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Volume 2 Properties and Selection: Nonferrous Alloys and Special-Purpose Materials

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Introduction to Aluminum and Aluminum Alloys

Elwin L. Rooy, Aluminum Company of America

ALUMINUM, the second most plentiful metallic element on earth, became an economic competitor in engineering applications as recently as the end of the 19th century. It was to become a metal for its time. The emergence of three important industrial developments 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.

When the electrolytic reduction of alumina (Al_2O_3) dissolved in molten cryolite was independently developed by Charles Hall in Ohio and Paul Heroult in France in 1886, the first internal-combustion-engine-powered vehicles were appearing, and aluminum would play a role as an automotive material of increasing engineering value. Electrification would require immense quantities of light-weight conductive metal for long-distance transmission and for construction of the towers needed to support the overhead network of cables which deliver electrical energy from sites of power generation. Within a few decades the Wright brothers 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.

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

Properties. Among the most striking characteristics of aluminum is its versatility. The range of physical and mechanical properties that can be developed—from refined high-purity aluminum (see the article "Properties of Pure Metals" in this Volume) to the most complex alloys—is re-

markable. More than three hundred alloy compositions are commonly recognized, and many additional variations have been developed internationally and in supplier/consumer relationships. Compositions for both wrought and cast aluminum alloys are provided in the article "Alloy and Temper Designation Systems for Aluminum and Aluminum Alloys" that immediately follows.

The properties of aluminum that make this metal and its alloys the most economical and attractive for a wide variety of uses are appearance, light weight, fabricability, physical properties, mechanical properties, and corrosion resistance.

Aluminum has a density of only 2.7 g/cm³, approximately one-third as much as steel (7.83 g/cm³), copper (8.93 g/cm³), or brass (8.53 g/cm³). It can display excellent corrosion resistance in most environments, including atmosphere, water (including salt water), petrochemicals, and many chemical systems. The corrosion characteristics of aluminum are examined in detail in Volume 13, *Corrosion*, of the 9th Edition of *Metals Handbook*.

Aluminum surfaces can be highly reflective. Radiant energy, visible light, radiant heat, and electromagnetic waves are efficiently reflected, while anodized and dark anodized surfaces can be reflective or absorbent. The reflectance of polished aluminum, over a broad range of wave lengths, leads to its selection for a variety of decorative and functional uses.

Aluminum typically displays excellent electrical and thermal conductivity, but specific alloys have been developed with high degrees of electrical resistivity. These alloys are useful, for example, in high-torque electric motors. Aluminum is often selected for its electrical conductivity, which is nearly twice that of copper on an equivalent weight basis. The requirements of high conductivity and mechanical strength can be met by use of long-line, high-voltage, aluminum steel-cored reinforced transmission cable. The thermal conductivity of alumi-

num alloys, about 50 to 60% that of copper, is advantageous in heat exchangers, evaporators, electrically heated appliances and utensils, and automotive cylinder heads and radiators.

Aluminum is nonferromagnetic, a property of importance in the electrical and electronics industries. It is nonpyrophoric, which is important in applications involving inflammable or explosive-materials handling or exposure. Aluminum is also non-toxic and is routinely used in containers for foods and beverages. It 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.

Some aluminum alloys exceed structural steel in strength. However, pure aluminum and certain aluminum alloys are noted for extremely low strength and hardness.

Aluminum Production

All aluminum production is based on the Hall-Heroult process. Alumina refined from bauxite is dissolved in a cryolite bath with various fluoride salt additions made to control bath temperature, density, resistivity, and alumina solubility. An electrical current is then passed through the bath to electrolyze the dissolved alumina with oxygen forming at and reacting with the carbon anode, and aluminum collecting as a metal pad at the cathode. The separated metal is periodically removed by siphon or vacuum methods into crucibles, which are then transferred to casting facilities where remelt or fabricating ingots are produced.

The major impurities of smelted aluminum are iron and silicon, but zinc, gallium, titanium, and vanadium are typically present as minor contaminants. Internationally, minimum aluminum purity is the primary criterion for defining composition and value. In the United States, a convention for considering the relative concentrations of iron and silicon as the more important criteria has evolved. Reference to grades of unalloyed metal may therefore be by purity

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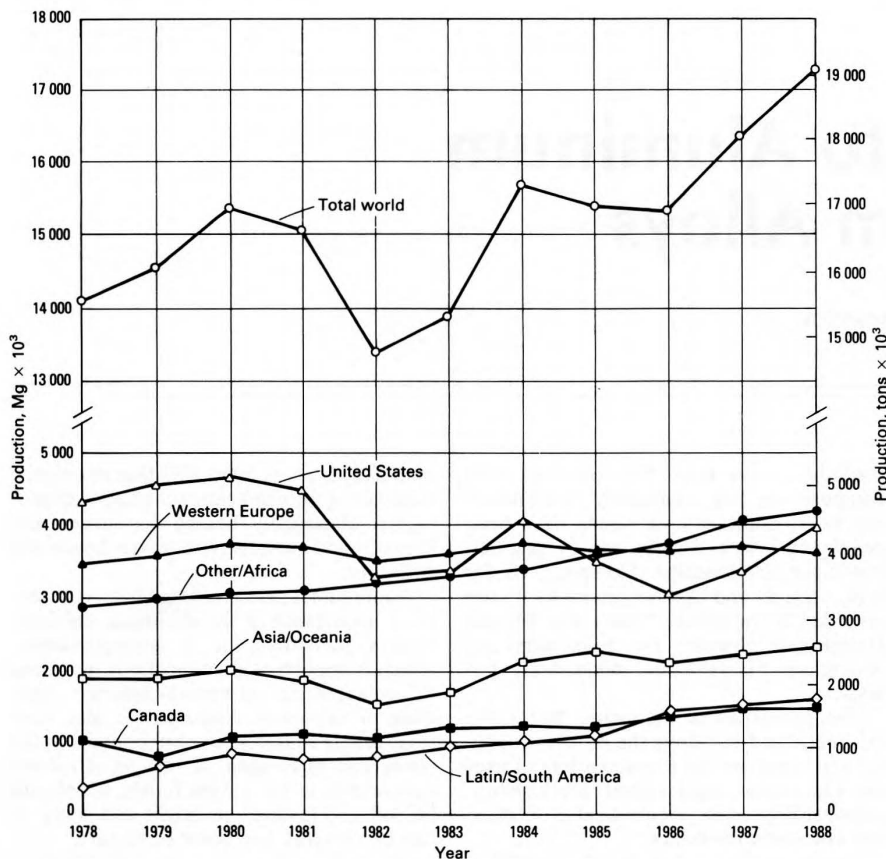


