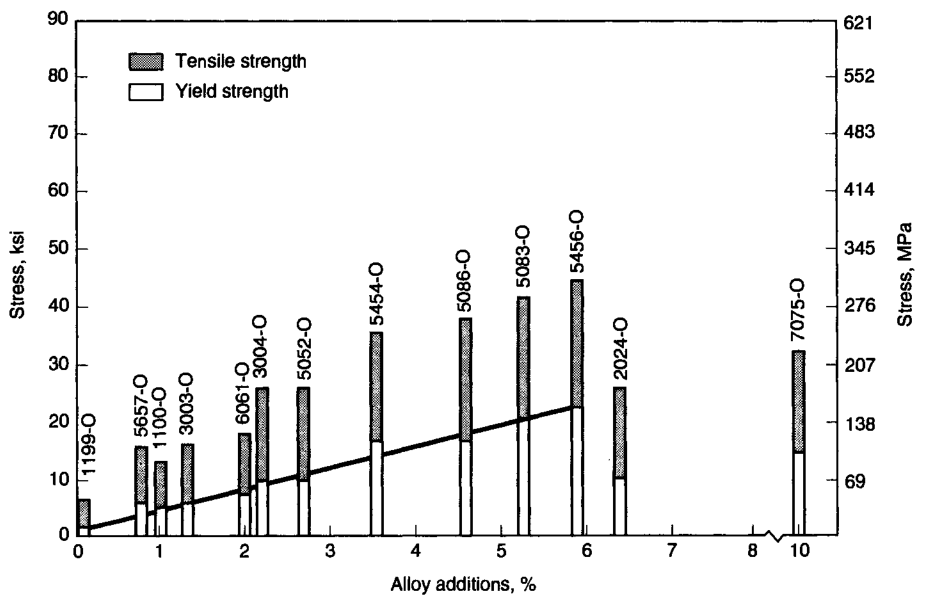

Fig. 4 Relationship between strength and amount of alloy additions for annealed wrought aluminum alloys

Preview for: *Corrosion of Aluminum and Aluminum Alloys*, edited by J.R. Davis, ASM International, 1999
Full digital book available at https://doi.org/10.31399/asm.tb.caaa.9781627082990

num is a useful material for many low-temperature applications. The wrought alloys most often considered for low-temperature service are alloys 1100, 2014, 2024, 2090, 2219, 3003, 5083, 5456, 6061, 7005, 7039, and 7075.

Mechanical Properties at Elevated Temperatures. A limitation to the use of aluminum is its loss of strength at elevated temperatures. Figure 7 demonstrates this clearly for both heat treatable and non-heat-treatable alloys. The strength of the age-hardenable alloys declines rapidly if they are exposed to elevated temperatures, due mainly to coarsening of the fine precipitates on which the alloys depend for their strength. Strength at temperatures above about 150 °C (300 °F) is improved mainly by solid-solution strengthening or second-phase hardening.

Fracture Toughness. Aluminum alloys chosen for fracture-critical applications are based on Al-Cu (2*xxx* series, e.g., 2024 and 2124), Al-Mg-Si (6*xxx* series, e.g., 6061), Al-Zn-Mg (7*xxx* series, e.g., 7075, 7150, and 7475), and more recently, lithium-containing alloys such as 8090 and 2091 series. High-strength

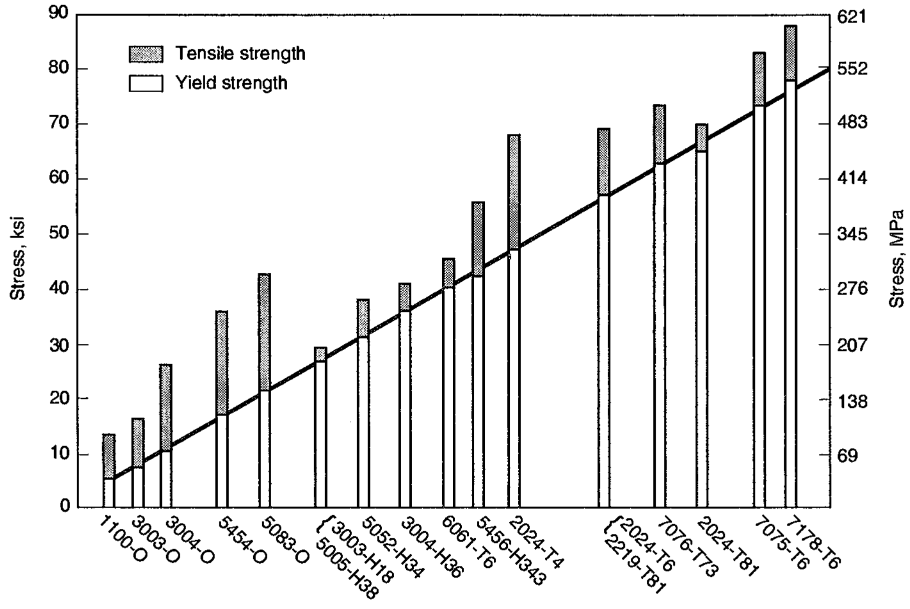

Fig. 5 Comparison of strengths of wrought aluminum alloys

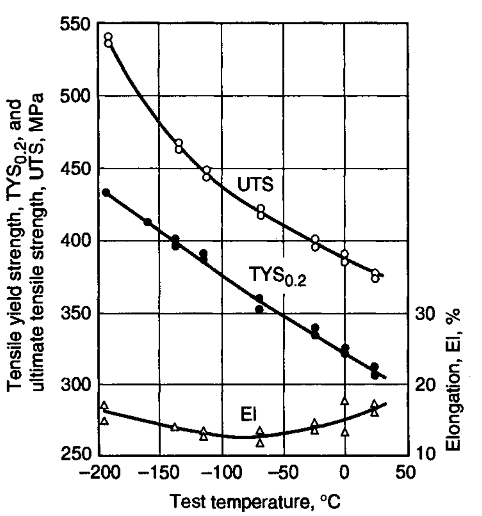

Fig. 6 Low-temperature properties of 6061-T6 aluminum alloy

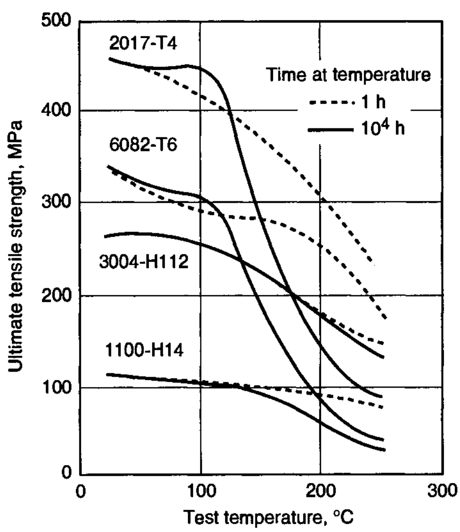

Fig. 7 Elevated-temperature properties of various aluminum alloys

Table 7 Typical physical properties of representative annealed wrought aluminum alloys

