4

ALUMINUM

Aluminum is the most plentiful metal on Earth, representing 8% of its crust. Although plentiful, aluminum exists primarily as oxides. The process of extracting aluminum from oxide is very energy intensive. In fact, approximately 2% to 3% of the electricity used in the United States is consumed in aluminum production. This high energy requirement makes recycling of aluminum products economical. Of the 24 million tons of aluminum produced annually, approximately 75% is from ore reduction and 25% is from recycled materials.

The properties of pure aluminum are not suitable for structural applications. Some industrial applications require pure aluminum, but otherwise, alloying elements are almost always added. These alloying elements, along with cold working and heat treatments, impart characteristics to the aluminum that make this product suitable for a wide range of applications. Figures 4.1 and 4.2 show aluminum used in two construction applications. Here, the term *aluminum* is used to refer to both the pure element and to alloys.

In terms of the amount of metal produced, aluminum is second only to steel. About 25% of aluminum produced is used for containers and packaging, 20% for architectural applications, such as doors, windows, and siding, and 10% for electrical conductors. The balance is used for industrial goods, consumer products, aircraft, and highway vehicles.

Aluminum accounts for 80% of the structural weight of aircraft, and its use in the automobile and light truck industry has increased 300% since 1971 (Reynolds Metals Company 1996). However, use of aluminum for infrastructure applications has been limited. Of the approximately 600,000 bridges in the United States, only nine have primary structural members made of aluminum. Two reasons for the limited use of aluminum are the relatively high initial cost when compared with steel and the lack of performance information on aluminum structures.

FIGURE 4.1 Aluminum frame used for structural support of a building.

FIGURE 4.2 Building facade made of aluminum.

Aluminum has many favorable characteristics and a wide variety of applications. The advantages of aluminum are that it (Budinski 1996)

- has one-third the density of steel
- has good thermal and electrical conductivity
- has high strength-to-weight ratio
- can be given a hard surface by anodizing and hard coating
- has alloys that are weldable
- will not rust
- has high reflectivity
- can be die cast
- is easily machined
- has good formability
- is nonmagnetic
- is nontoxic

Aluminum's high strength-to-weight ratio and its ability to resist corrosion are the primary factors that make aluminum an attractive structural engineering material. Although aluminum alloys can be formulated with strengths similar to steel products, the modulus of elasticity of aluminum is only about one-third that of steel. Thus, the dimensions of structural elements must be increased to compensate for the lower modulus of elasticity of aluminum.

4.1 Aluminum Production

Aluminum production uses processes that were developed in the 1880s. Bayer developed the sodium aluminate leaching process to produce pure alumina (Al_2O_3). Hall and Héroult, working independently, developed an electrolytic process for reducing the alumina to pure aluminum. The essence of the aluminum production process is shown in Figure 4.3.

The production of aluminum starts with the mining of the aluminum ore, bauxite. Commercial grade bauxite contains between 45% and 60% alumina. The bauxite is crushed, washed to remove clay and silica materials, and is kiln dried to remove most of the water. The crushed bauxite is mixed with soda ash and lime and passed through a digester, pressure reducer, and settling tank to produce a concentrated solution of sodium aluminate. This step removes silica, iron oxide, and other impurities from the sodium aluminate solution. The solution is seeded with hydrated alumina crystals in precipitator towers. The seeds attract other alumina crystals and form groups that are heavy enough to settle out of solution. The alumina hydrate crystals are washed to remove remaining traces of impurities and are calcined in kilns to remove all water. The resulting alumina is ready to be reduced with the Hall–Héroult process. The alumina is melted in a cryolite bath (a molten salt of sodium–aluminum–fluoride). An electric current is passed between anodes and cathodes of carbon to