Fig. 1 Annual world production of primary aluminum. Source: Aluminum Association, Inc.

alone, for example, 99.70% aluminum, or by the method sanctioned by the Aluminum Association in which standardized Pxx grades have been established. In the latter case, the digits following the letter P refer to the maximum decimal percentages of silicon and iron, respectively. For example, P1020 is unalloyed smelter-produced metal containing no more than 0.10% Si and no more than 0.20% Fe. P0506 is a grade which contains no more than 0.05% Si and no more than 0.06% Fe. Common P grades range from P0202 to P1535, each of which incorporates additional impurity limits for control purposes.

Refining steps are available to attain much higher levels of purity. Purities of 99.99% are achieved through fractional crystallization or Hoopes cell operation. The latter process is a three-layer electrolytic process which employs molten salt of greater density than pure molten aluminum. Combinations of these purification techniques result in 99.999% purity for highly specialized applications.

Production Statistics. World production of primary aluminum totaled 17 304 thousand metric tonnes (17.304×10^6 Mg) in 1988 (Fig. 1). From 1978 to 1988, world production increased 22.5%, an annual growth rate of 1.6%. As shown in Fig. 2, the United

States accounted for 22.8% of the world's production in 1988, while Europe accounted for 21.7%. The remaining 55.5% was produced by Asia (5.6%), Canada (8.9%), Latin/South America (8.8%), Oceania (7.8%), Africa (3.1%), and others (21.3%). The total U.S. supply in 1988 was 7 533 749 Mg in 1988, with primary production representing 54% of total supply, imports accounting for 20%, and secondary recovery representing 26% (Fig. 3). The source of secondary production is scrap in all forms, as well as the product of skim and dross processing. Primary and secondary production of aluminum are integrally related and complementary. Many wrought and cast compositions are constructed to reflect the impact of controlled element contamination that may accompany scrap consumption. A recent trend has been increased use of scrap in primary and integrated secondary fabricating facilities for various wrought products, including can sheet.

Aluminum Alloys

It is convenient to divide aluminum alloys into two major categories: casting compositions and wrought 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. Some casting alloys are essentially not heat treatable and are used only in as-cast or in thermally modified conditions unrelated to solution 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 (see the article "Alloy and Temper Designation Systems for Aluminum and Aluminum Alloys" in this Volume for details). For wrought alloys a four-digit system is used to produce a list of wrought composition families as follows:

- 1xxx Controlled unalloyed (pure) compositions
- 2xxx Alloys in which copper is the principal alloying element, though other elements, notably magnesium, may be specified
- 3xxx Alloys in which manganese is the principal alloying element
- 4xxx Alloys in which silicon is the principal alloying element
- 5xxx Alloys in which magnesium is the principal alloying element
- 6xxx Alloys in which magnesium and silicon are principal alloying elements
- 7xxx Alloys in which zinc is the principal alloying element, but other elements such as copper, magnesium, chromium, and zirconium may be specified
- 8xxx Alloys including tin and some lithium compositions characterizing miscellaneous compositions
- 9xxx Reserved for future use

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 specification requirements. Alloy families for casting compositions are:

- 1xx.x Controlled unalloyed (pure) compositions, especially for rotor manufacture
- 2xx.x Alloys in which copper is the principal alloying element, but other alloying elements may be specified