Alloy	Density g/cm^3	Approximate melting range °C	Approximate melting range °F	Thermal conductivity at 25 °C (77 °F) W/m · K	Thermal conductivity at 25 °C (77 °F) Btu/ft · h · °F	Electrical conductivity(a), %IACS
Non-heat-treatable alloys						
1100	2.71	643–657	1190–1215	222	128	59
3003	2.73	643–654	1190–1210	193	112	50
3004	2.72	629–654	1165–1210	163	94	42
5005	2.70	632–654	1170–1210	200	116	52
5052	2.68	607–649	1125–1200	138	80	35
5456	2.66	568–638	1055–1180	117	67.5	29
Heat treatable alloys						
2219	2.84	543–643	1010–1190	121	70	30
2024	2.77	502–638	935–1180	121	70	30
4032	2.68	532–571	990–1060	155	90	40
6061	2.70	582–652	1080–1205	167	97	43
7005	2.78	607–646	1125–1195	...	...	...
7075	2.80	477–635	890–1175	130	75	33

(a) Equal volume at 20 °C (68 °F)

alloys with improved fracture toughness have evolved through microstructure control obtained by increased purity, modified composition, and better fabrication and heat treatment practice. Figure 8 shows the relationship between fracture toughness and yield strength for 2*xxx* and 7*xxx* alloys.

Physical Properties. Table 7 lists densities, melting points, thermal conductivities, and electrical conductivities for selected wrought aluminum alloys.

Properties of Cast Alloys

Casting alloys cannot, of course, be work hardened and are either used in the as-cast or heat treated conditions. Heat treatable casting alloys include the 2*xx*, 3*xx*, and 7*xx* series.

Mechanical Properties. Table 8 lists typical mechanical properties and nominal compositions of some representative cast aluminum alloys. Typical tensile properties and nominal compositions of some representative cast aluminum alloys. Typical tensile properties for commonly used casting alloys range from about 145 to 485 MPa (20 to 70 ksi) for ultimate tensile strength, 70 to 415 MPa (10 to 60 ksi) for yield strength, and <1.0 to 20% elongation. As with wrought alloys compositional changes and heat treatment can have a significant effect on properties.

Physical Properties. Table 9 lists densities, melting points, thermal conductivities, and electrical conductivities for selected cast aluminum alloys.

Manufactured Forms

As shown in Table 10, mill products, which include wrought products and powder and paste, constitute the

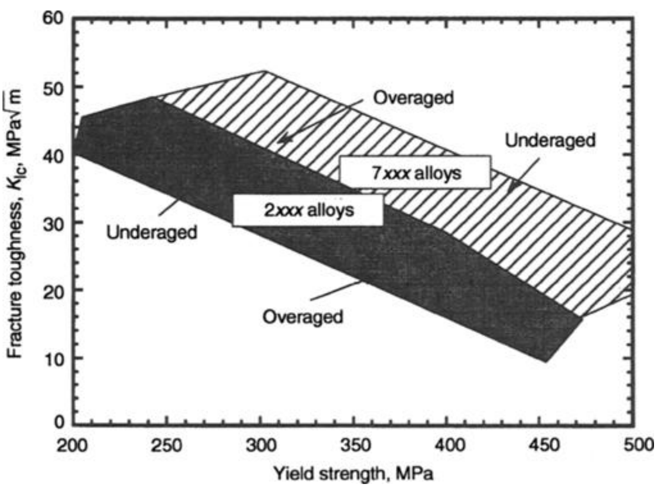

Fig. 8 The effects of alloy type and aged condition on the strength/fracture toughness relationship for aluminum alloys

majority (~74%) of aluminum shipments in the United States. Aluminum ingot for castings, destructive uses, and exports represent the remainder of net shipments.

Wrought aluminum products can be divided into two groups. Standardized wrought products include sheet, plate, foil, rod, bar, wire, tube, pipe, and structural forms. Engineered wrought products are those designed for specific applications and include extruded shapes, forgings, and impacts. Typical examples of wrought products include plate or sheet, which is subsequently formed or machined into products such as aircraft or building components, household foil, and extruded shapes such as storm window frames.

Cast Aluminum Products. Aluminum castings are produced in a great variety of shapes and sizes by pressure-die, permanent-mold, green- and dry-sand, investment, and plaster casting. Process variations include vacuum, low-pressure, centrifugal, and pattern-related processes such as lost foam casting. Table 11 provides shipment statistics for aluminum castings. Transportation is the leading market, and the trend toward increasing use in automotive applications is increasing the importance of castings in the total industry picture.

Powder Metallurgy Products. Structural parts made by powder metallurgy (P/M) methods constitute only a very small part of the overall aluminum industry. In fact, the majority of aluminum powder produced is used for nonstructural applications (e.g., paints, pigments, and explosives). Aluminum P/M parts are produced by pressing and sintering of atomized powders or by vacuum hot pressing or hot isostatically pressing aluminum powders into billets, which are subsequently rolled, extruded, or forged.

