CHAPTER 3

ALUMINUM AND ITS ALLOYS

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3.1 INTRODUCTION

Aluminum is the most abundant metal and the third most abundant chemical element in the earth's crust, comprising over 8% of its weight. Only oxygen and silicon are more prevalent. Yet, until about 150 years ago aluminum in its metallic form was unknown to man. The reason for this is that aluminum, unlike iron or copper, does not exist as a metal in nature. Because of its chemical activity and its affinity for oxygen, aluminum is always found combined with other elements, mainly as aluminum oxide. As such it is found in nearly all clays and many minerals. Rubies and sapphires are aluminum oxide colored by trace impurities, and corundum, also aluminum oxide, is the second hardest naturally occurring substance on earth—only a diamond is harder.

It was not until 1886 that scientists learned how to economically extract aluminum from aluminum oxide via electrolytic reduction. Yet in the more than 100 years since that time, aluminum has become the second most widely used of the approximately 60 naturally occurring metals, behind only iron.

3.2 PROPERTIES OF ALUMINUM

Let us consider the properties of aluminum that lead to its wide use.

One property of aluminum that everyone is familiar with is its light weight or, technically, its low specific gravity. The specific gravity of aluminum is only 2.7 times that of water, and roughly one-

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third that of steel or copper. An easy number to remember is that 1 in.^{3} of aluminum weighs 0.1 lb; 1 ft^3 weighs 170 lb compared to 62 lb for water and 490 lb for steel. The following are some other properties of aluminum and its alloys that will be examined in more detail in later sections:

Formability. Aluminum can be formed by every process in use today and in more ways than any other metal. Its relatively low melting point, 1220°F, while restricting high-temperature applications to about 500–600°F, does make it easy to cast, and there are over 1000 foundries casting aluminum in this country.

Mechanical Properties. Through alloying, naturally soft aluminum can attain strengths twice that of mild steel.

Strength-to-Weight Ratio. Some aluminum alloys are among the highest strength to weight materials in use today, in a class with titanium and superalloy steels. This is why aluminum alloys are the principal structural metal for commercial and military aircraft.

Cryogenic Properties. Unlike most steels, which tend to become brittle at cryogenic temperatures, aluminum alloys actually get tougher at low temperatures and hence enjoy many cryogenic applications.

Corrosion Resistance. Aluminum possesses excellent resistance to corrosion by natural atmospheres and by many foods and chemicals.

High Electrical and Thermal Conductivity. On a volume basis the electrical conductivity of pure aluminum is roughly 60% of the International Annealed Copper Standard, but pound for pound aluminum is a better conductor of heat and electricity than copper and is surpassed only by sodium, which is a difficult metal to use in everyday situations.

Reflectivity. Aluminum can accept surface treatment to become an excellent reflector and it does not dull from normal oxidation.

Finishability. Aluminum can be finished in more ways than any other metal used today.

3.3 ALUMINUM ALLOYS

While commercially pure aluminum (defined as at least 99% aluminum) does find application in electrical conductors, chemical equipment, and sheet metal work, it is a relatively weak material, and its use is restricted to applications where strength is not an important factor. Some strengthening of the pure metal can be achieved through cold working, called strain hardening. However, much greater strengthening is obtained through alloying with other metals, and the alloys themselves can be further strengthened through strain hardening or heat treating. Other properties, such as castability and machinability, are also improved by alloying. Thus, aluminum alloys are much more widely used than is the pure metal, and in many cases, when aluminum is mentioned, the reference is actually to one of the many commercial alloys of aluminum.

The principal alloying additions to aluminum are copper, manganese, silicon, magnesium, and zinc; other elements are also added in smaller amounts for metallurgical purposes. Since there have been literally hundreds of aluminum alloys developed for commercial use, the Aluminum Association formulated and administers special alloy designation systems to distinguish and classify the alloys in a meaningful manner.

3.4 ALLOY DESIGNATION SYSTEMS

Aluminum alloys are divided into two classes according to how they are produced: wrought and cast. The wrought category is a broad one, since aluminum alloys may be shaped by virtually every known process, including rolling, extruding, drawing, forging, and a number of other, more specialized processes. Cast alloys are those that are poured molten into sand (sand casting) or high-strength steel (permanent mold or die casting) molds, and are allowed to solidify to produce the desired shape. The wrought and cast alloys are quite different in composition; wrought alloys must be ductile for fabrication, while cast alloys must be fluid for castability.

In 1974, the Association published a designation system for wrought aluminum alloys that classifies the alloys by major alloying additions. This system is now recognized worldwide under the International Accord for Aluminum Alloy Designations, administered by the Aluminum Association, and is published as American Standards Institute (ANSI) Standard H35.1. More recently, a similar system for casting alloys was introduced.