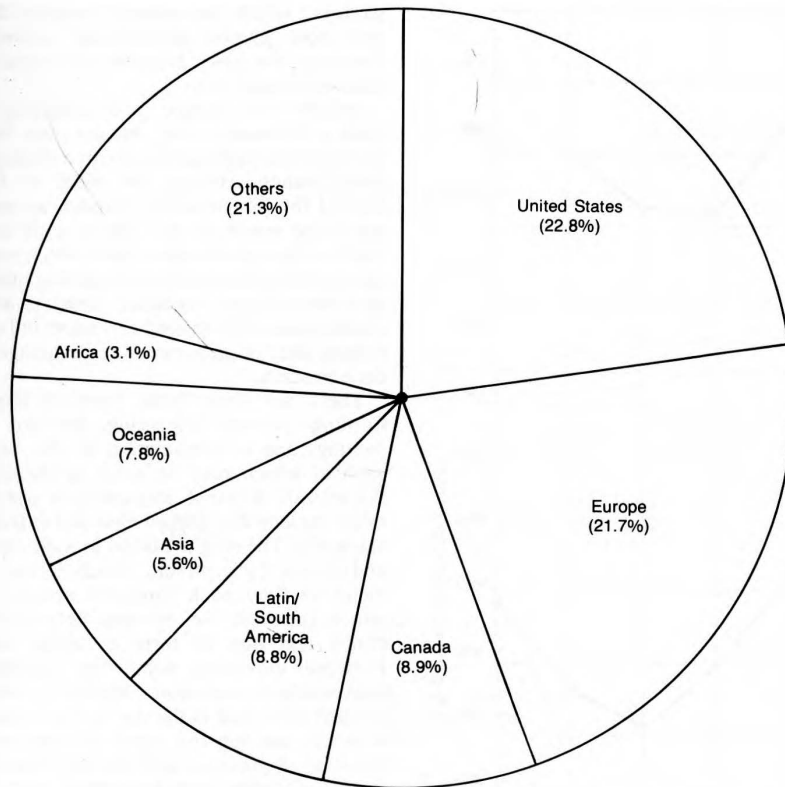


Fig. 2 Percentage distribution of world primary aluminum production in 1988. Source: Aluminum Association, Inc.

- 3xx.x Alloys in which silicon is the principal alloying element, but other alloying elements such as copper and magnesium are specified
- 4xx.x Alloys in which silicon is the principal alloying element
- 5xx.x Alloys in which magnesium is the principal alloying element
- 6xx.x Unused
- 7xx.x Alloys in which zinc is the principal alloying element, but other alloying elements such as copper and magnesium may be specified
- 8xx.x Alloys in which tin is the principal alloying element
- 9xx.x Unused

Manufactured Forms

Aluminum and its alloys may be cast or formed by virtually all known processes. Manufactured forms of aluminum and aluminum alloys can be broken down into two groups. Standardized products include sheet, plate, foil, rod, bar, wire, tube, pipe, and structural forms. Engineered products are those designed for specific applications and include extruded shapes, forgings, impacts, castings, stampings, powder metallurgy (P/M) parts, machined parts, and metal-matrix composites. A percentage distribution of major aluminum products is presented in Fig. 4.

Properties and applications of the various aluminum product forms can be found in the articles "Aluminum Mill and Engineered Wrought Products" and "Aluminum Foundry Products" that follow.

Standardized Products

Flat-rolled products include plate (thickness equal to or greater than 6.25 mm, or 0.25 in.), sheet (thickness 0.15 mm through 6.25 mm, or 0.006 through 0.25 in.), and foil (thickness less than 0.15 mm, or 0.006 in.). These products are semifabricated to rectangular cross section by sequential reductions in the thickness of cast ingot by hot and cold rolling. Properties in work-hardened tempers are controlled by degree of cold reduction, partial or full annealing, and the use of stabilizing treatments. Plate, sheet, and foil produced in heat-treatable compositions may be solution heat treated, quenched, precipitation hardened, and thermally or mechanically stress relieved.

Sheet and foil may be rolled with textured surfaces. Sheet and plate rolled with specially prepared work rolls may be embossed to produce products such as tread plate. By roll forming, sheet in corrugated or other contoured configurations can be produced for such applications as roofing, siding, ducts, and gutters.

While the vast majority of flat-rolled products are produced by conventional rolling mills, continuous processes are now in use to convert molten alloy directly to reroll gages (Fig. 5). Strip casters employ counterrotating water-cooled cylinders or rolls to solidify and partially work coilable gage reroll stock in line. Slab casters of either twin-belt or moving block design cast stock typically 19 mm (0.75 in.) in thickness which is reduced in thickness by in-line hot reduction mill(s) to produce coilable reroll. Future developments based on technological and operational advances in continuous processes may be expected to globally affect industry expansions in flat-rolled product manufacture.

Wire, rod, and bar are produced from cast stock by extrusion, rolling, or combinations of these processes. Wire may be of any cross section in which distance between parallel faces or opposing surfaces is less than 9.4 mm (0.375 in.). Rod exceeds 9.4 mm (0.375 in.) in diameter and bar in square, rectangular, or regular hexagonal or octagonal cross section is greater than 9.4 mm (0.375 in.) between any parallel or opposing faces.

An increasingly large proportion of rod and wire production is derived from continuous processes in which molten alloy is cast in water-cooled wheel/mold-belt units to produce a continuous length of solidified bar which is rolled in line to approximately 9.4 to 12 mm (0.375 to 0.50 in.) diameter.

Engineered Products

Aluminum alloy castings are routinely produced by pressure-die, permanent-mold, green- and dry-sand, investment, and plaster casting. Shipment statistics are provided in Fig. 6. Process variations include vacuum, low-pressure, centrifugal, and pattern-related processes such as lost foam. Castings are produced by filling molds with molten aluminum and are used for products with intricate contours and hollow or cored areas. The choice of castings over other product forms is often based on net shape considerations. Reinforcing ribs, internal passageways, and complex design features, which would be costly to machine in a part made from a wrought product, can often be cast by appropriate pattern and mold or die design. Premium engineered castings display extreme integrity, close dimensional tolerances, and consistently controlled mechanical properties in the upper range of existing high-strength capabilities for selected alloys and tempers.