Table 8 Typical mechanical properties of representative aluminum casting alloys

Alloy	Nominal composition	Product(a)	Temper	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation, %	Hardness(b), HB
201.0	4.6% Cu	S	T4	365	53	215	31	20	95
		S	T6	485	70	435	63	7	135
		S	T7	460	67	415	60	4.5	130
355.0	5% Si, 1.3% Cu	S	T51	195	28	160	23	1.5	65
		S	T6	240	35	175	25	3.0	80
		S	T61	270	39	240	35	1.0	90
		S	T7	265	38	250	36	0.5	85
		S	T71	175	35	200	29	1.5	75
		P	T51	210	30	165	24	2.0	75
		P	T6	290	42	190	27	4.0	90
		P	T62	310	45	280	40	1.5	105
		P	T7	280	40	210	30	2.0	85
		P	T71	250	36	215	31	3.0	85
356.0	7% Si, 0.3% Mg	S	T51	175	25	140	20	2.0	60
		S	T6	230	33	165	24	3.5	70
		S	T7	235	34	210	30	2.0	75
		S	T71	195	28	145	21	3.5	60
		P	T6	265	38	185	27	5.0	80
		P	T7	220	32	165	24	6.0	70
380.0	8.5% Si, 3.5% Cu	D	F	330	48	165	24	3.0	...
390.0	17% Si, 4.5% Cu	D	F	280	41	240	35	1.0	120
		D	T5	300	43	260	38	1.0	125
413.0	12% Si	D	F	300	43	140	21	2.5	...
B443.0	5.2% Si	P	F	159	23	62	9	10.0	...

(a) S, sand; P, permanent mold; D, die cast. (b) 500 kg load on 10 mm ball

Table 9 Typical physical properties of representative aluminum casting alloys

Alloy	Density g/cm^3	Approximate melting range °C	Approximate melting range °F	Thermal conductivity at 25 °C (77 °F) W/m · K	Thermal conductivity at 25 °C (77 °F) Btu/ft · h · °F	Electrical conductivity(a), %IACS
201.0	2.80	571–649	1060–1200	121	70	30
355.0	2.71	549–621	1020–1150	150	87	39
356.0	2.69	560–616	1040–1140	150	87	41
380.0	2.71	521–588	970–1090	108	62	27
390.0	2.73	505–650	945–1200	134	77	27
413.0	2.66	577–588	1070–1090	154	89	39
B443.0	2.69	577–632	1070–1170	146	84	37

(a) Equal volume at 20 °C (68 °F)

Applications

In the United States the aluminum industry has identified its major markets as building and construction, transportation, consumer durables, electrical, machinery and equipment, containers and packaging, exports, and other end uses. As described here, each major market comprises a wide range of end uses. Table 12 provides data on U.S. shipments of aluminum by major markets. The characteristics of aluminum and their importance for different end uses were addressed in this chapter in Table 2 and associated text. Tables 13 and 14 list typical applications for some of the more commonly used wrought and cast alloys, respectively.

Building and Construction Applications

Aluminum is used extensively in buildings of all kinds, bridges, towers, and storage tanks. Because structural steel shapes and plate are usually lower in initial cost, aluminum is used when engineering advantages, construction features, unique architectural designs, light weight, and/or corrosion resistance are considerations.

Static Structures. Design and fabrication of aluminum static structures differ little from practices used with steel. The modulus of elasticity of aluminum is one-third that of steel and requires special attention to compression members. However, it offers advantages under shock loads and in cases of minor misalignments. When properly designed, aluminum typically saves over 50% of the weight required by low-carbon steel in small structures; similar savings are possible in long-span or movable bridges. Savings also result from low maintenance costs and in resistance to atmospheric or environmental corrosion.

Forming, shearing, sawing, punching, and drilling are readily accomplished on the same equipment used for fabricating structural steel. Since structural aluminum alloys owe their strength to properly controlled heat treatment, hot forming or other subsequent thermal operations are to be avoided. Special attention must be given to the strength requirements of welded areas because of the possibility of localized annealing effects.

Buildings. Corrugated or otherwise stiffened sheet products are used in roofing and siding for industrial and agricultural building construction. Ventilators, drainage slats, storage bins, window and door frames, and other components are additional applications for sheet, plate, castings, and extrusions.

Aluminum products such as roofing, flashing, gutters, and downspouts are used in homes, hospitals, schools, and commercial and office buildings. Exterior walls, curtain walls, and interior applications such as wiring, conduit, piping, ductwork, hardware, and railings utilize aluminum in many forms and finishes.

Aluminum is used in bridges and highway accessories such as bridge railings, highway guard rails, lighting standards, traffic control towers, traffic signs, and chain-link fences.

Aluminum is also commonly used in bridge structures, especially in long-span or movable bascule and vertical-lift construction. Construction of portable military bridges and superhighway overpass bridges has increasingly relied on aluminum elements. Aluminum is also used for prefabricated pedestrian bridges.

Scaffolding, ladders, electrical substation structures, and other utility structures utilize aluminum, chiefly in the form of structural and special extruded shapes. Cranes, conveyors, and heavy-duty handling systems incorporate significant amounts of aluminum. Water

Table 10 U.S. aluminum industry net shipments in 1997

Product	Shipment, millions of pounds	Percentage of total
Sheet	>9,795	43.4
Plate	479	2.1
Foil	1,262	5.6
Rod, bar, and wire	619	2.7
Electrical conductor	658	2.9
Extruded shapes and tube	3,473	15.4
Powder and paste	146	0.6
Forgings and impacts	232	1.0
Total mill products	**16,664**	**73.8**
Ingot for castings and other	5,904	26.2
Total industry shipments	**22,568**	**100.0**

Source: The Aluminum Association Inc.

Table 11 Shipments of aluminum castings by type in 1996

Type of casting	Shipments(a)		Percentage of
	10^6 kg	10^6 lb	total
Die castings	1076.1	2372.3	57.7
Permanent mold and semi-permanent mold castings	548.4	1209.1	29.4
Sand castings	153.9	339.4	8.2
Others	87.9	193.9	4.7
Total	**1866.4**	**4114.6**	**100**

(a) Rounded values might not add up to the totals shown. Source: The Aluminum Association Inc.

Table 12 U. S. net shipments by major market in 1997

Major market	Shipment, millions of pounds	Percentage of total
Building and construction	2,921	12.9
Transportation	6,592	29.2
Consumer durables	1,529	6.8
Electrical	1,561	6.9
Machinery and equipment	1,381	6.1
Containers and packaging	4,895	21.7
Other	701	3.1
Domestic, total	**19,580**	**86.8**
Exports	2,988	13.2
Total shipments	**22,568**	**100.0**

Source: The Aluminum Association Inc.

storage tanks are often constructed of aluminum alloys to improve resistance to corrosion and to provide attractive appearance.