Each wrought or cast aluminum alloy is designated by a number to distinguish it as a wrought or cast alloy and to categorize the alloy. A wrought alloy is given a four-digit number. The first digit classifies the alloy by alloy series, or principal alloying element. The second digit, if different than 0, denotes a modification in the basic alloy. The third and fourth digits form an arbitrary number

Table 3.1 Designation System for Wrought Aluminum Alloys

Alloy Series	Description or Major Alloying Element
1xxx	99.00% minimum aluminum
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and silicon
7xxx	Zinc
8xxx	Other element
9xxx	Unused series

which identifies the specific alloy in the series.* A cast alloy is assigned a three-digit number followed by a decimal. Here again the first digit signifies the alloy series or principal addition; the second and third digits identify the specific alloy; the decimal indicates whether the alloy composition is for the final casting (0.0) or for ingot (0.1 or 0.2). A capital letter prefix (A, B, C, etc.) indicates a modification of the basic alloy.

The designation systems for wrought and cast aluminum alloys are shown in Tables 3.1 and 3.2, respectively.

Specification of an aluminum alloy is not complete without designating the metallurgical condition, or temper, of the alloy. A temper designation system, unique for aluminum alloys, was developed by the Aluminum Association and is used for all wrought and cast alloys. The temper designation follows the alloy designation, the two being separated by a hyphen. Basic temper designations consist of letters; subdivisions, where required, are indicated by one or more digits following the letter. The basic tempers are:

F—As-Fabricated. Applies to the products of shaping processes in which no special control over thermal conditions or strain hardening is employed. For wrought products, there are no mechanical property limits.

O—Annealed. Applies to wrought products that are annealed to obtain the lowest strength temper, and to cast products that are annealed to improve ductility and dimensional stability. The O may be followed by a digit other than zero.

Table 3.2 Designation System for Cast Aluminum Alloys

Alloy Series	Description or Major Alloying Element
1xx.x	99.00% minimum aluminum
2xx.x	Copper
3xx.x	Silicon plus copper and/or magnesium
4xx.x	Silicon
5xx.x	Magnesium
6xx.x	Unused series
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other element

*An exception is for the 1xxx series alloys, where the last two digits indicate the minimum aluminum percentage. For example, alloy 1060 contains a minimum of 99.60% aluminum.

Table 3.3 Subdivisions of H Temper: Strain Hardened

First digit indicates basic operations:
- H1—Strain hardened only
- H2—Strain hardened and partially annealed
- H3—Strain hardened and stabilized
- H4—Strain hardened, lacquered, or painted

Second digit indicates degree of strain hardening:
- HX2—Quarter hard
- HX4—Half hard
- HX8—Full hard
- HX9—Extra hard

Third digit indicates variation of two-digit temper.

H—Strain-Hardened (Wrought Products Only). Applies to products that have their strength increased by strain hardening, with or without supplementary thermal treatments to produce some reduction in strength. The H is always followed by two or more digits. (See Table 3.3.)

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 ½ hr.

T—Thermally Treated to Produce Stable Tempers Other than F, O, or H. Applies to products that are thermally treated, with or without supplementary strain hardening, to produce stable tempers. The T is always followed by one or more digits. (See Table 3.4.)

3.5 MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

Wrought aluminum alloys are generally thought of in two categories: nonheat-treatable and heat-treatable. Nonheat-treatable alloys are those that derive their strength from the hardening effect of elements such as manganese, iron, silicon, and magnesium, and are further strengthened by strain hardening. They include the 1xxx, 3xxx, 4xxx, and 5xxx series alloys. Heat-treatable alloys are

Table 3.4 Subdivions of T Temper: Thermally Treated

First digit indicates specific sequence of treatments:
- T1—Cooled from an elevated-temperature shaping process and naturally aged to a substantially stable condition
- T2—Cooled from an elevated-temperature shaping process, cold worked, and naturally aged to a substantially stable condition
- T3—Solution heat-treated, cold worked, and naturally aged to a substantially stable condition
- T4—Solution heat-treated and naturally aged to a substantially stable condition
- T5—Cooled from an elevated-temperature shaping process and then artifically aged
- T6—Solution heat-treated and then artifically aged
- T7—Solution heat-treated and overaged/stabilized
- T8—Solution heat-treated, cold worked, and then artificially aged
- T9—Solution heat-treated, artificially aged, and then cold worked
- T10—Cooled from an elevated-temperature shaping process, cold worked, and then artificially aged

Second digit indicates variation in basic treatment:

Examples:
- T42 or T62—Heat treated to temper by user

Additional digits indicate stress relief:

Examples:
- TX51 or TXX51—Stress relieved by stretching
- TX52 or TXX52—Stress relieved by compressing
- TX54 or TXX54—Stress relieved by combination of stretching and compressing

strengthened by a combination of solution heat treatment and natural or controlled aging for precipitation hardening, and include the 2xxx, some 4xxx, 6xxx, and 7xxx series alloys. Castings are not normally strain hardened, but many are solution heat-treated and aged for added strength.