Extrusions are produced by forcing solid metal through aperture dies. Designs that are symmetrical around one axis are especially adaptable to production in extruded form. With current technology, it is also possible to extrude complex, mandrel-cored, and asymmetrical configurations. Precision extrusions display exceptional di-

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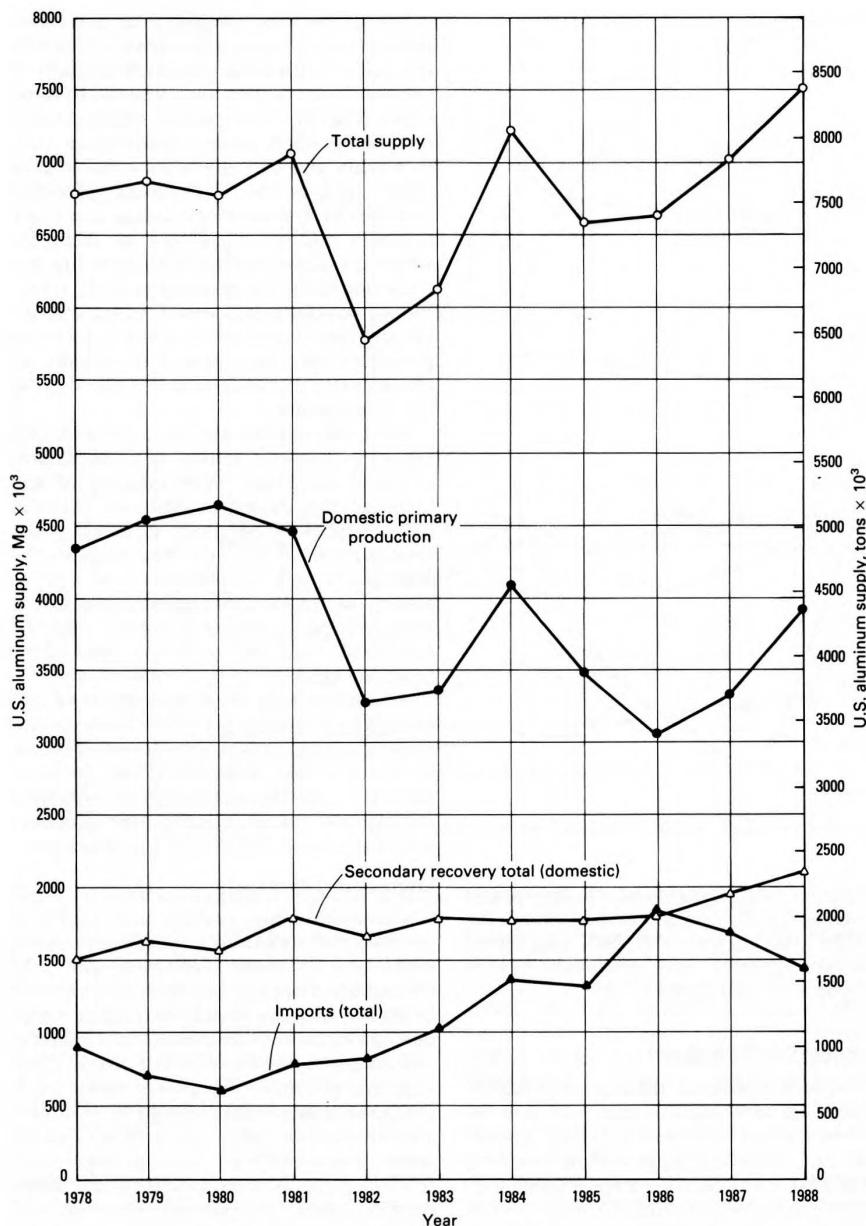


Fig. 3 U.S. aluminum production and supply statistics. Source: Aluminum Association, Inc.

dimensional control and surface finish. Major dimensions usually require no machining; tolerance of the as-extruded product often permits completion of part manufacture with simple cutoff, drilling, broaching, or other minor machining operations. Extruded and extruded/drawn seamless tube competes with mechanically seamed and welded tube.

Forgings are produced by inducing plastic flow through the application of kinetic, mechanical, or hydraulic forces in either closed or open dies. Hand forgings are

simple geometric shapes, formable between flat or modestly contoured open dies such as rectangles, cylinders (multiface rounds), disks (biscuits), or limited variations of these shapes. These forgings fill a frequent need in industry when only a limited number of pieces is required, or when prototype designs are to be proven.

Most aluminum forgings are produced in closed dies to produce parts with good surface finish, dimensional control, and exceptional soundness and properties. Precision forgings emphasize near net shape ob-

jectives, which incorporate reduced draft and more precise dimensional accuracy. Forgings are also available as rolled or mandrel-forged rings.

Impacts are formed in a confining die from a lubricated slug, usually cold, by a single-stroke application of force through a metal punch causing the metal to flow around the punch and/or through an opening in the punch or die. The process lends itself to high production rates with a precision part being produced to exacting quality and dimensional standards. Impacts are a combination of both cold extrusion and cold forging and, as such, combine advantages of each process.

There are three basic types of impact forming—reverse impacting, forward impacting, and a combination of the two—each of which may be used in aluminum fabrication. Reverse impacting is used to make shells with a forged base and extruded sidewalls. The slug is placed in a die cavity and struck by a punch, which forces the metal to flow back (upward) around the punch, through the opening between the punch and die, to form a simple shell. Forward impacting somewhat resembles conventional extrusion. Metal is forced through an orifice in the die by the action of a punch, causing the metal to flow in the direction of pressure application. Punch/die clearance limits flash formation. Forward impacting with a flat-face punch is used to form round, contoured, straight, and ribbed rods. With a stop-race punch, thin-walled parallel or tapered sidewall tubes with one or both ends open may be formed. In the combination method, the punch is smaller than an orificed die resulting in both reverse and forward metal flow.