Containers and Packaging

The food and drug industries use aluminum extensively because it is nontoxic, nonadsorptive, and splinterproof. It also minimizes bacterial growth, forms colorless salts, and can be steam cleaned. Low volumetric specific heat results in economies when containers or conveyors must be moved in and out of heated or refrigerated areas. The nonsparking property of aluminum is valuable in flour mills and other plants subject to fire and explosion hazards. Corrosion resistance is important in shipping fragile merchandise, valuable chemicals, and cosmetics. Sealed aluminum containers designed for air, shipboard, rail, or truck shipments are used for chemicals not suited for bulk shipment.

Packaging has been one of the fastest growing markets for aluminum. Products include household wrap, flexible packaging and food containers, bottle caps, collapsible tubes, and beverage and food cans. Aluminum foil works well in packaging and for pouches and wraps for foodstuffs and drugs, as well as for household uses.

Table 13 Selected applications for wrought aluminum alloys

Alloy	Description and selected applications
1100	Commercially pure aluminum highly resistant to chemical attack and weathering. Low cost, ductile for deep drawing, and easy to weld. Used for high-purity applications such as chemical processing equipment. Also for nameplates, fan blades, flue lining, sheet metal work, spun holloware, and fin stock
1350	Electrical conductors
2011	Screw machine products. Appliance parts and trim, ordnance, automotive, electronic, fasteners, hardware, machine parts
2014	Truck frames, aircraft structures, automotive, cylinders and pistons, machine parts, structurals
2017	Screw machine products, fittings, fasteners, machine parts
2024	For high-strength structural applications. Excellent machinability in the T-tempers. Fair workability and fair corrosion resistance. Alclad 2024 combines the high strength of 2024 with the corrosion resistance of the commercially pure cladding. Used for truck wheels, many structural aircraft applications, gears for machinery, screw machine products, automotive parts, cylinders and pistons, fasteners, machine parts, ordnance, recreation equipment, screws and rivets
2219	Structural uses at high temperature (to 315 °C, or 600 °F). High-strength weldments
3003	Most popular general-purpose alloy. Stronger than 1100 with same good formability and weldahility. For general use including sheet metal work, stampings, fuel tanks, chemical equipment, containers, cabinets, freezer liners, cooking utensils, pressure vessels, builder's hardware, storage tanks, agricultural applications, appliance parts and trim, architectural applications, electronics, fin stock, fan equipment, name plates, recreation vehicles, trucks and trailers. Used in drawing and spinning.
3004	Sheet metal work, storage tanks, agricultural applications, building products, containers, electronics, furniture, kitchen equipment, recreation vehicles, trucks and trailers
3105	Residential siding, mobile homes, rain-carrying goods, sheet metal work, appliance parts and trim, automotive parts, building products, electronics, fin stock, furniture, hospital and medical equipment, kitchen equipment, recreation vehicles, trucks and trailers
5005	Specified for applications requiring anodizing; anodized coating is cleaner and lighter in color than 3003. Uses include appliances, utensils, architectural, applications requiring good electrical conductivity, automotive parts, containers, general sheet metal, hardware, hospital and medical equipment, kitchen equipment, name plates, and marine applications.
5052	Stronger than 3003 yet readily formable in the intermediate tempers. Good weldability and resistance to corrosion. Uses include pressure vessels, fan blades, tanks, electronic panels, electronic chassis, medium-strength sheet metal parts, hydraulic tube, appliances, agricultural applications, architectural uses, automotive parts, building products,
5052 (continued)	chemical equipment, containers, cooking utensils, fasteners, hardware, highway signs, hospital and medical equipment, kitchen equipment, marine applications, railroad cars, recreation vehicles, trucks and trailers
5056	Cable sheathing, rivets for magnesium, screen wire, zippers, automotive applications, fence wire, fasteners
5083	For all types of welded assemblies, marine components, and tanks requiring high weld efficiency and maximum joint strength. Used in pressure vessels up to 65 °C (150 °F) and in many cryogenic applications, bridges, freight cars, marine components, TV towers, drilling rigs, transportation equipment, missile components, and dump truck bodies. Good corrosion resistance
5086	Used in generally the same types of applications as 5083, particularly where resistance to either stress corrosion or atmospheric corrosion is important
5454	For all types of welded assemblies, tanks, pressure vessels. ASME code approved to 205 °C (400 °F). Also used in trucking for hot asphalt road tankers and dump bodies; also, for hydrogen peroxide and chemical storage vessels
5456	For all types of welded assemblies, storage tanks, pressure vessels, and marine components. Used where best weld efficiency and joint strength are required. Restricted to temperatures below 65 °C (150 °F)
5657	For anodized auto and appliance trim and nameplates
6061	Good formability, weldability, corrosion resistance, strength in the T-tempers. Good general-purpose alloy used for a broad range of structural applications and welded assemblies including truck components, railroad cars, pipelines, marine applications, furniture, agricultural applications, aircrafts, architectural applications, automotive parts, building products, chemical equipment, dump bodies, electrical and electronic applications, fasteners, fence wire, fan blades, general sheet metal, highway signs, hospital and medical equipment, kitchen equipment, machine parts, ordnance, recreation equipment, recreation vehicles, and storage tanks.
6063	Used in pipe railing, furniture, architectural extrusions, appliance parts and trim, automotive parts, building products, electrical and electronic parts, highway signs, hospital and medical equipment, kitchen equipment, marine applications, machine parts, pipe, railroad cars, recreation equipment, recreation vehicles, trucks and trailers
7050	High-strength alloy in aircraft and other structures. Also used in ordnance and recreation equipment
7075	For aircraft and other applications requiring highest strengths. Alclad 7075 combines the strength advantages of 7075 with the corrosion-resisting properties of commercially pure aluminum-clad surface. Also used in machine parts and ordnance

Beverage cans have been the greatest success story of the aluminum industry and market penetrations by the food can are accelerating. Soft drinks, beer, coffee, snack foods, meat, and even wine are packaged in aluminum cans. Draft beer is shipped in alclad aluminum barrels. Aluminum is used extensively in collapsible tubes for ointments, food, and paints.