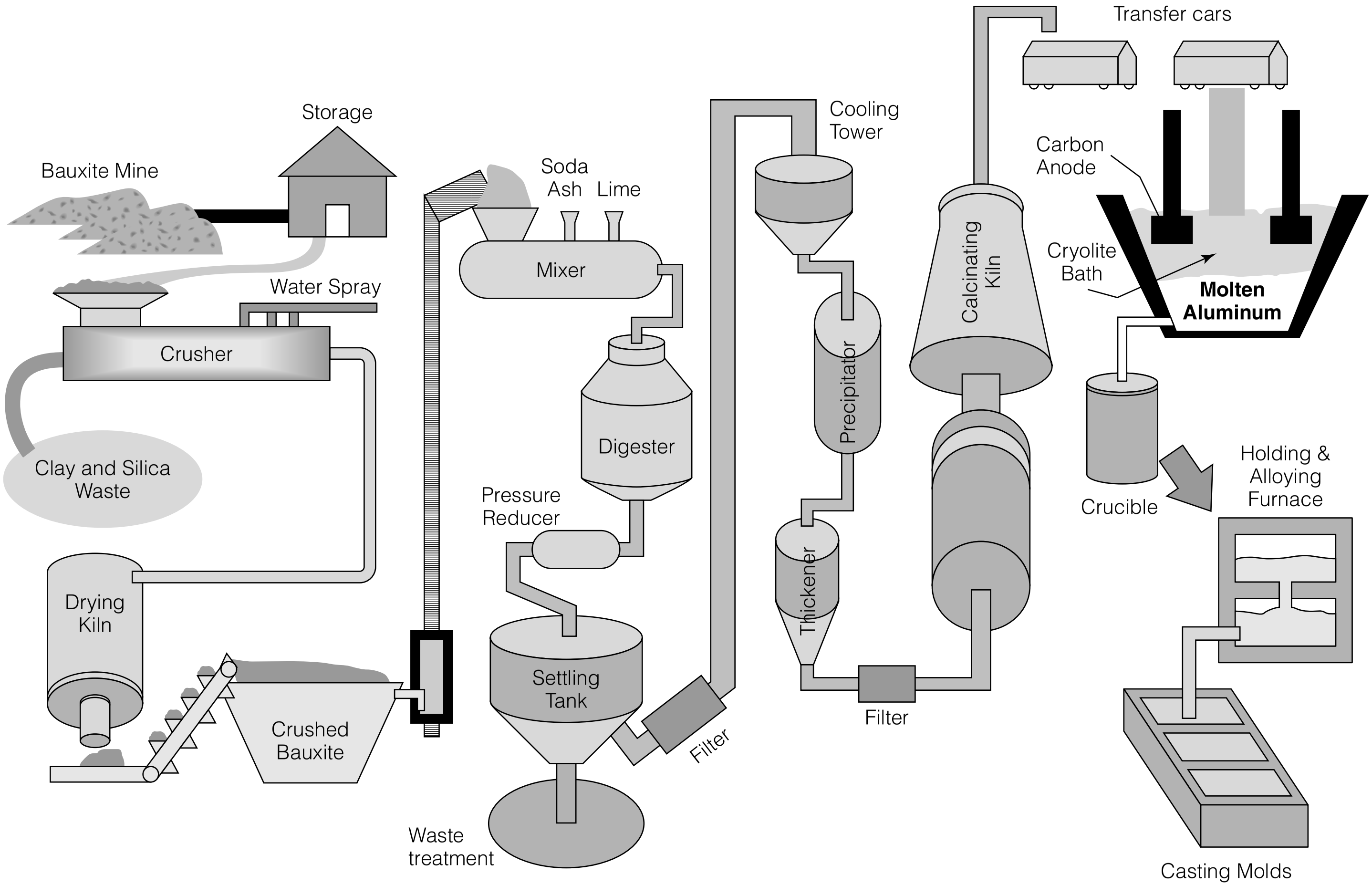

FIGURE 4.3 Aluminum production process.

separate the aluminum and oxygen molecules. The molten aluminum is collected at the cathode at the bottom of the bath. The molten aluminum, with better than 99% purity, is siphoned off to a crucible. It is then processed in a holding furnace. Hot gases are passed through the molten material to further remove any remaining impurities. Alloying elements are then added.

The molten aluminum is either shipped to a foundry for casting into finished products or is cast into ingots. The ingots are formed by a direct-chill process that produces huge sheets for rolling mills, round loglike billets for extrusion presses, or square billets for production of wire, rod, and bar stock.

Final products are made by either casting, which is the oldest process, or deforming solid aluminum stock. Three forms of casting are used: die casting, permanent mold casting, and sand casting. The basic deformation processes are forging, impact extrusion, stamping, drawing, and drawing plus ironing. Many structural shapes are made with the extrusion process. Either cast or deformed products can be machined to produce the final shape and surface texture, and they can be heat treated to alter the mechanical behavior of the aluminum. Casting and forming methods are summarized in Table 4.1.

When recycling aluminum, the scrap stock is melted in a furnace. The molten aluminum is purified and alloys are added. This process takes only about 5% of the electricity that is needed to produce aluminum from bauxite.

In addition to these conventional processes, very high strength aluminum parts can be produced using powder metallurgy methods. A powdered aluminum alloy is compacted in a mold. The material is heated to a temperature that fuses the particles into a unified solid.

4.2 Aluminum Metallurgy

Aluminum has a face center cubic (FCC) lattice structure. It is very malleable, with a typical elongation over a 50-mm (2-in.) gauge length of over 40%. It has limited tensile strength, on the order of 28 MPa (4000 psi). The modulus of elasticity of aluminum is about 69 GPa (10,000 ksi). Commercially pure aluminum (i.e., more than 99% aluminum content) is limited to nonstructural applications, such as electrical conductors, chemical equipment, and sheet metal work.

Although the strength of pure aluminum is relatively low, aluminum alloys can be as much as 15 times stronger than pure aluminum, through the addition of small amounts of alloying element, strain hardening by cold working, and heat treatment. The common alloying elements are copper, manganese, silicon, magnesium, and zinc. Cold working increases strength by causing a disruption of the slip planes in the material that resulted from the production process.