In Table 3.5 typical mechanical properties are shown for several representative nonheat-treatable alloys in the annealed, half-hard and full-hard tempers; values for super purity aluminum (99.99%) are included for comparison. Typical properties are usually higher than minimum, or guaranteed, properties and are not meant for design purposes but are useful for comparisons. It should be noted that pure aluminum can be substantially strain hardened, but a mere 1% alloying addition produces a comparable tensile strength to that of fully hardened pure aluminum with much greater ductility in the alloy. And the alloys can then be strain hardened to produce even greater strengths. Thus, the alloying effect is compounded. Note also that, 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 in the fully hardened temper. Ductility and workability are reduced as the material is strain hardened, and most alloys have limited formability in the fully hardened tempers.

Table 3.6 lists typical mechanical properties and nominal compositions of some representative heat-treatable aluminum alloys. One can readily see that the strengthening effect of the alloying ingredients in these alloys is not reflected in the annealed condition to the same extent as in the nonheat-treatable alloys, but the true value of the additions can be seen in the aged condition. Presently, heat-treatable alloys are available with tensile strengths approaching 100,000 psi.

Again, casting alloys cannot be work hardened and are either used in as-cast or heat-treated conditions. Typical mechanical properties for commonly used casting alloys range from 20 to 50 ksi for ultimate tensile strength, from 15 to 50 ksi tensile yield strength and up to 20% elongation. The range of strengths available with wrought aluminum alloys is shown graphically in Fig. 3.1.

3.6 WORKING STRESSES

Aluminum is used in a wide variety of structural applications. These range from curtain walls on buildings to tanks and piping for handling cryogenic liquids, and even bridges and major buildings and roof structures. In establishing appropriate working stresses the factors of safety applied to the ultimate strength and yield strength of the aluminum alloy vary with the specific application. For building and similar type structures a factor of safety of 1.95 is applied to the tensile ultimate strength

Table 3.5 Typical Mechanical Properties of Representative Nonheat-Treatable Aluminum Alloys (Not for Design Purposes)

Alloy	Nominal Composition	Temper	Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (% in 2 in)	Hardness (BHN)
1199	99.9+% Al	O	6.5	1.5	50	—
		H18	17	16	5	—
1100	99+% Al	O	13	5	35	23
		H14	18	17	9	32
		H18	24	22	5	44
3003	1.2% Mn	O	16	6	30	28
		H14	22	21	8	40
		H18	29	27	4	55
3004	1.2% Mn	O	26	10	20	43
	1.0% Mg	H34	35	29	9	63
		H38	41	36	5	77
5005	0.8% Mg	O	13	6	25	28
		H14	23	22	6	41
		H18	29	28	4	51
5052	2.5% Mg	O	28	13	25	47
		H34	38	31	10	68
		H38	42	37	7	77
5456	5.1% Mg	O	45	23	24	70
	0.8% Mn	H321, H116	51	37	16	90
B443.0	5.0% Si	F[a]	19	8	8	40
		F[b]	23	9	10	45
514.0	4.0% Mg	F[a]	25	12	9	50

[a]Sand cast.

[b]Permanent mold cast.

Table 3.6 Typical Mechanical Properties of Representative Heat-Treatable Aluminum Alloys (Not for Design Purposes)

Alloy	Nominal Composition	Temper	Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (% in 2 in)	Hardness (BHN)
2024	4.4% Cu	O	27	11	20	47
	1.5% Mg	T4	68	47	20	120
	0.6% Mn	T6	69	57	10	125
		T86	75	71	6	135
2219	6.3% Cu	T62	60	42	10	—
6061	1.0% Mg	O	18	8	25	30
	0.6% Si	T4	35	21	22	65
		T6	45	40	12	95
6063	0.40 Si	O	13	7	—	25
	0.70 Mg	T6	35	31	12	73
7075	5.6% Zn	O	33	15	17	60
	2.5% Mg	T6	83	73	11	150
	1.6% Cu	T73	73	63	13	—
356.0	7.0% Si	T6[a]	33	24	3.5	70
	0.3% Mg	F[b]	26	18	5	—
		T6[b]	37	27	5	80

[a]Sand cast.

[b]Permanent mold cast.