Transportation

Automotive. Both wrought and cast aluminum have found wide use in automobile construction (Table 15). Although aluminum currently accounts for less than 10% of the total weight of a vehicle, this percentage is expected to increase dramatically as average fuel economy mandates and emphasis on recycling continues. As an example of environmental strengths of aluminum for automotive applications, more than 85% of post-consumer automotive scrap and virtually all post-manufacturing automotive scrap is recycled. Some 60 to 70% of all automotive aluminum originates from recycled metal.

Aluminum sand, die, and permanent mold castings are critically important in engine construction; engine blocks, pistons, cylinder heads, intake manifolds, crankcases, carburetors, transmission housings, and rocker arms are proven components. Brake valves and brake calipers join innumerable other components in car design importance. Cast aluminum wheels continue to grow in popularity. Aluminum sheet is used for hoods, trunk decks, bright finish trim, air intakes, and bumpers. Extrusions and forgings are finding new and extensive uses. Forged aluminum alloy wheels are a premium option.

Because of its lighter weight and corrosion resistance, aluminum is also a prime candidate to replace steel sheet in "body-in-white" (structural shell/skin) applications. Aluminum has one-third the density of steel, which means a component can be 1.5 times thicker than a steel version while remaining 50% lighter. It can absorb twice as much energy as steel at the same weight. Aluminum is corrosion resistant, unlike steel, which must be coated with other metals such as zinc (galvanized steel) to improve its resistance to corrosion. The lighter weight and stiffness of aluminum can enhance vehicle acceleration and handling and reduce noise and vibration characteristics.

Trucks. Because of weight limitations and a desire to increase effective payloads, manufacturers have intensively employed aluminum in cab, trailer, and truck designs. Sheet alloys are used in truck cab bodies, and dead weight is also reduced using extruded stringers, frame rails, and cross members. Extruded or formed sheet bumpers and forged wheels are usual. Fuel tanks of aluminum offer weight reduction, corrosion resis-

Table 14 Selected applications for aluminum casting alloys

Alloy	Representative applications
100.0	Electrical rotors larger than 152 mm (6 in.) in diameter
201.0	Structural members; cylinder heads and pistons; gear, pump, and aerospace housings
208.0	General-purpose castings; valve bodies, manifolds, and other pressure-tight parts
222.0	Bushings; meter parts; bearings; bearing caps; automotive pistons; cylinder heads
238.0	Sole plates for electric hand irons
242.0	Heavy-duty pistons; air-cooled cylinder heads; aircraft generator housings
A242.0	Diesel and aircraft pistons; air-cooled cylinder heads; aircraft generator housings
B295.0	Gear housings; aircraft fittings; compressor connecting rnds; railway car seat frames
308.0	General-purpose permanent mold castings; ornamental grilles and reflectors
319.0	Engine crankcases; gasoline and oil tanks; oil pans; typewriter frames; engine parts
332.0	Automotive and heavy-duty piston pulleys, sheaves
333.0	Gas meter and regulator parts; gear blocks; pistons; general automotive castings
354.0	Premium-strength castings for the aerospace industry
355.0	Sand: air compressor pistons; printing press bedplates; water jackets; crankcases. Permanent: impellers; aircraft fittings; timing gears; jet engine compressor cases
356.0	Sand: flywheel castings; automotive transmission cases; oil pans; pump bodies. Permanent: machine tool parts; aircraft wheels; airframe castings; bridge railings
A356.0	Structural parts requiring high strength; machine parts; truck chassis parts
357.0	Corrosion-resistant and pressure-tight applications
359.0	High-strength castings for the aerospace industry
360.0	Outboard motor parts; instrument cases; cover plates; marine and aircraft castings
A360.0	Cover plates; instrument cases; irrigation system parts; outboard motor parts; hinges
380.0	Housings for lawn mowers and radio transmitters; air brake castings; gear cases
A380.0	Applications requiring strength at elevated temperature
384.0	Pistons and other severe service applications; automatic transmission
390.0	Internal combustion engine pistons, blocks manifolds, and cylinder heads
413.0	Architectural, ornamental, marine, and food and dairy equipment applications
A413.0	Outboard motor pistons; dental equipment; typewriter frames; street lamp housings
443.0	Cookware; pipe fittings; marine fittings; tire molds; carburetor bodies
514.0	Fittings for chemical and sewage use; dairy and fond handling equipment; tire molds
A514.0	Permanent mold casting of architectural fittings and ornamental hardware
518.0	Architectural and ornamental castings; conveyor parts; aircraft and marine castings
520.0	Aircraft fittings; railway passenger care frames; truck and bus frame sections
535.0	Instrument parts and other applications where dimensional stability is important
A712.0	General-purpose castings that require subsequent brazing
713.0	Automotive parts; pumps; trailer parts; mining equipment
850.0	Bushings and journal bearings for railroads
A850.0	Rolling mill bearings and similar applications

tance, and attractive appearance. Castings and forgings are used extensively in engines and suspension systems.

Truck trailers are designed for maximum payload and operating economy in consideration of legal weight requirements. Aluminum is used in frames, floors, roofs, cross sills, and shelving. Forged aluminum wheels are commonly used. Tanker and dump bodies are made from sheet and/or plate in riveted and welded assemblies.

Mobile homes and travel trailers usually are constructed of aluminum alloy sheet used bare or with mill-applied baked-enamel finish on wood, steel, or extruded aluminum alloy frames.

Bus manufacturers also are concerned with minimizing dead weight. Aluminum sheet, plate, and extrusions are used in body components and bumpers. Forged wheels are common. Engine and structural components in cast, forged, and extruded form are extensively used.

Bearings. Aluminum-tin and aluminum-silicon alloys are used in medium and heavy-duty gasoline and diesel engines for connecting-rod and main bearings. Cast and wrought bearings can be a composite with a steel backing and babbited or other plated overlay.

Railroad Cars. Aluminum is used in the construction of railroad hopper cars, box cars, refrigerator cars, and tank cars. Aluminum is also used extensively in passenger rail cars for mass transit systems.