TABLE 4.1 Casting and Forming Methods for Aluminum Products (Extracted from *Reynolds Infrastructure*, 1996)

Casting Methods	
Sand Casting	Sand with a binder is packed around a pattern. The pattern is removed and molten aluminum is poured in, reproducing the shape. Produces a rough texture which can be machined or otherwise surfaced if desired. Economical for low volume production and for making very large parts. Also applicable when an internal void must be formed in the product.
Permanent Mold Casting	Molten aluminum is poured into a reusable metal mold. Economical for large volume production.
Die Casting	Molten aluminum is forced into a permanent mold under high pressure. Suitable for mass production of precisely formed castings.
Forming Methods	
Extrusion	Aluminum heated to 425 to 540°C (800 to 1000°F) is forced through a die. Complex cross sections are possible, including incompletely or completely enclosed voids. A variety of architectural and structural members are formed by extrusion, including tubes, pipes, I-beams, and decorative components, such as window and door frames.
Rolling	Rollers compress and elongate heated aluminum ingots, producing plates (more than 6 mm (0.25 in.) thick), sheets (0.15 to 6 mm (0.006 to 0.25 in.) thick, and foil (less than 0.15 mm (0.006 in.)).
Roll Forming	Shaping of sheet aluminum by passing stock between a series of special rollers, usually in stages. Used for mass production of architectural products, such as moldings, gutters, downspouts, roofing, siding and frames for windows and screens.
Brake Forming	Forming of sheet products with a brake press. Uses simpler tooling than roll forming but production rates are lower and the size of the product is limited.
Cutting Operations	Production of outline shapes by blanking and cutting. In blanking, a punch with the desired shape is pressed through a matching die. Used for mass production of flat shapes. Holes through a sheet are produced by piercing and perforating. Stacks of sheets can be trimmed or cut to an outline shape by a router or sheared in a guillotine-action shear.
Embossing	Shaping an aluminum sheet by pressing between mated rollers or dies, producing a raised pattern on one side and its negative indent on the other side.
Drawing	Shaping an aluminum sheet by drawing it through the gap between two mated dies in a press.
Superplastic Forming	An aluminum sheet is heated and forced over or into a mold by air pressure. Complex and deep contour shapes can be produced but the process is slow.

Figure 4.4 shows the two-phase diagram for aluminum and copper. This diagram is typical of the phase diagrams of other two-phase aluminum alloys. The alloying elements have low solubility in aluminum, and the solubility reduces as temperature drops.

As described previously, the properties of metals with this characteristic are very sensitive to heat treatments, which affect the grain size of the material and the distribution of the alloying element throughout the matrix of the lattice structures. Heat treatments typically used on aluminum alloys include annealing, hardening, aging, and stabilizing.

4.2.1 Alloy Designation System

Aluminum classification starts by separating the product according to its production method, either casting or wrought methods. Aluminum alloys designed for casting are formulated to flow into the mold. Wrought aluminum alloys are used for products fabricated by deforming the aluminum into its final shape. The Aluminum Association has developed an aluminum alloy classification system shown in Table 4.2.

The designation system for wrought alloys consists of a four-digit code. The first digit indicates the alloy series. The second digit, if different from 0, indicates a modification in the basic alloy. The third and forth digits identify the specific alloy in the series; these digits are arbitrarily assigned, except for the 1xxx series, in which the final two digits indicate the minimum aluminum content. For the 1xxx series, the aluminum content is 99% plus the

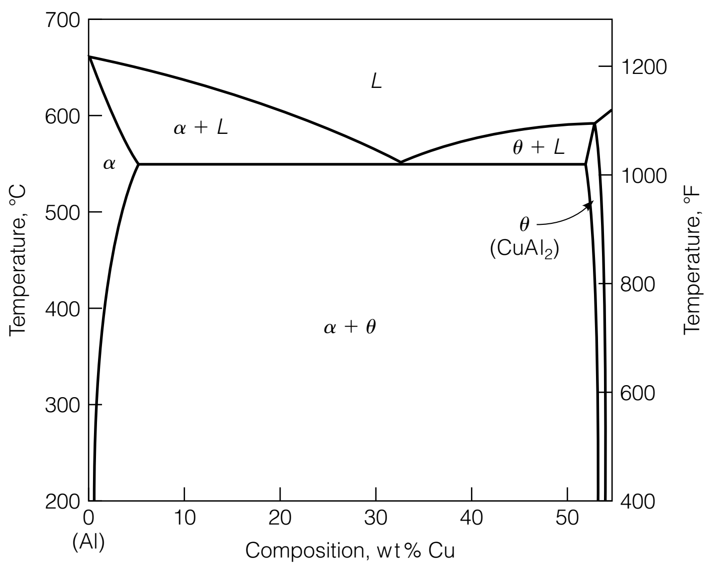

FIGURE 4.4 Aluminum-copper phase diagram.