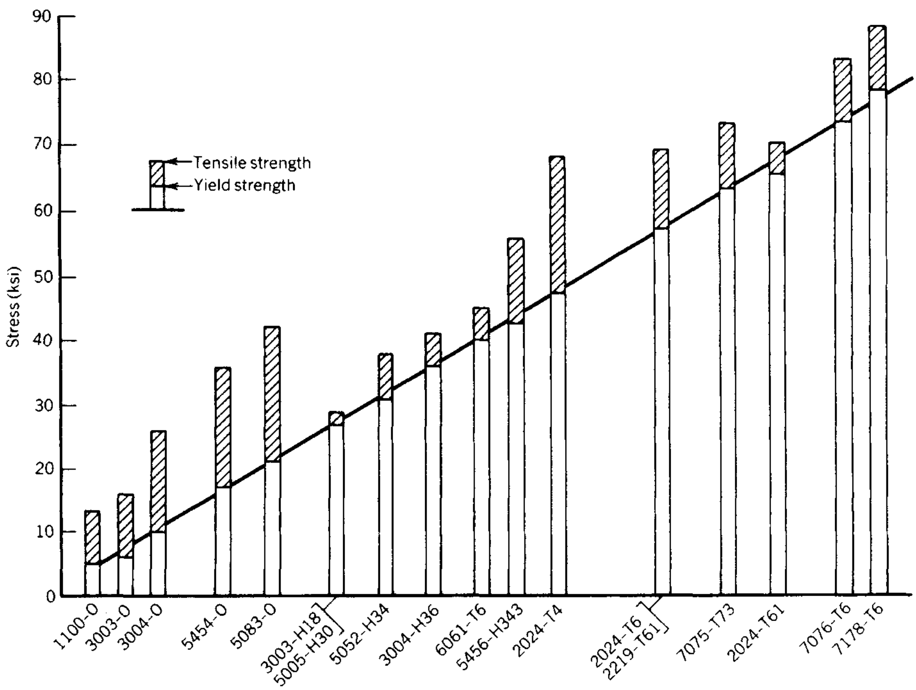

Fig. 3.1 Comparison of strengths of wrought aluminum alloys.

and 1.65 on the yield strength. For bridges and similar type structures the factors of safety are 2.20 on tensile ultimate strength and 1.85 on yield strength. For other types of applications the factors of safety may differ.

Selection of the working stresses and safety factors for a particular application should be based on codes, specifications, and standards covering that application published by agencies of government or nationally recognized trade and professional organizations.

For building and bridge design, reference should be made to the *Aluminum Design Manual*, published by the Aluminum Association. For boiler and pressure vessel design, reference should be made to the *Boiler and Pressure Vessel Code* published by the American Society of Mechanical Engineers.

For information on available codes, standards and specifications for other applications, the Aluminum Association may be consulted at 900 19th Street, NW, Washington, DC 20006.

3.7 CHARACTERISTICS

In addition to strength, the combination of alloy and temper determine other characteristics such as corrosion resistance, workability, machinability, etc. Some of the more important characteristics of representative aluminum alloys are compared in Table 3.7. The ratings A through E are relative ratings to compare wrought and cast aluminum alloys *within each category* and are explained below. Where a range of ratings is given, the first rating applies to the alloy in the annealed condition and the second rating is for the alloy when fully hardened. Alloys shown are representative and other alloys of the same type generally have comparable ratings.

3.7.1 Resistance to General Corrosion

Ratings are based on exposures to sodium chloride solution by intermittent spraying or immersion. In general, alloys with A and B ratings can be used in industrial and seacoast atmospheres and in many applications without protection. Alloys with C, D, and E ratings generally should be protected, at least on faying surfaces.

3.7.2 Workability

Ratings A through D for workability (cold) are relative ratings in decreasing order of merit.

3.7.3 Weldability and Brazeability

Aluminum alloys can be joined by most fusion and solid-state welding processes as well as by brazing and soldering. Fusion welding is commonly done by gas metal-arc welding (GMAW) and gas tungsten-arc welding (GTAW).

The relative weldability and brazeability of representative aluminum alloys is covered in Table 3.7, where ratings A through D are defined as follows:

A = Generally weldable by all commercial procedures and methods.

Table 3.7 Comparative Characteristics of Representative Aluminum Alloys

Alloy	Resistance to General Corrosion	Workability[c]	Machinability	Brazeability	Weldability (Arc)
1100	A	A–C	E–D	A	A
2024	D[a]	C–D	B	D	B–C
3003	A	A–C	E–D	A	A
3004	A	A–C	D–C	B	A
5005	A	A–C	E–D	B	A
5052	A	A–C	D–C	C	A
5456	A[b]	B–C	D–C	D	A
6061	B	A–C	D–C	A	A
7075	C[a]	D	B	D	C
356.0	B	A	C	—	A
B443.0	B	A	E	—	A
514.0	A	D	A	—	C

[a]E in thick sections.

[b]May differ if material heated for long periods.

[c]Castability for casting alloys.

Table 3.8 Practical Aluminum Thickness Ranges for Various Joining Processes

	Thickness (in) [or Area (in^2)]	
Joining Process	Minimum	Maximum
Gas metal-arc welding	0.12	No limit
Gas tungsten-arc welding	0.02	1
Resistance spot welding	Foil	0.18
Resistance seam welding	0.01	0.18
Flash welding	0.05	(12)
Stud welding	0.02	No limit
Cold welding—butt joint	(0.0005)	(0.2)
Cold welding—lap joint	Foil	0.015
Ultrasonic welding	Foil	0.12
Electron beam welding	0.02	6
Brazing	0.006	No limit

[a]Reprinted from the American Welding Society, *Welding Handbook*, 7th ed., Miami, FL, 1982.

B = Weldable with special techniques or for specific applications that justify preliminary trials or testing to develop welding procedures 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.