Marine Applications. Aluminum is commonly used for a large variety of marine applications, including main strength members such as hulls and deckhouses, and other applications such as stack enclosures, hatch covers, windows, air ports accommodation ladders, gangways, bulkheads, deck plate, ventilation equipment, lifesaving equipment, furniture,

Table 15 Aluminum alloys used for automotive applications

Alloy	Typical applications
	Wrought alloy series
1000 series	
1100	Trim, nameplates, appliqués
1200	Extruded condenser tubes and fins
2000 series	
2008	Outer and inner body panels (also suitable for structural applications)
2010	Outer and inner body panels (also suitable for structural applications)
2011(a)	Screw machine parts
2017(a)	Mechanical fasteners
2024	Mechanical fasteners
2036	Outer and inner body panels, load floors, seat shells
2117(a)	Mechanical fasteners
3000 series	
3002	Trim, nameplates, appliqués
3003(a)	Braze-clad welded radiator tubes, heater cores, radiator, heater and evaporator fins, heater inlet and outlet tubes, oil coolers, and air conditioner liquid lines
3004	Interior panels and components
3005	Radiator, heater and evaporator fins
3102	Extruded condenser tubes
4000 series	
4004	Cladding for brazing sheet
4032	Forged pistons
4043	Welding wire
4045	Cladding for brazing sheet
4104	Cladding for brazing sheet
4343	Cladding for brazing sheet
5000 series	
5005	Trim, nameplates, appliqués
5052(a)	Interior panels and components, truck bumpers and body panels
5182(a)	Inner body panels, splash guards, heat shields, air cleaner trays and covers, structural and weldable parts, load floors (sheet)
5252	Trim
5454(a)	Various components, wheels, engine accessory brackets and mounts, welded structures (i.e. dump bodies, tank trucks, trailer tanks)
5457	Trim
5657	Trim
5754(a)	Inner body panels, splash guards, heat shields, air cleaner trays and covers, structural and weldable parts, load floors (sheet)
6000 series	
6009	Outer and inner body panels, load floors, bumper face bars, bumper reinforcements, structural and weldable parts, seat shells
6010	Outer and inner body panels, seat shells and tracks
6022(a)	Outer and inner body panels
6053	Mechanical fasteners
6061(a)	Body components (extruded), brackets (extruded and sheet), suspension parts (forgings), driveshafts (tubes), driveshaft yokes (impacts and forgings), spare tire carrier parts (extruded), bumper reinforcements, mechanical fasteners, brake cylinders (extruded), wheels (sheet), fuel delivery systems
6063	Body components (extruded)
6082	General structural, brake housings
6111(a)	Body panels
6262	Brake housings, brake pistons, general screw machine parts (anodized)
6463	Luggage racks, air deflectors
7000 series	
7003	Seat tracks, bumper reinforcements
7004	Seat tracks, bumper reinforcements
7021	Bumper face bars, brackets (sheet), bumper face bars (bright), bumper face bars (bright anodized), bumper reinforcements
7072(a)	Condenser and radiator fins
7116	Headrest bars
7129(a)	Bumper face bars, bumper reinforcements, headrest bars (extruded), seat track
	Casting alloys
319.0(a)	Manifolds, cylinder heads, blocks, internal engine parts
332.0	Pistons
356.0(a)	Cylinder heads, manifolds
A356.0(a)	Wheels
A380.0(a)	Blocks, transmission housings/parts, fuel metering devices
383.0	Brackets, housings, internal engine parts, steering gears
B390.0	High-wear applications such as ring gears and internal transmission parts

(a) More recent and commonly used alloys hardware, fuel tanks and bright trim. In addition, ships are making extensive use of welded aluminum alloy plate in the large tanks used for transportation of liquefied gases.

The corrosion-resistant aluminum alloys in current use permit designs that save approximately 50% of the weight of similar designs in steel. Substantial savings of weight in deckhouses and topside equipment permit lighter supporting structures. The cumulative savings in weight improve the stability of the vessel and allow the beam to be decreased. For comparable speed, the lighter, narrower craft will require a smaller power plant and will burn less fuel. Consequently, 1 kg (2.2 lb) of weight saved by the use of lighter structures or equipment frequently leads to an overall decrease in displaced weight of 3 kg (6.5 lb). Aluminum also reduces maintenance resulting from corrosive or biological attack.

The relatively low modulus of elasticity for aluminum alloys offers advantages in structures erected on a steel hull. Flexure of the steel hull results in low stresses in an aluminum superstructure, as compared with the stresses induced in a similar steel superstructure. Consequently, continuous aluminum deckhouses can be built without expansion joints.

Casting alloys are used in outboard motor structural parts and housings subject to continuous or intermittent immersion, motor hoods, shrouds, and miscellaneous parts, including fittings and hardware. Additional marine applications are in sonobuoys, navigation markers, rowboats, canoes, oars, and paddles.

Aerospace. Aluminum is used in virtually all segments of the aircraft, missile, and spacecraft industry—in airframes, engines, accessories, and tankage for liquid fuel and oxidizers. Aluminum is widely used because of its high strength-to-density ratio, corrosion resistance, and weight efficiency, especially in compressive designs.

Increased resistance to corrosion is secured through the use of alclad alloys or anodic coatings. The exterior of aircraft exposed to saltwater environment is usually fabricated from clad alloys. Anodized bare stock successfully resists corrosion when only occasional exposure to salt water is encountered. Corrosion resistance can be further enhanced by organic finishes or other protective coatings. The use of coatings to extend the corrosion resistance of aluminum is described in Chapter 11, "Corrosion Prevention Methods."

Electrical Applications

Conductor Alloys. The use of aluminum predominates in most conductor applications. Aluminum of controlled composition is treated with trace additions of boron to remove titanium, vanadium, and zirconium, each of which increases resistivity. The use of aluminum rather than competing materials is based on a combination of low cost, high electrical conductivity, adequate mechanical strength, low specific gravity, and excellent resistance to corrosion.

The most common conductor alloy (1350) offers a minimum conductivity of 61.8% of the International Annealed Copper Standard (IACS) and from 55 to 124 MPa (8 to 18 ksi) minimum tensile strength, depending on size. When compared with IACS on the basis of mass instead of volume, minimum conductivity of hard drawn aluminum 1350 is 204.6%. Other alloys are used in bus bar, in service at slightly elevated temperatures, and in cable television installations.

Cable sheathing is achieved by extruding the sheath in final position and dimensions around the cable as it is fed through an axial orifice in the extrusion die. It can also be done by threading the cable through an oversized prefabricated tube and then squeezing the tube to final dimensions around the cable by tube reducers and draw dies.