Powder metallurgy (P/M) parts are formed by a variety of processes. For less demanding applications, metal powder is compressed in a shaped die to produce green compacts, and then the compacts are sintered (diffusion bonded) at elevated temperature under protective atmosphere. During sintering, the compacts consolidate and strengthen. The density of sintered compacts may be increased by re-pressing. When re-pressing is performed primarily to improve dimensional accuracy, it is termed "sizing;" when performed to alter configuration, it is termed "coining." Re-pressing may be followed by resintering, which relieves stresses induced by cold work and may further consolidate the structure. By pressing and sintering only, parts having densities of greater than 80% theoretical density can be produced. By re-pressing, with or without resintering, parts of 90% theoretical density or more can be produced. Additional information on conventionally pressed and sintered aluminum P/M products can be found in the Appendix to the article "High-Strength Aluminum P/M Alloys" in this Volume.

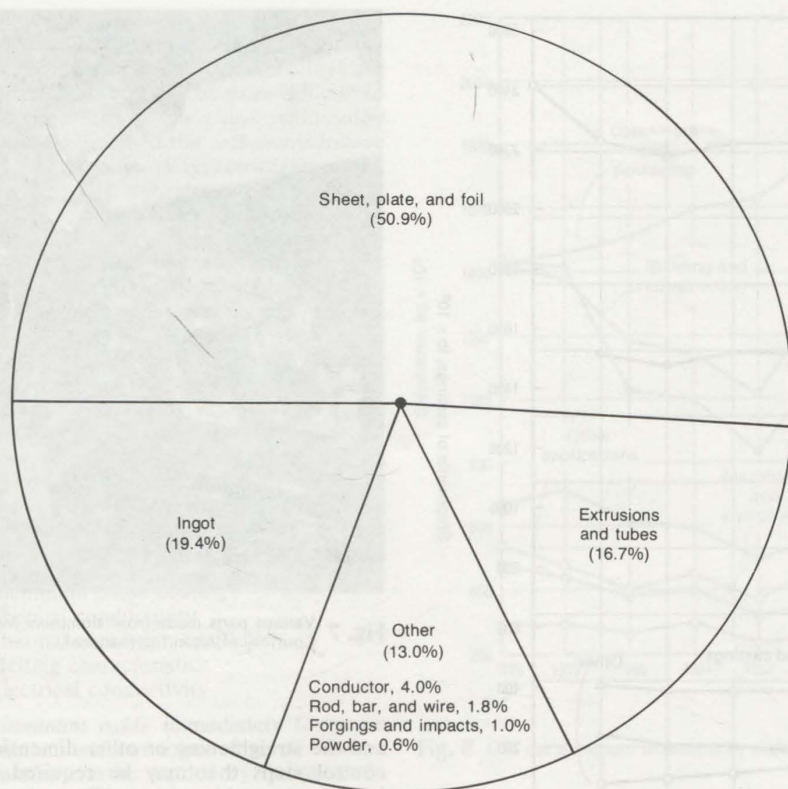


Fig. 4 Percentage distribution of major aluminum products in 1988. Source: Aluminum Association, Inc.

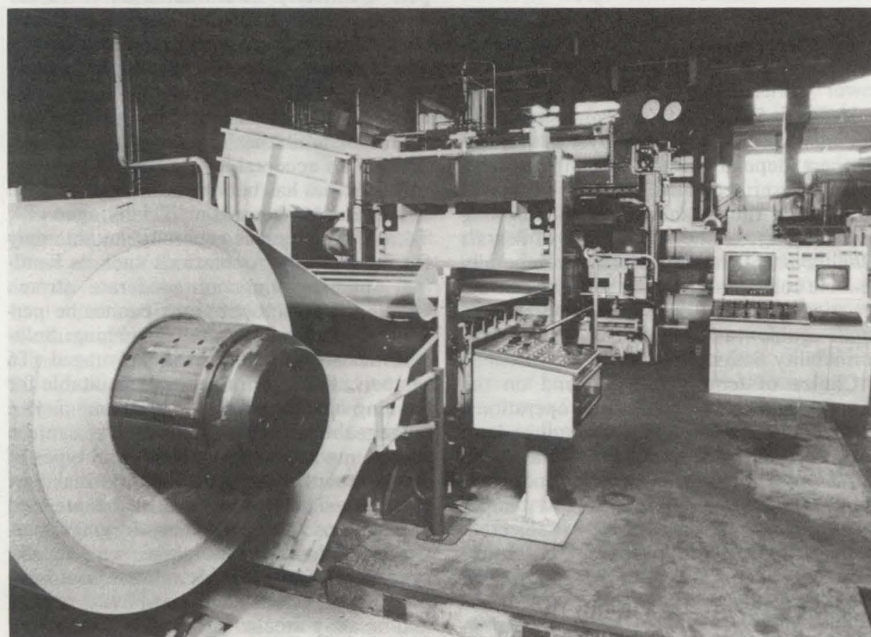


Fig. 5 Facility for producing aluminum sheet reroll directly from molten aluminum

For more demanding applications, such as aerospace parts or components requiring

enhanced resistance to stress-corrosion cracking, rapidly solidified or mechanically

attrited aluminum powders are consolidated by more advanced techniques that result in close to 100% of theoretical density. These consolidation methods include hot isostatic pressing, rapid omnidirectional compaction, ultra-high strain rate (dynamic) compaction, and spray deposition techniques. Using advanced P/M processing methods, alloys that cannot be produced through conventional ingot metallurgy methods are routinely manufactured. The aforementioned article "High-Strength Aluminum P/M Alloys" provides detailed information on advanced P/M processing.

Powder metallurgy parts may be competitive with forgings, castings, stampings, machined components, and fabricated assemblies. Certain metal products can be produced only by powder metallurgy; among these are oxide-dispersed strengthened alloys and materials whose porosity (number distribution and size of pores) is controlled (filter elements and self-lubricating bearings).