Table 3.8 gives practical thickness or cross-sectional areas that can be joined by various processes.

3.8 TYPICAL APPLICATIONS

Typical applications of commonly used wrought aluminum alloys are listed in Tables 3.9 and 3.10. By comparing these with Tables 3.5, 3.6, and 3.7, one can readily see that application is based on properties such as strength, corrosion resistance, weldability, etc. Where one desired property, such as high strength, is the prime requisite, then steps must be taken to overcome a possible undesirable characteristic, such as relatively poor corrosion resistance. In this case, the high-strength alloy would be protected by a protective coating such as cladding, which will be described in a later section. Conversely, where resistance to attack is the prime requisite, then one of the more corrosion-resistant

Table 3.9 Typical Applications of Wrought Nonheat-Treatable Aluminum Alloys

Alloy Series	Typical Alloys	Typical Applications
1xxx	1350	Electrical conductor
	1060	Chemical equipment, tank cars
	1100	Sheet metal work, cooking utensils, decorative
3xxx	3003, 3004	Sheet metal work, chemical equipment, storage tanks, beverage cans, heat exchangers
4xxx	4043	Welding electrodes
	4343	Brazing alloy
5xxx	5005, 5050, 5052, 5657	Decorative and automotive trim, architectural and anodized, sheet meal work, appliances bridge and building structures, beverage can ends
5xxx (>2.5% Mg)	5083, 5086, 5182, 5454, 5456	Marine, welded structures, storage tanks, pressure vessels, armor plate, cryogenics, beverage can easy open ends, automotive structures

Table 3.10 Typical Applications of Wrought Heat-Treatable Alloys

Alloy Series	Typical Alloys	Typical Applications
2xxx	2011	Screw machine products
(Al-Cu)	2219	Structural, high temperature
2xxx (Al-Cu-Mg)	2014, 2024, 2618	Aircraft structures and engines, truck frames and wheels, automotive structures
6xxx	6061, 6063	Marine, truck frames and bodies, structures, architectural, furniture, bridge decks, automotive structures
7xxx (Al-Zn-Mg)	7004, 7005	Structural, cryogenic, missile
7xxx (Al-Zn-Mg-Cu)	7001, 7075, 7178	High-strength structural and aircraft

alloys would be employed and assurance of adequate strengths would be met through proper design. The best combination of strength and corrosion resistance for consumer applications in wrought products is found among the 5xxx and 6xxx series alloys. Several casting alloys have good corrosion resistance, and aluminum castings are widely used as cooking utensils and components of food processing equipment as well as for valves, fittings, and other components in various chemical applications.

3.9 MACHINING ALUMINUM

Aluminum alloys are readily machined and offer such advantages as almost unlimited cutting speed, good dimensional control, low cutting force, and excellent life. Relative machinability of commonly used alloys are classified as A, B, C, D, or E (see Table 3.7).

3.9.1 Cutting Tools

Cutting tool geometry is described by seven elements: top or back rake angle, side rake angle, end relief angle, side relief angle, end cutting edge angle, and nose radius.

The depth of cut may be in the range of 1/16–1/4 in. for small work up to 1/2–1 1/2 in. for large work. The feed depends on finish. Rough cuts vary from 0.006 to 0.080 in. and finishing cuts from 0.002 to 0.006 in. Speed should be as high as possible, up to 15,000 fpm.

Cutting forces for an alloy such as 6061-T651 are 0.30-0.50 hp/in.^{3}/min for a 0° rake angle and 0.25-0.35 hp/in.^{3}/min for a 20° rake angle.

Lubrication such as light mineral or soluble oil is desirable for high production. Alloys with a machinability rating of A or B may not need lubrication.

The main types of cutting tool materials include water-hardening steels, high-speed steels, hard-cast alloys, sintered carbides and diamonds:

1. Water-hardening steels (plain carbon or with additions of chromium, vanadium, or tungsten) are lowest in first cost. They soften if cutting edge temperatures exceed 300–400°F; have low resistance to edge wear; and are suitable for low cutting speeds and limited production runs.
2. High-speed steels are available in a number of forms, are heat treatable, permit machining at rapid rates, allow cutting edge temperatures of over 1000°F, and resist shock better than hard-cast or sintered carbides.
3. Hard-cast alloys are cast closely to finish size, are not heat treated, and lie between high-speed steels and carbides in terms of heat resistance, wear, and initial cost. They will not take severe shock loads.
4. Sintered carbide tools are available in solid form or as inserts. They permit speeds 10–30 times faster than for high-speed steels. They can be used for most machining operations. They should be used only when they can be supported rigidly and when there is sufficient power and speed. Many types are available.
5. Mounted diamonds are used for finishing cuts where an extremely high-quality surface is required.

3.9.2 Single-Point Tool Operations

1. *Turning.* Aluminum alloys should be turned at high speeds with the work held rigidly and supported adequately to minimize distortion.