Conductor accessories can be rolled, extruded, cast, or forged. Common forms of aluminum conductors are single wire and multiple wire (stranded, bunched, or rope layed). Each is used in overhead or other tensioned applications, as well as in nontensioned insulated applications.

Size for size, the direct current resistance of the most common aluminum conductor is from approximately 1.6 to 2.0 times IACS. For equivalent direct current resistance, an aluminum wire that is two American Wire Gage sizes larger than copper wire must be used. Nevertheless, as a result of the lower specific gravity, the conductivity-based aluminum required weighs only about half as much as an equivalent copper conductor.

Aluminum conductors, steel reinforced (ACSR) consist of one or more layers of concentric-lay stranded aluminum wire around a high-strength galvanized or aluminized steel wire core, which itself may be a single wire or a group of concentric-lay strands. Electrical resistance is determined by the aluminum cross section, whereas tensile strength is determined on the composite with the steel core providing 55 to 60% of the total strength.

The ACSR construction is used for mechanical strength. Strength-to-weight ratio is usually about two times that of copper of equivalent direct current resistance. Use of ACSR cables permits longer spans and fewer or shorter poles or towers.

Bus Bar Conductors. Commercial bus design in the United States utilizes four types of bus conductors: rectangular bar, solid round bar, tubular and structural shapes.

Motors and Generators. Aluminum has long been used for cast rotor windings and structural parts. Rotor rings and cooling fans are pressure cast integrally with bars through slots of the laminated core in caged motor rotors.

Aluminum structural parts, such as stator frames and end shields, often are economically die cast. Their corrosion resistance may be necessary in specific environments—in motors for spinning natural and synthetic fiber, and in aircraft generators when light weight is equally important, for example.

Additional applications are field coils for direct current machines, stator windings in motors, and transformer windings. Alloyed wire is used in extremely large turbogenerator field coils, where operating temperatures and centrifugal forces might otherwise result in creep failure.

Transformers. Aluminum windings have been excessively used in dry-type power transformers and have been adapted to secondary coil windings in magnetic-suspension type constant current transformers. Their use decreases weight and permits the coil to float in electromagnetic suspension. In a closely associated application, aluminum is being used in concrete reactor devices that protect transformers from overloads.

Extruded shapes and punched sheet are used in radar antennas, extruded and roll-formed tubing in television antennas, rolled strips in coiled line traps; drawn or impact-extruded-cans in condensers and shields, and vaporized high-purity coatings in cathode-ray tubes.

Examples of applications in which electrical properties other than magnetic are not dominant are chassis for electronic equipment, spun pressure receptacles for airborne equipment, etched nameplates, and hardware such as bolts, screws, and nuts. In addition, finned shapes are used in electronic components to facilitate heat removal. Aluminum can be used as the cell base for the deposition of selenium in the manufacture of selenium rectifiers.

Lighting. Aluminum in incandescent and fluorescent lamp bases and other sheet alloys for sockets are established uses. Cast, stamped, and spun parts are used, often artistically, in table, floor, and other lighting fixtures. Aluminum reflector is common in fluorescent and other installed lighting systems.

Capacitors. Aluminum in the form of foil dominates all other metals in the construction of capacitor electrodes. Dry electrolytic and nonelectrolytic capacitors are the basic condenser types in extensive commercial use. Dry electrolytic capacitors usually employ parallel coiled or wrapped aluminum foil ribbons as electrodes. Paper saturated with an operative electrolyte and wrapped into the coil mechanically separates the ribbons. In designs for intermittent use in alternating circuits, both electrodes are anodized in a hot boric acid electrolyte. The resulting thin anodic films constitute the dielectric element.

Only the anode foil is anodized in dry electrolytic assemblies intended for direct current applications. Anodized electrodes are of high purity, whereas the nonanodized electrodes utilize foil ribbons of lower purity. Prior to anodizing, the foil is usually (but not always) etched to increase effective surface area. Containers for dry electrolytic capacitors can be either drawn or impact extruded.

Ordinary clean foil ribbons serve as electrodes in commercial nonelectrolytic capacitors. Oil-impregnated paper separates the electrodes and adjacent coils of the wrap. Nonelectrolytic foil assemblies are packed in either aluminum alloy or steel cans.

Consumer Durables

Household Appliances. Light weight, excellent appearance, adaptability to all forms of fabrication, and low cost of fabrication are the reasons for the broad usage of aluminum in household electrical appliances. Light weight is an important characteristic in vacuum cleaners, electric irons, portable dishwashers, food processors, and blenders. Low fabricating costs depend on several properties, including adaptability to die casting and ease of finishing. Because of a naturally pleasing appearance and good corrosion resistance, expensive finishing is not necessary.

In addition to other desirable characteristics, the brazeability of aluminum makes it useful for refrigerator and freezer evaporators. Tubing is placed on embossed sheet over strips of brazing alloy with a suitable flux. The assembly is then furnace brazed, and the residual flux is removed by successive washes in boiling water, nitric acid, and cold water. The result is an evaporator with high thermal conductivity and efficiency, good corrosion resistance, and low manufacturing cost.

With the exception of a few permanent mold parts, virtually all aluminum castings in electrical appliances are die cast. Cooking utensils may be cast, drawn, spun, or drawn and spun from aluminum. Handles are often joined to the utensil by riveting or spot welding. In some utensils, an aluminum exterior is bonded to a stainless steel interior; in others, the interior is coated with porcelain or Teflon. Silicone resin, Teflon, or other coatings enhance the utility of heated aluminum utensils. Many die castings in appliances are internal functional parts and are used without finish. Organic finishes are usually applied to external die-cast parts such as appliance housings.

Wrought forms fabricated principally from sheet, tube, and wire are used in approximately the same quantities as die castings. Wrought alloys are selected on the basis of corrosion resistance, anodizing characteristics, formability, or other engineering properties.

The natural colors some alloys assume after anodizing are extremely important for food-handling equipment. Applications include refrigerator vegetable/meat pans and wire shelves. In the production of wire shelves, full hard wire is cold headed over extruded strips, which form the borders.

Furniture. Light weight, low maintenance, corrosion resistance, durability, and attractive appearance are the principal advantages of aluminum in furniture.