Metal-matrix composites (MMCs) basically consist of a nonmetallic reinforcement incorporated into a metallic matrix. The combination of light weight, corrosion resistance, and useful mechanical properties, which has made aluminum alloys so popular, lends itself well to aluminum MMCs. The melting point of aluminum is high enough to satisfy many application requirements, yet is low enough to render composite processing reasonably convenient. Aluminum can also accommodate a variety of reinforcing agents. Reinforcements, characterized as either continuous or discontinuous fibers, typically constitute 20 vol% or more of the composite. The family of aluminum MMC reinforcements includes continuous boron; aluminum oxide; silicon carbide and graphite fibers; and various particles, short fibers, and whiskers. Figure 7 shows a variety of parts produced from aluminum MMCs. Information on the processing and properties of these materials can be found in the article "Metal-Matrix Composites" in this Volume.

Fabrication Characteristics

This section will briefly review important considerations in the machining, forming, forging, and joining of aluminum alloys. Additional information can be found in the articles "Aluminum Mill and Engineered Wrought Products" and "Aluminum Foundry Products" in this Volume and in articles found in other Handbooks that are referenced below.

Machinability of most aluminum alloys is excellent. Among the various wrought and cast aluminum alloys and among the tempers in which they are produced, there is considerable variation in machining characteristics, which may require special tooling or techniques (see the article "Machining of

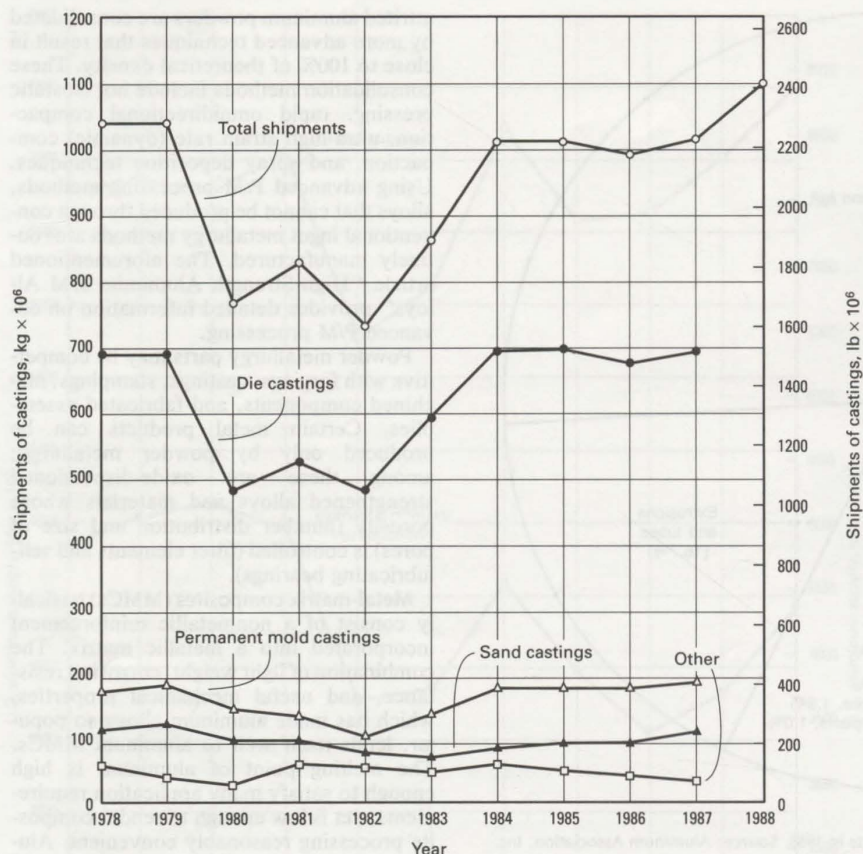


Fig. 6 U.S. casting shipments from 1978 through 1988. Source: Aluminum Association, Inc.

Aluminum and Aluminum Alloys" in Volume 16, *Machining*, of the 9th Edition of *Metals Handbook*). Hardness and yield strength are variously used as approximations of machinability.

Chemical milling, the removal of metal by chemical attack in an alkaline or acid solution, is routine for specialized reductions in thickness. For complex large surface areas in which uniform metal removal is required, chemical milling is often the most economical method. The process is used extensively to etch preformed aerospace parts to obtain maximum strength-to-weight ratios. Integrally stiffened aluminum wing and fuselage sections are chemically milled to produce an optimum cross section and minimum skin thickness. Spars, stringers, floor beams, and frames are frequent applications as well. See the article "Chemical Milling" in Volume 16, *Machining*, of the 9th Edition of *Metals Handbook* for more information.

Formability is among the more important characteristics of aluminum and many of its alloys. Specific tensile and yield strengths, ductility, and respective rates of work hardening control differences in the amount of permissible deformation.

Ratings of comparable formability of the commercially available alloys in various tempers depend on the forming process, and are described in the article "Forming of Aluminum Alloys" in Volume 14, *Forming and Forging*, of the 9th Edition of *Metals Handbook*. Such ratings provide generally reliable comparisons of the working characteristics of metals, but serve as an approximate guide rather than as quantitative formability limits.

Choice of temper may depend on the severity and nature of operations. The annealed temper may be required for severe forming operations such as deep drawing, or for roll forming or bending on small radii. Usually, the strongest temper that can be formed consistently is selected. For less severe forming operations, intermediate tempers or even fully hardened conditions may be acceptable.