TABLE 4.2 Designation System for Aluminum Alloys (Aluminum Association, 1993)

Wrought Aluminum Alloys		Cast Aluminum Alloys	
Alloy Series	**Description or Major Alloying Elements**	**Alloy Series**	**Description or Major Alloying Elements**
1xxx	99.00% Minimum Aluminum	1xx.x	99.00% Minimum Aluminum
2xxx	Copper	2xx.x	Copper
3xxx	Manganese	3xx.x	Silicon plus copper and/or magnesium
4xxx	Silicon	4xx.x	Silicon
5xxx	Magnesium	5xx.x	Magnesium
6xxx	Magnesium and silicon	6xx.x	Unused series
7xxx	Zinc	7xx.x	Zinc
8xxx	Other element	8xx.x	Tin
9xxx	Unused Series	9xx.x	Other element

last two digits of the code, expressed as a decimal fraction. For example, a 1060 contains a minimum aluminum content of 99.60%.

Cast alloys are assigned a three-digit number followed by one digit after the decimal point, as shown in Table 4.2. The first digit represents the alloy series. Note that series 3, 6, 8, and 9 have different meanings for cast versus wrought alloys. The second and third digits are arbitrarily assigned to identify specific alloys. The digit after the decimal indicates whether the alloy composition is for the final casting (xxx.0) or for ingot (xxx.1 and xxx.2).

4.2.2 Temper Treatments

The mechanical properties of aluminum are greatly altered by both heat treatment and strain hardening. Therefore, specification of an aluminum material must include the manner in which the product was tempered. The processes described in Table 4.3 define the types of tempering aluminum products undergo.

Aluminum alloys used for structural applications are classified as being either heat treatable or not. Non–heat-treatable or “common” alloys contain elements that remain substantially in solid solution or that form insoluble constituents. Thus, heat treatment does not influence their mechanical properties. The properties of these alloys are dependent on the amount of cold working introduced after annealing. Heat-treatable or “strong” alloys contain elements, groups of elements, or constituents that have a considerable solid solubility at elevated temperatures and limited solubility at lower temperatures. The strength of these alloys is increased primarily by heat treatment.

4.3 Aluminum Testing and Properties

Typical properties are provided in Tables 4.4 and 4.5 for non–heat-treatable and heat-treatable wrought aluminum alloys, respectively. Typical properties for cast aluminum alloys that may be used for structural applications are given in Table 4.6. These values are only an indication of the properties of cast aluminum alloys. Material properties of cast members can vary throughout the body of the casting due to differential cooling rates.

Tests performed on aluminum are similar to those described for steel. These typically include stress–strain tensile tests to determine elastic modulus, yield strength, ultimate strength, and percent elongation. In contrast to steel, aluminum alloys do not display an upper and lower yield point. Instead, the stress–strain curve is linear up to the proportional limit, and then is a smooth curve up to the ultimate strength. Yield strength is defined based on the 0.20% strain offset method, as shown in Figure 4.5. As indicated earlier, the modulus of elasticity of aluminum alloys is on the order of 69 GPa (10,000 ksi) and is not very sensitive to types of alloys or temper treatments.

Sample Problem 4.1

An aluminum alloy rod with 10 mm diameter is subjected to a 5-kN tensile load. After the load was applied, the diameter was measured and found to be 9.997 mm. If the yield strength is 139 MPa, calculate the Poisson's ratio of the material.

Solution

$$\sigma = \frac{5000}{\pi d^2/4} = 63.7 \times 10^6 \text{ Pa} = 63.7 \text{ MPa}$$

It is clear that the applied stress is well below the yield stress and, as a result, the deformation is elastic. Hence, assume that

$$E = 69 \text{ GPa}$$

$$\varepsilon_{axial} = \frac{\sigma}{E} = \frac{63.7 \times 10^6}{69 \times 10^9} = 0.000923 \text{ m/m}$$

$$\Delta d = 9.997 - 10.000 = 0.003 \text{ m}$$

$$\varepsilon_{lateral} = -{}^{0.003}/_{10.000} = -0.0003 \text{ m/m}$$

$$\nu = \frac{-\varepsilon_{lateral}}{\varepsilon_{axial}} = \frac{0.0003}{0.000923} = 0.33$$

TABLE 4.3 Temper Designations for Aluminum Alloys

Symbol	Meaning	Comment
F	as fabricated	No special control over thermal conditions or strain hardening is employed.
O	annealed	Wrought products—annealed to the lowest strength temper Cast products—annealed to improve ductility and dimensional stability. The "O" may be followed by a digit other than zero, indicating a variation with special characteristics.
H	strain hardened	Wrought products only. Strength is increased by strain hardening, with or without supplemental thermal treatments. The "H" is always followed by two or more numerical digits. The first digit indicates a specific combination of basic operations. The second digit indicates the degree of strain hardening. (Codes for the second digit are 2—quarter hard, 4—half hard, 8—full hard, 9—extra hard.) When used, the third digit indicates a variation of the two digit temper. The basic operations identified by the first digit are as follows: H1—strain hardening only. Applies to products that are strain hardened to obtain the desired strength, without supplementary thermal treatment. H2—strain hardened and partial annealed. Applies to products that are strain hardened more than the desired final amount, and then reduced in strength to the desired level by partial annealing. H3—strain hardened and stabilized. Applies to products that are strain hardened and whose mechanical properties are stabilized either by a low temperature thermal treatment or as a result of heat introduced during fabrication. Stabilization usually improves ductility.
W	solution heat treated	An unstable temper applicable only to alloys that spontaneously age at room temperature after solution heat treatment. This designation is specific only when the period of natural aging is indicated—for example, W$\frac{1}{2}$hr,
T	thermally treated to produce stable tempers other than F, O, or H	Applies to thermally treated products, with or without supplementary strain hardening to produce stable tempers. The "T" is always followed by one or two digits: T1—cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition. Products not cold worked after cooling from an elevated temperature shaping process, or in which the effect of cold working flattening or straightening may not be recognized in mechanical property limits. T2—cooled from an elevated temperature shaping process, cold worked, and naturally aged to a substantially stable condition. Products cold worked to improve strength after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