2. *Boring.* All types of tooling are suitable. Much higher speeds can be employed than for boring ferrous materials. Carbide tips are normally used in high-speed boring in vertical or horizontal boring machines.
3. *Planing and Shaping.* Aluminum permits maximum table speeds and high metal removal rates. Tools should not strike the work on the return stroke.

3.9.3 Multipoint Tool Operations

Milling

Removal rate is high with correct cutter design, speed and feed, machine rigidity, and power. When cutting speeds are high, the heat developed is retained mostly in the chips, with the balance absorbed by the coolant. Speeds are high with cutters of high-speed and cast alloys, and very high with sintered carbide cutters.

All common types of solid-tooth, high-carbon, or high-speed steel cutters can be employed. High-carbon cutters operating at a maximum edge temperature of 400°F are preferred for short run production. For long runs, high-speed steel or inserted-tooth cutters are used.

Speeds of 15,000 fpm are not uncommon for carbide cutters. Maximum speeds for high-speed and high-carbon-steel cutters are around 5000 fpm and 600 fpm, respectively.

Drilling

General-purpose drills with bright finishes are satisfactory for use on aluminum. Better results may be obtained with drills having a high helix angle. Flute areas should be large; the point angle should be 118° (130°–140° for deeper holes). Cutting lips should be equal in size. Lip relief angles are between 12° and 20°, increasing toward the center to hold the chisel angle between 130° and 145°.

No set rule can be given for achieving the correct web thickness. Generally, for aluminum, it may be thinner at the point without tool breakage.

A ⅛-in. drill at 6000 rpm has a peripheral speed of 2000 fpm. For drilling aluminum, machines are available with speeds up to 80,000 rpm.

If excessive heat is generated, hold diameter may be reduced even below drill size. With proper drills, feeds, speeds, and lubrication, no heat problem should occur.

For a feed of 0.008 ipr, and a depth to diameter ratio of 4:1, the thrust value is 170 lb and the torque value is 10 lb-in. for a ¼-in. drill with alloy 6061-T651. Aluminum alloys can be counterbored, tapped, threaded by cutting or rolling, and broached. Machining fluid should be used copiously.

Grinding

Resin-bounded silicon carbide wheels of medium hardness are used for rough grinding of aluminum. Finish grinding requires softer, vitrified-bonded wheels. Wheels speeds can vary from 5500 to 6000 fpm. Abrasive belt grinding employs belt speeds from 4600 to 5000 sfpm. Grain size of silicon carbide abrasive varies from 36 to 80 for rough cuts and from 120 to 180 for finishing cuts. For contact wheel abrasive belt grinding, speeds are 4500–6500 sfpm. Silicon carbide or aluminum oxide belts (24–80 grit) are used for rough cuts.

Sawing, Shearing, Routing, and Arc Cutting Aluminum

Correct tooth contour is most important in *circular sawing.* The preferred saw blade has an alternate hollow ground side—rake teeth at about 15°. Operating speeds are 4000–15,000 fpm. Lower speeds are recommended for semi-high-speed steel, intermediate speeds for high-speed inserted-tooth steel blades, and high speeds for carbide-tipped blades.

Band sawing speeds should be between 2000 and 5000 fpm. Spring-tempered blades are recommended for sheet and soft blades with hardened teeth for plate. Tooth pitch should not exceed material thickness: four to five teeth to the inch for spring tempered, six to eight teeth to the inch for flexible backed. Contour sawing is readily carried out. Lubricant should be applied to the back of the blade.

Shearing of sheet may be done on guillotine shears. The clearance between blades is generally 10–12% of sheet thickness down to 5–6% for light gauge soft alloy sheet. Hold-down pads, shear beds, and tables should be covered to prevent marring. Routing can also be used with 0.188–0.50 in. material routed at feeds of 10–30 ipm. Plates of 3-in.-thick heat-treated material can be routed at feeds up to 10 ipm.

Chipless machining of aluminum can be carried out using shear spinning rotary swaging, internal swaging, thread rolling, and flame cutting.

3.10 CORROSION BEHAVIOR

Although aluminum is a chemically active metal, its resistance to corrosion is attributable to an invisible oxide film that forms naturally and is always present unless it is deliberately prevented from forming. Scratch the oxide from the surface and, in air, the oxide immediately reforms. Once formed, the oxide effectively protects the metal from chemical attack and also from further oxidation. Some properties of this natural oxide are:

1. It is very thin—200–400 billionths of an inch thick.
2. It is tenacious. Unlike iron oxide or rust which spalls from the surface leaving a fresh surface to oxidize, aluminum oxide adheres tightly to aluminum.
3. It is hard. Aluminum oxide is one of the hardest substances known.
4. It is relatively stable and chemically inert.
5. It is transparent and does not detract from the metal's appearance.

3.10.1 General Corrosion

The general corrosion behavior of aluminum alloys depends basically on three factors: (1) the stability of the oxide film, (2) the environment, and (3) the alloying elements; these factors are not independent of one another. The oxide film is considered stable between pH 4.5 and 9.0; however, aluminum can be attacked by certain anions and cations in neutral solutions, and it is resistant to some acids and alkalies.