Heat-treatable alloys can be formed in applications for which a high strength-to-weight ratio is required. The annealed temper of these alloys is the most workable condition, but the effects of dimensional change and distortion caused by subsequent heat treatment for property development,

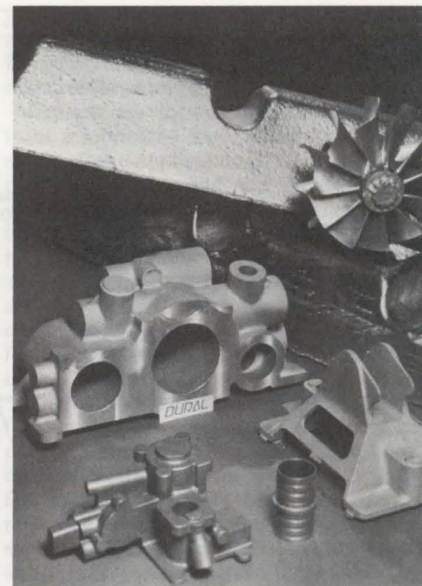


Fig. 7 Various parts made from aluminum MMCs. Courtesy of Alcan International

and the straightening or other dimensional control steps that may be required, are important considerations. Alloys that are formed immediately following solution heat treatment and quench (T3, T4, or W temper) are nearly as formable as when annealed, and can be subsequently hardened by natural or artificial aging. Parts can be stored at low temperatures (approximately -30 to -35 °C, or -20 to -30 °F or lower) in the W temper for prolonged periods as a means of inhibiting natural aging and preserving an acceptable level of formability. Material that has been solution heat treated and quenched but not artificially aged (T3, T4, or W temper) is generally suitable only for mild forming operations such as bending, mild drawing, or moderate stretch forming if these operations cannot be performed immediately after quenching. Solution heat-treated and artificially aged (T6 temper) alloys are in general unsuitable for forming operations.

Forgeability. Aluminum alloys can be forged into a variety of shapes and types of forgings with a broad range of final part forging design criteria based on the intended application. Aluminum alloy forgings, particularly closed-die forgings, are usually produced to more highly refined final forging configurations than hot-forged carbon and/or alloy steels. For a given aluminum alloy forging shape, the pressure requirements in forging vary widely, depending primarily on the chemical composition of the alloy being forged, the forging process being employed, the forging strain rate, the type of forging being manufactured, the

lubrication conditions, and the forging and die temperatures.

As a class of alloys, aluminum alloys are generally considered to be more difficult to forge than carbon steels and many alloy steels. Compared to the nickel/cobalt-base alloys and titanium alloys, however, aluminum alloys are considerably more forgeable, particularly in conventional forging process technology, in which dies are heated to 540 °C (1000 °F) or less. The factors influencing the forgeability of aluminum alloys as well as applicable forging methods are described in the article "Forging of Aluminum Alloys" in Volume 14, *Forming and Forging*, of the 9th Edition of *Metals Handbook*.

Joining. Aluminum can be joined by a wide variety of methods, including fusion and resistance welding, brazing, soldering, adhesive bonding, and mechanical methods such as riveting and bolting. Factors that affect the welding of aluminum include:

- Aluminum oxide coating
- Thermal conductivity
- Thermal expansion coefficient
- Melting characteristics
- Electrical conductivity

Aluminum oxide immediately forms on aluminum surfaces exposed to air. Before aluminum can be welded by fusion methods, the oxide layer must be removed mechanically by machining, filing, wire brushing, scraping, or chemical cleaning. If oxides are not removed, oxide fragments may be entrapped in the weld and will cause a reduction in ductility, a lack of fusion, and possibly weld cracking. During welding, the oxide must be prevented from re-forming by shielding the joint area with a nonoxidizing gas such as argon, helium, or hydrogen, or chemically by use of fluxes.

Thermal conductivity is the physical property that most affects weldability. The thermal conductivity of aluminum alloys is about one-half that of copper and four times that of low-carbon steel. This means that heat must be supplied four times as fast to aluminum alloys as to steel to raise the temperature locally by the same amount. However, the high thermal conductivity of aluminum alloys helps to solidify the molten weld pool of aluminum and, consequently, facilitates out-of-position welding.

The coefficient of linear thermal expansion, which is a measure of the change in length of a material with a change in its temperature, is another physical property of importance when considering weldability. The coefficient of linear thermal expansion for aluminum is twice that for steel. This means that extra care must be taken in welding aluminum to ensure that the joint space remains uniform. This may necessitate preliminary joining of the parts of the assembly by tack welding prior to the main welding operation.