TABLE 4.3 (Continued)

Symbol	Meaning	Comment
		T3—solution heat treated, cold worked, and naturally aged to a substantially stable condition. Products cold worked to improve strength after solution heat treatment, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.
		T4—solution heat treated and naturally aged to a substantially stable condition. Products not cold worked after solution heat treatment, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits
		T5—cooled from an elevated temperature shaping process, then artificially aged. Products not cold worked after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits
		T6—solution heat treated and then artificially aged. Products which are not cold worked after solution heat treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.
		T7—solution heat treated and overaged/stabilized. Wrought products artificially aged after solution heat treatment to carry them beyond a point of maximum strength to provide control of some significant characteristic. Cast products artificially aged after solution heat treatment to provide dimensional and strength stability.
		T8—solution heat treated, cold worked, and then artificially aged. Products cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.
		T9—solution heat treated, artificially aged, and then cold worked. Products cold worked to improve strength.
		T10—cooled from an elevated temperature shaping process, cold worked and then artificially aged. Products worked to improve strength, or in which the effect of cold work in flattening and straightening is recognized in mechanical property limits. Additional digits can be appended to the preceding temper designations to indicate significant variations.

TABLE 4.4 Properties of Select Non-Heat-Treatable Wrought Aluminum Alloys

Alloy		Tension						Hardness[2]	Shear Ultimate		Fatigue[3] Endurance Limit		Nominal Chemical Composition
		Ultimate		Yield		Elongation[1] (thickness)							
		ksi	MPa	ksi	MPa	1/16″	1/2″		ksi	MPa	ksi	MPa	
1060	O	10	69	4	28	43		19	7	48	3	21	99.6 Al
	H-12	12	83	11	76	16		23	8	55	4	28	
	H-14	14	97	13	90	12		26	9	62	5	34	
	H-16	16	110	15	103	5		30	10	69	6.5	45	
	H-18	19	131	18	124	6		35	11	76	6.5	45	
1100	O	13	90	5	34	35	45	23	9	62	5	34	99.Al
	H-12	16	110	15	103	12	25	28	10	69	6	41	
	H-14	18	124	17	117	9	50	32	11	76	7	48	
	H-16	21	145	20	138	6	17	38	12	83	9	62	
	H-18	24	165	22	152	5	15	44	13	90	9	62	
3003	O	16	110	6	41	30	40	28	11	76	7	48	1.2 Mn
	H-12	19	131	18	124	10	20	35	12	83	8	55	
	H-14	22	152	21	145	8	16	40	14	97	9	62	
	H-16	26	179	25	172	5	14	47	15	103	10	69	
	H-18	29	200	27	186	4	10	55	16	110	10	69	

TABLE 4.4 (Continued)

5005	O	18	124	6	41	25		28	11	76			0.8 Mg
	H-12	20	138	19	131	10			14	97			
	H-14	23	159	22	152	6			14	97			
	H-16	26	179	25	172	5			15	103			
	H-18	29	200	28	193	4			16	110			
	H-32	20	138	17	117	11		36	14	97			
	H-34	23	159	20	138	8		41	14	97			
	H-36	26	179	24	165	6		46	15	103			
	H-38	29	200	27	186	5		51	16	110			
5086	O	38	262	17	117	22	30	60	23	159	21	145	Mg
	H-32	42	290	30	207	12	16	72	25	172	22	152	0.45 Mn
	H-34	47	324	37	255	10	14	82	27	186	23	159	
	H-111	40	276	27	186		17	65	23	159	21	145	
	H-112	39	269	19	131	14		64	23	159	21	145	
	H-116	42	290	30	207		16	72	25	173	22	152	
5456	O	45	310	23	159	20	24	70	27	186	22	152	5.1Mg
	H-111	47	324	33	228		18	75	27	186	24	165	0.7Mn
	H-112	45	310	24	156		22	70	27	186			0.12 Cr
	H-116	51	352	37	255		16	90	30	207	23	159	

[1] percent elongation over 2 in.
[2] Brinell number, 500-kg load
[3] 500,000,000 cycles of complete stress reversal using R.R. Moore type of machine and specimen.