Chair bases, seat frames, and arm rests are cast, drawn or extruded tube (round, square, or rectangular), sheet, or bar. Frequently, these parts are formed in the annealed or partially heat treated tempers and are subsequently heat treated and aged. Designs are generally based on service requirements; however, styling often dictates overdesign or inefficient sections. Fabrication is conventional; joining is usually by welding or brazing. Various finishing procedures are used: mechanical, anodic, color anodized, anodized and dyed, enamel coated, or painted.

Tubular sections, usually round and frequently formed and welded from flat strip, are the most popular form of aluminum for lawn furniture. Conventional tube bending and mechanically fitted joints can be used. Finishing is usually by grinding and buffing and is frequently followed by clear lacquer coating.

Machinery and Equipment

Processing Equipment. In the petroleum industry, aluminum tops are used on steel storage tanks, exteriors are covered with aluminum pigmented paint, and aluminum pipelines are carriers of petroleum products. Aluminum is used extensively in the rubber industry because it resists all corrosion that occurs in rubber processing and is nonadhesive. Aluminum alloys are widely used in the manufacture of explosives because of their nonpyrophoric characteristics. Strong oxidants are processed, stored, and shipped in aluminum systems. Aluminum is especially compatible with sulfur, sulfuric acid, sulfides, and sulfates. In the nuclear energy industry, aluminum-jacketed fuel elements protect uranium from water corrosion, prevent the entry of reaction products into the cooling water, transfer heat efficiently from uranium to water, and contribute to minimizing parasitic capture of neutrons. Aluminum tanks are used to contain heavy water.

Textile Equipment. Aluminum is used extensively in textile machinery and equipment in the form of extrusions, tube, sheet, castings, and forgings. It is resistant to many corrosive agents encountered in textile mills and in manufacture of yarns. A high strength-to-weight ratio reduces the inertia of high speed and reduces vibration. Painting is usually unnecessary. Spool beamheads and cores are usually permanent mold castings and extruded or welded tube, respectively.

Paper and Printing Industries. An interesting application of aluminum is found in returnable shipping cores. Cores may be reinforced with steel end-sleeves, which also constitute wear-resistant drive elements. Processing or rewinding cores are fabricated of aluminum alloys. Fourdrinier or table rolls for papermaking machines are also of aluminum construction.

Curved aluminum sheet printing plates permit higher rotary-press speeds and minimize misregister by decreasing centrifugal force. Aluminum lithographic sheet offers exceptional reproduction in mechanical electrograined finishes.

Coal Mine Machinery. The use of aluminum equipment in coal mines has increased in recent years. Applications include cars, tubs, and skips, roof props, nonsparking tools, portable jacklegs, and shaking conveyors. Aluminum is resistant to the corrosive conditions associated with surface and deep mining. Aluminum is self-cleaning and offers good resistance to abrasion, vibration, splitting, and tearing.

Portable Irrigation Pipe and Tools. Aluminum is extensively used in portable sprinkler and irrigation systems. Portable tools use large quantities of aluminum in electric and gas motors and motor housings. Precision cast housings and engine components, including pistons, are used for power drills, power saws, gasoline-driven chain saws, sanders, buffing machines, screwdrivers, grinders, power shears, hammers, various impact tools, and stationary bench tools. Aluminum alloy forgings are found in many of the same applications and in manual tools such as wrenches and pliers.

Jigs, Fixtures, and Patterns. Thick cast or rolled aluminum plates and bar, precisely machined to high finish and flatness, are used for tools and dies. Plate is suitable for hydropress form blocks, hydrostretch form dies, jigs, fixtures, and other tooling. Aluminum is used in the aircraft industry for drill jigs, as formers, stiffeners and stringers for large assembly jigs, router bases, and layout tables. Used in master tooling, cast aluminum eliminates warpage problems resulting from uneven expansion of the tool due to changes in ambient temperature. Large aluminum bars have been used to replace zinc alloys as a fixture base on spar mills with weight savings of two-thirds. Cast aluminum serves as matchplate in the foundry industry.

Instruments. On the basis of combinations of strength and dimensional stability, aluminum alloys are used in the manufacture of optical telescopic, space guidance, and other precision instruments and devices. To ensure dimensional accuracy and stability in manufacturing and assembling parts for such equipment, additional thermal stress-relief treatments are sometimes applied at stages of machining, or after welding or mechanical assembly.

Business Machines. The light weight of aluminum facilitates the design of business/copier machine parts that increase the speed of the machine and reduce the power requirements and vibration. Lighter weight aluminum components also reduce inertia on startup and stopping. Moving parts such as drive belt pulleys, hubs, end caps, and connecting collars have proven to be excellent applications for aluminum parts, many of which are produced by cost-effective P/M manufacturing. Their corrosion resistance eliminates the need for costly plating operations or rust preventative oils.

Other Applications

Reflectors. Reflectivity of light is as high as 95% on especially prepared surfaces of high-purity aluminum. Aluminum is generally superior to other metals in its ability to reflect infrared or heat rays. It resists tarnish from sulfides, oxides, and atmospheric contaminants, and has three to ten times the useful life of silver for mirrors in searchlights, telescopes, and similar reflectors. Heat reflectivity may be as much as 98% for a highly polished surface. Performance is reduced only slightly as the metal weathers and loses its initial brilliance. When maximum reflectivity is desired, chemical or electrochemical brightening treatments are used; quick anodic treatment usually follows, sometimes finished by a coat of clear lacquer. Reflectors requiring less brightness can simply be buffed and lacquered. Etching in a mild caustic solution produces a diffuse finish, which may also be protected by clear lacquer, an anodic coating, or both.

Powders and Pastes. The addition of aluminum flakes to paint pigments exploits the intrinsic advantages of high reflectance, durability, low emissivity, and minimum moisture penetration. Other applications for powder and pastes include printing inks, explosives and propellants, floating soap, aerated concrete, aluminothermic welding, and energy-enhancing fuel additives. A small percentage of aluminum powder is also used to manufacture structural parts.

Anode Materials. Highly electronegative aluminum alloys are routinely employed as sacrificial anodes, generally on steel structures or vessels such as pipelines, offshore construction, ships, and tank storage units. Most aluminum sacrificial anodes are produced from cast Al-Zn-Sn, Al-Zn-In, or Al-Zn-Hg alloys containing about 94 to 95% Al and 3.5 to 5% Zn.

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Chapter 7: Environmentally Assisted Cracking

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Chapter 8: Types of Corrosive Environments

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