In general, aluminum alloys have good corrosion resistance in the following environments: atmosphere, most fresh waters, seawater, most soils, most foods, and many chemicals. Since "good corrosion resistance" is intended to mean that the material will give long service life without surface protection, in support of this rating is the following list of established applications of aluminum in various environments:

In Atmosphere. Roofing and siding, truck and aircraft skin, architectural.

With Most Fresh Waters. Storage tanks, pipelines, heat exchangers, pleasure boats.

In Seawater. Ship hulls and superstructures, buoys, pipelines.

In Soils. Pipelines and drainage pipes.

With Foods. Cooking utensils, tanks and equipment, cans and packaging.

With Chemicals. Storage tanks, processing and transporting equipment.

It is generally true that the higher the aluminum purity, the greater is its corrosion resistance. However, certain elements can be alloyed with aluminum without reducing its corrosion resistance and in some cases an improvement actually results. Those elements having little or no effect include Mn, Mg, Zn, Si, Sb, Bi, Pb, Ti; those having a detrimental effect include Cu, Fe, Ni:

Al–Mn Alloys. Al–Mn alloys (3xxx series) have good corrosion resistance and may possibly be better than 1100 alloy in marine environments and for cooking utensils because of a reduced effect by Fe in these alloys.

Al–Mg Alloys. Al–Mg alloys (5xxx series) are as corrosion resistant as 1xxx alloys and even more resistant to salt water and some alkaline solutions. In general, they offer the best combination of strength and corrosion resistance of all aluminum alloys.

Al–Mg–Si Alloys. Al–Mg–Si alloys (6xxx series) have good resistance to atmosphere corrosion, but generally slightly lower resistance than Al–Mg alloys. They can be used unprotected in most atmospheres and waters.

Alclad Alloys. Alclad alloys are composite wrought products comprised of an aluminum alloy core with a thin layer of corrosion—protective pure aluminum or aluminum alloy metallurgically bonded to one or both surfaces of the core. As a class, alclad alloys have a very high resistance to corrosion. The cladding is anodic to the core and thus protects the core.

3.10.2 Pitting Corrosion

Pitting is the most common corrosive attack on aluminum alloy products. Pits form at localized discontinuities in the oxide film on aluminum exposed to atmosphere, fresh water, or saltwater, or other neutral electrolytes. Since in highly acidic or alkaline solutions the oxide film is usually unstable pitting generally occurs in a pH range of about 4.5–9.0. The pits can be minute and concentrated and can vary in size and be widely scattered, depending on alloy composition, oxide film quality, and the nature of the corrodent.

The resistance of aluminum to pitting depends significantly on its purity; the purest metal is the most resistant. The presence of other elements in aluminum, except Mn, Mg, and Zn, increases in susceptibility to pitting. Copper and iron have the greatest effect on susceptibility. Alclad alloys have greatest resistance to penetration since any pitting is confined to the more anodic cladding until the cladding is consumed.

3.10.3 Galvanic Corrosion

Aluminum in contact with a dissimilar metal in the presence of an electrolyte tends to corrode more rapidly than if exposed by itself to the same environment; this is referred to as galvanic corrosion.

The tendency of one metal to cause galvanic corrosion of another can be predicted from a "galvanic series," which depends on environments. Such a series is listed below; the anodic metal is usually corroded by contact with a more cathodic one:

Anodic	Magnesium and zinc	Protect aluminum
	Aluminum, cadmium, and chromium	Neutral and safe in most environments
	Steel and iron	Cause slow action on aluminum except in marine environments
	Lead	Safe except for severe marine or industrial atmospheres
	Copper and nickel	Tend to corrode aluminum
Cathodic	Stainless steel	Safe in most atmospheres and fresh water; tends to corrode aluminum in severe marine atmospheres

Since galvanic corrosion is akin to a battery and depends on current flow, several factors determine the severity of attack. These are:

Electrolyte Conductivity. The higher the electrical conductivity, the greater the corrosive effect.

Polarization. Some couples polarize strongly to reduce the current flow appreciably. For example, stainless steel is highly cathodic to aluminum, but because of polarization the two can safely be used together in many environments.

Anode/Cathode Area Ratios. A high ratio minimizes galvanic attack; a low ratio tends to cause severe galvanic corrosion.

3.11 FINISHING ALUMINUM

The aluminum surface can be finished in more different ways than any other metal. The normal finishing operations fall into four categories: mechanical, chemical, electrochemical, and applied. They are usually performed in the order listed although one or more of the processes can be eliminated depending on the final effect desired.

3.11.1 Mechanical Finishes

This is an important starting point since even with subsequent finishing operations, a rough, smooth, or textured surface may be retained and observed. For many applications, the as-fabricated finish may be good enough. Or this surface can be changed by grinding, polishing, buffing, abrasive or shot blasting, tumbling or burnishing, or even hammering for special effects. Rolled surfaces of sheet or foil can be made highly specular by use of polishing rolls; one side or two sides bright and textures can be obtained by using textured rolls.