TABLE 4.5 Properties of Select Heat-Treatable Wrought Aluminum Alloys

Alloy		Tension						Hardness[2]	Shear Ultimate		Fatigue[3] Endurance Limit		Nominal Chemical Composition
		Ultimate		Yield		Elongation[1] (thickness)							
		ksi	MPa	ksi	MPa	1/16″	1/2″		ksi	MPa	ksi	MPa	
2014	O	27	186	14	97		18	45	18	124	13	90	4.5 Cu, 0.8 Mn
	T4/T451	62	427	42	290		50	105	38	262	20	138	0.8 Si, 0.4 M
	T6/T651	70	483	60	414		13	135	42	290	18	124	
6053	O	16	110	8	55		35	26	11	76	8	55	1.2 Mg,
	T6	37	255	32	221		13	80	23	159	12	90	0.25 CR
6061	O	18	124	8	55	25	30	30	12	83	9	62	1.0 Mg, 0.6 SI
	T4/T451	35	241	21	145	22	25	65	24	165	14	97	0.25 Cu,
	T6/T651	45	310	40	276	12	17	95	30	207	14	97	0.25 Cr
6063	O	13	90	7	48			25	10	69	8	55	0.7 Mg
	T1	22	152	13	90	20	33	42	14	97	9	62	0.4 Si
	T4	25	172	13	90	22			16	110			
	T5	27	186	21	145	12	22	60	17	117	10	69	
	T6	35	241	31	214	12	18	73	22	152	10	69	
	T83	37	255	35	241	9		82	22	152			
	T831	30	207	27	186	10		70	18	124			
	T832	42	290	39	269	12		95	27	186			
7178	O	33	228	15	103	15	16	60	22	152			6.8 Zn, 2.0 Cu
	T6/T651	88	607	78	538	10	11	160	52	359	22	152	2.7 Mg, 0.3 Mn
	T76/ T765	83	572	73	503		11						

[1]Percent elongation over 2 in.
[2]Brinell number, 500-kg load
[3]500,000,000 cycles of complete stress reversal using R.R. Moore type of machine and specimen.

TABLE 4.6 Typical Properties of Select Cast Aluminum Alloys

Cast Alloy Designation	Tension					Hardness[2]	Shear Ultimate		Fatigue[3] Endurance Limit	
	Ultimate		Yield		Elongation[1]					
	ksi	MPa	ksi	MPa			ksi	MPa	ksi	MPa
356.0-T6[4]	40	276	27	186	5	90	32	221	13	90
356.0-T7[4]	33	228	24	165	5	70	25	172	11	76
A356.0-T61[4]	41	283	30	207	10	80				
A357.0-T6[4]	50	345	40	276	10	85	43	296	16	110
A444.0-T4[4]	23	159	10	69	21	45				
356.0-T6[5]	33	228	24	165	3.5	70	26	179	8.5	59
356.0-T7[5]	34	234	30	207	2.0	75	24	165	9.0	62
Almag 35 535.0[5]	40	276	21	145	13	70	28	193	10	69

[1] Percent elongation over 2 in.
[2] Brinell number, 500-kg load
[3] 500,000,000 cycles of complete stress reversal using R.R. Moore type of machine and specimen.
[4] Permanent mold
[5] Sand casting

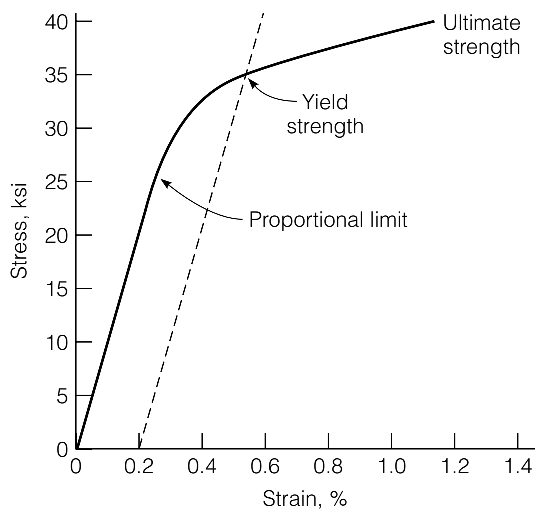

FIGURE 4.5 Aluminum stress-strain diagram

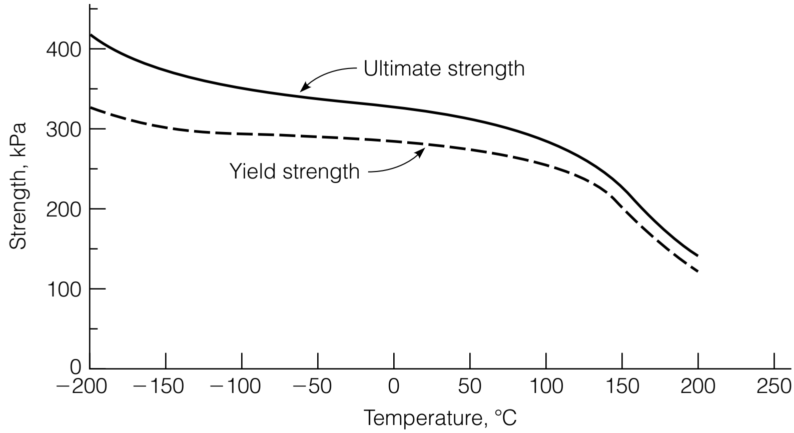

FIGURE 4.6 Tensile strength of aluminum at different temperatures. (Courtesy of the Aluminum Association, 1987.)

Aluminum's coefficient of thermal expansion is 0.000023/°C (0.000013/°F), about twice as large as that of steel and concrete. Thus, joints between aluminum and steel or concrete must be designed to accommodate the differential movement.

Strengths of aluminum are considerably affected by temperature, as shown in Figure 4.6. At temperatures above 150°C (300°F), tensile strengths are reduced considerably. The temperature at which the reduction begins and the extent of the reduction depends on the alloy. At temperatures below room temperature, aluminum becomes stronger and tougher as the temperature decreases.

4.4 Welding and Fastening

Aluminum pieces can be joined either by welding or by using fasteners. Welding requires that the tough oxide coating on aluminum be broken and kept from reforming during welding, so arc welding is generally performed in the presence of an inert gas that shields the weld from oxygen in the atmosphere. The two common processes by which aluminum is welded are gas metal arc welding, GMAW, and gas tungsten arc welding, GTAW. In the GMAW process, the filler wire also serves as the electrode. GTAW uses a tungsten electrode and a separate filler wire. Welding can alter the tempering of the aluminum in the area of the weld. For example, the tensile strength of 6061-T6 is 290 MPa (42 ksi), but the tensile strength of a weld in this alloy is only about 165 MPa (24 ksi). For design purposes, it is assumed the weld affects an area of 25 mm (1 in.) on each side of the weld.

In addition to welding, either bolts or rivets can join aluminum pieces. Bolts can be either aluminum or steel. When steel bolts are used, they must be either galvanized, aluminized, cadmium plated, or made of stainless steel to prevent the development of galvanic corrosion. Rivet fasteners are made of aluminum and are cold driven. Both bolt and rivet joints are designed based on the shear strength of the fastener and the bearing strength of the material being fastened.

4.5 Corrosion

Aluminum develops a thin oxidation layer immediately upon exposure to the atmosphere. This tough oxide film protects the surface from further oxidation. The alloying elements alter the corrosion resistance of the aluminum. The alloys used for airplanes are usually given extra protection by painting or "cladding" with a thin coat of a corrosion-resistant alloy. Painting is generally not needed for medium-strength alloys used for structural applications.

Galvanic corrosion occurs when aluminum is in contact with any of several metals in the presence of an electrical conductor, such as water. The best protection for this problem is to break the path of the galvanic cell by painting, using an insulator, or keeping the dissimilar metals dry.

SUMMARY

Although aluminum has many desirable attributes, its use as a structural material in civil engineering has been limited, primarily by economic considerations and a lack of performance information. Aluminum alloys and heat treatments provide products with a wide range of characteristics. The advantages of aluminum relative to steel include lightweight, high strength-to-weight ratio, and corrosion resistance.

QUESTIONS AND PROBLEMS

4.1 Name the two primary factors that make aluminum an attractive structural engineering material.

4.2 Compare the strength and modulus of elasticity of aluminum alloys with those of steel.

4.3 An aluminum alloy specimen with a radius of 0.28 in. was subjected to tension until fracture and produced results shown in Table P4.3.

Table P4.3

Stress, ksi	Strain, 10^{-3} in./in.
8	0.6
17	1.5
27	2.4
35	3.2
43	4.0
50	4.6
58	5.2
62	5.8
64	6.2
65	6.5
67	7.3
68	8.1
70	9.7

a. Using a spreadsheet program, plot the stress–strain relationship.
b. Calculate the modulus of elasticity of the aluminum alloy.
c. Determine the proportional limit.
d. What is the maximum load if the stress in the bar is not to exceed the proportional limit?
e. Determine the 0.2% offset yield strength.
f. Determine the tensile strength.
g. Determine the percent of elongation at failure.

4.4 A round aluminum alloy bar with a 0.5-inch diameter and 2-inch gauge length was subjected to tension to fracture. The load and deformation data were as shown in Table P4.4.

Table P4.4

Load (lb)	ΔL (in.)	Load (lb)	ΔL (in.)
0	0.0000	10,853	0.0136
1395	0.0014	11,461	0.0168
2800	0.0028	12,050	0.0220
4195	0.0042	12,599	0.0310
5600	0.0055	12,953	0.0420
7010	0.0070	13,188	0.0528
8282	0.0083	13,345	fracture
9852	0.0103		

Using a spreadsheet program, obtain the following:
a. A plot of the stress–strain relationship. Label the axes and show units.

b. A plot of the linear portion of the stress–strain relationship. Determine modulus of elasticity using the best fit approach.
c. Proportional limit.
d. Yield stress at an offset strain of 0.002 in/in.
e. Tangent modulus at a stress of 60 ksi.
f. Secant modulus at a stress of 60 ksi.