3.11.2 Chemical Finishes

A chemical finish is often applied after the mechanical finish. The most widely used chemical finishes include caustic etching for a matte finish, design etching, chemical brightening, conversion coatings, and immersion coatings. Conversion coatings chemically convert the natural oxide coating on aluminum to a chromate, a phosphate, or a combination chromate-phosphate coating, and they are principally used and are the recommended ways to prepare the aluminum surface for painting.

3.11.3 Electrochemical Finishes

These include electrobrightening for maximum specularity, electroplating of another metal such as nickel or chromium for hardness and wear resistance, and, most importantly, anodizing. Anodizing is an electrochemical process whereby the natural oxide layer is increased in thickness over a thousand times and made more dense for increased resistance to corrosion and abrasion resistance.

The anodic oxide forms by the growth of cells, each cell containing a central pore. The pores are sealed by immersing the metal into very hot or boiling water. Sealing is an important step and will affect the appearance and properties of the anodized coating. There are several varieties of anodized coatings.

3.11.4 Clear Anodizing

On many aluminum alloys a thick, transparent oxide layer can be obtained by anodizing in a sulfuric acid solution—this is called clear anodizing. The thickness of the layer depends on the current density and the time in solution, and is usually between 0.1 and 1 mil in thickness.

3.11.5 Color Anodizing

Color can be added to the film simply by immersing the metal immediately after anodizing and before sealing into a vat containing a dye or metallic coloring agents and then sealing the film. A wide range of colors have been imparted to aluminum in this fashion for many years. However, the colors imparted in this manner tend to fade from prolonged exposure to sunlight.

3.11.6 Integral Color Anodizing

More lightfast colors for outdoor use are achieved through integral color anodizing. These are proprietary processes utilizing electrolytes containing organic acids and, in some cases, small amounts of impurities are added to the metal itself to bring about the desired colors. This is usually a one-stage process and the color forms as an integral part of the anodize. Colors are for the most part limited to golds, bronzes, grays, and blacks.

3.11.7 Electrolytically Deposited Coloring

Electrolytically deposited coloring is another means of imparting lightfast colors. Following sulfuric acid anodize, the parts are transferred to a second solution containing metallic pigments that are driven into the coating by an electric current.

3.11.8 Hard Anodizing

Hard anodizing, or hardcoating as it is sometimes called, usually involves anodizing in a combination of acids and produces a very dense coating, often 1–5 mils thick. It is very resistant to wear and is normally intended for engineering applications rather than appearance.

3.11.9 Electroplating

In electroplating, a metal such as chromium or nickel is deposited on the aluminum surface from a solution containing that metal. This usually is done for appearance or to improve the hardness or abrasion resistance of the surface. Electroplating has a "smoothing out" effect, whereas anodized coatings follow the contours of the base metal surface thus preserving a matte or a polished surface as well as any other patterns applied prior to the anodize.

3.11.10 Applied Coatings

Applied coatings include porcelain enamel, paints and organic coatings, and laminates such as plastic, paper, or wood veneers. Probably as much aluminum produced today is painted as is anodized. Adhesion can be excellent when the surface has been prepared properly. For best results paint should be applied over a clean conversion-coated or anodized surface.

3.12 SUMMARY

Listed below are some of the characteristics of aluminum and its alloys that lead to their widespread application in nearly every segment of the economy. It is safe to say that no other material offers the same combination of properties.

- *Lightweight.* Very few metals have a lower density than aluminum, and they are not in common usage. Iron and copper are roughly three times as dense, titanium over 60% more dense than aluminum.
- *Good Formability.* Aluminum can be fabricated or shaped by just about every known method and is consequently available in a wide variety of forms.
- *Wide Range of Mechanical Properties.* Aluminum can be utilized as a weak, highly ductile material or, through alloying, as a material with a tensile strength approaching 100,000 psi.
- *High Strength-to-Weight Ratio.* Because of the combination of low density and high tensile strength, some aluminum alloys possess superior strength to weight-ratios, equalled or surpassed only by highly alloyed and strengthened steels and titanium.
- *Good Cryogenic Properties.* Aluminum does not become brittle at very low temperatures; indeed, mechanical properties of most aluminum alloys actually improve with decreasing temperature.
- *Good Weatherability and General Corrosion Resistance.* Aluminum does not rust away in the atmosphere and usually requires no surface protection. It is highly resistant to attack from a number of chemicals.
- *High Electrical and Thermal Conductivity.* Pound for pound, aluminum conducts electricity and heat better than any other material except sodium, which can only be used under very special conditions. On a volume basis, only copper, silver, and gold are better conductors.
- *High Reflectivity.* Normally, aluminum reflects 80% of white light, and this value can be increased with special processing.

- *Finishability.* Aluminum is unique among the architectural metals in respect to the variety of finishes employed.

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