4.5 An aluminum alloy bar with a rectangular cross section that has a width of 12.5 mm, thickness of 6.25 mm, and a gage length of 50 mm was tested in tension to fracture according to ASTM E-8 method. The load and deformation data were as shown in Table P4.5.

Table P4.5

Load (kN)	ΔL (mm)	Load (kN)	ΔL (mm)
0	0	33.5	1.486
3.3	0.025	35.3	2.189
14.0	0.115	37.8	3.390
25.0	0.220	39.8	4.829
29.0	0.406	40.8	5.961
30.6	0.705	41.6	7.386
31.7	0.981	41.2	8.047
32.7	1.245		

Using a spreadsheet program, obtain the following:
a. A plot of the stress–strain relationship. Label the axes and show units.
b. A plot of the linear portion of the stress–strain relationship. Determine the modulus of elasticity using the best fit approach.
c. Proportional limit.
d. Yield stress at an offset strain of 0.002 in/in.
e. Tangent modulus at a stress of 450 MPa.
f. Secant modulus at a stress of 450 MPa.

4.6 A round aluminum alloy bar with a 0.25-inch diameter and a 1-inch gauge length was tested in tension to fracture according to ASTM E-8 method. The load and deformation data were as shown in Table P4.6.

Table P4.6

Load (lb)	Displacement (in.)	Load (lb)	Displacement (in.)
0	0	2957	0.02926
288	0.00050	3119	0.04310
1239	0.00225	3337	0.06674
2207	0.00432	3513	0.09506
2562	0.00799	3604	0.11734
2703	0.01388	3677	0.14539
2800	0.01930	3643	0.15841
2886	0.02451		

Using a spreadsheet program, obtain the following:

a. A plot of the stress–strain relationship. Label the axes and show units.
b. A plot of the linear portion of the stress–strain relationship. Determine modulus of elasticity using the best fit approach.
c. Proportional limit.
d. Yield stress at an offset strain of 0.002 in/in.
e. Initial tangent modulus:
    1. If the specimen is loaded to 3200 lb only and then unloaded, what is the permanent change in gage length?
    2. When the applied load was 1239 lb, the diameter was measured as 0.249814 inches. Determine Poisson's ratio.

4.7 An aluminum alloy rod has a circular cross section with a diameter of 8 millimeters. This rod is subjected to a tensile load of 4 kN. Assume E = 69 GPa.

a. What will be the lateral strain if Poisson's ratio is 0.33?
b. What will be the diameter after load application?

4.8 A 3003-H14 aluminum alloy rod with 0.5 in. diameter is subjected to 2000-lb tensile load. Calculate the resulting diameter of the rod. If the rod is subjected to a compressive load of 2000 lb, what will be the diameter of the rod? Assume that the modulus of elasticity is 10,000 ksi, Poisson's ratio is 0.33, and the yield strength is 21 ksi.

4.9 The stress–strain relation of an aluminum alloy bar having a length of 2 m and a diameter of 10 mm is expressed by the equation

$$\varepsilon = \frac{\sigma}{70{,}000}\left[1 + \frac{3}{7}\left(\frac{\sigma}{270}\right)^9\right]$$

where σ is in MPa. If the rod is axially loaded by a tensile force of 20 kN and then unloaded, what is the permanent deformation of the bar?

4.10 A tension test was performed on an aluminum alloy specimen to fracture. The original diameter of the specimen is 0.5 in. and the gage length is 2.0 in. The information obtained from this experiment consists of applied tensile load (P) and increase in length (ΔL). The results are tabulated in Table P4.10. Using a spreadsheet program, complete the table by calculating engineering stress (σ) and engineering strain (ε). Determine the toughness of the material (u_t) by calculating the area under the stress–strain curve, namely,

$$u_t = \int_0^{\varepsilon_f} \sigma \, d\varepsilon$$

where ε_f is the strain at fracture. The preceding integral can be approximated numerically using a trapezoidal integration technique:

$$u_t = \sum_{i=1}^{n} u_i = \sum_{i=1}^{n} \frac{1}{2}(\sigma_i + \sigma_{i-1})(\varepsilon_i - \varepsilon_{i-1})$$

Table P4.10

Observation No.	*P* (lb)	Δ*L* (in.)	σ (psi)	ε (in./in.)	u_i (psi)
0	0	0			N/A
1	1181	0.0015			
2	2369	0.003			
3	3550	0.0045			
4	4738	0.0059			
5	5932	0.0075			
6	7008	0.0089			
7	8336	0.011			
8	9183	0.0146			
9	9698	0.018			
10	10,196	0.0235			
11	10,661	0.0332			
12	10,960	0.0449			
13	11,159	0.0565			
14	11,292	0.0679			
					$u_t =$

4.11 Discuss galvanic corrosion of aluminum. How can aluminum be protected from galvanic corrosion?

4.6 References

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