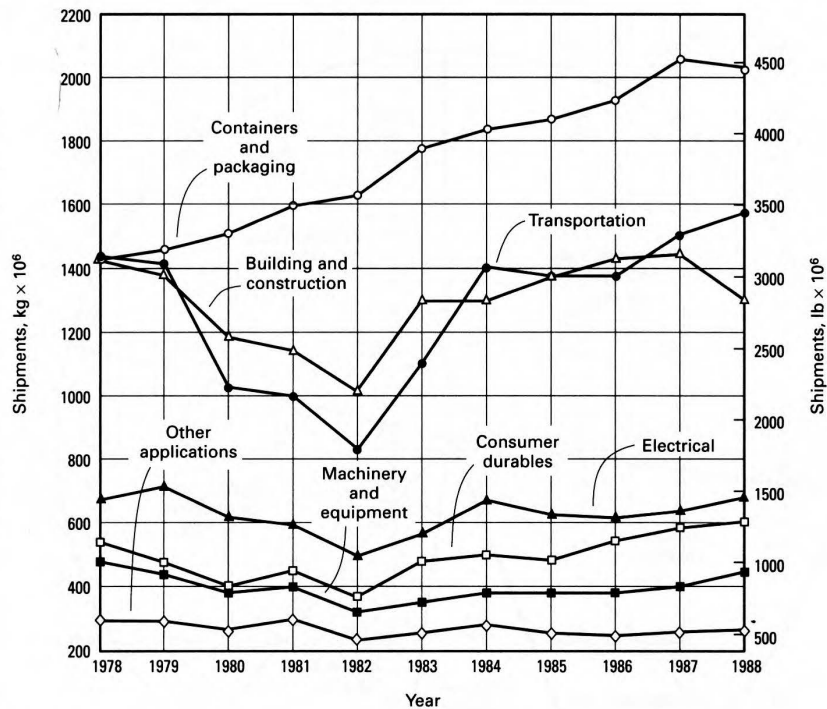


Fig. 8 U.S. net aluminum shipments by major market. Source: Aluminum Association, Inc.

The combination of high coefficient of thermal expansion and high thermal conductivity would cause considerable distortion of aluminum during welding were it not for the high welding speed possible.

Melt Characteristics. The melting ranges for aluminum alloys are considerably lower than those for copper or steel. Melting temperatures and the volumetric specific heats and heats of fusion of aluminum alloys determine that the amount of heat required to enter the welding temperature range is much lower for aluminum alloys.

Electrical conductivity has little influence on fusion welding but is a very important property for materials that are to be resistance welded. In resistance welding, resistance of the metal to the flow of welding current produces heat, which causes the portion of the metal through which the current flows to approach or reach its melting point. Aluminum has higher conductivity than steel, which means that much higher currents are required to produce the same heating effect. Consequently, resistance welding machines for aluminum must have much higher output capabilities than those normally used for steel, for welding comparable sections. More detailed information on welding of aluminum alloys as well as other joining methods can be found in Volume 6, *Welding, Brazing, and Soldering*, of the 9th Edition of *Metals Handbook* and in Volume 3, *Adhesives and Sealants*, of the *Engineered Materials Handbook*.

Product Classifications

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 below, each of these major markets comprises a wide range of end uses. Figure 8 provides data on annual U.S. shipments of aluminum by major markets. The percentage distribution of these markets is illustrated in Fig. 9.

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 may be

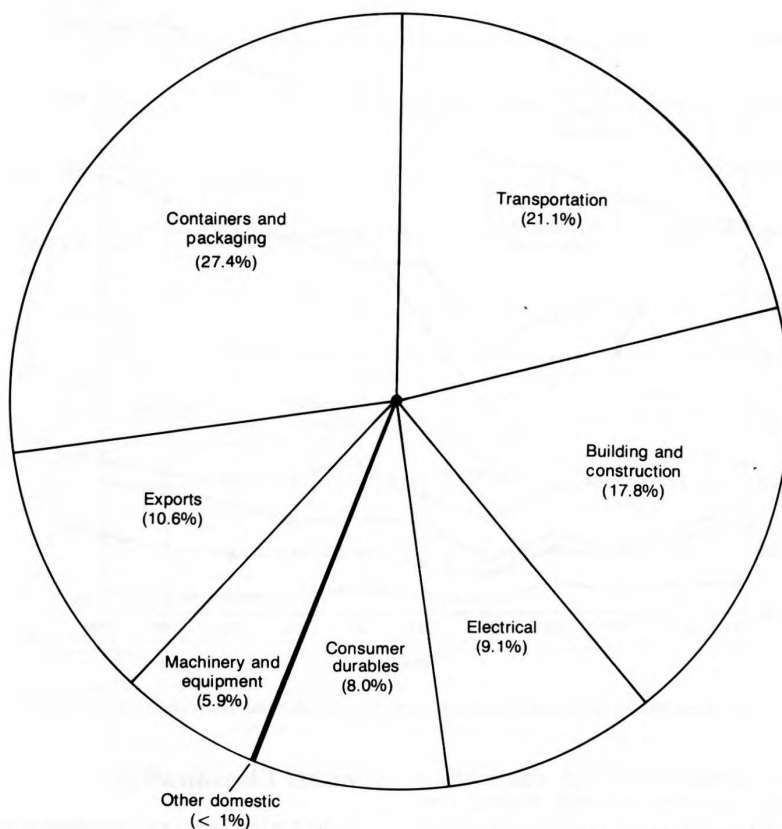


Fig. 9 Percentage distribution of net U.S. aluminum product shipments by major market. Source: Aluminum Association, Inc.

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, hard-

ware, 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.

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 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 splinter-proof. 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.

Beverage cans have been the aluminum industry's greatest success story, 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 toothpaste, ointments, food, and paints.

Transportation

Automotive. Both wrought and cast aluminum have found wide use in automobile construction (Table 1). Typical aluminum usage per unit of approximately 70 kg (150 lb) is expected to increase dramatically as average fuel economy mandates and emphasis on recycling continue. The most intensive use of aluminum in a passenger car approximates 295 kg (650 lb), defining the present target for further material substitutions. 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.

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 resistance, and attractive appearance.

Table 1 Trends in aluminum usage in the U.S. transportation industry

Usage	1988	1987	1986	1985	1984	1983	1982	1981	1980	1979	1978
Trucks & buses											
Ingot	235	205	200	200	212	183	151	148	136	216	199
Total mill products	271	265	236	219	254	174	122	162	151	281	250
Sheet	148	144	128	123	151	96	68	85	77	158	137
Plate	6	6	5	5	4	4	3	4	4	8	7
Foil	1	1	1	1	1	...	...	...	...	...	...
Rod and bar(a)	2	2	1	1	1	2	2	2	2	5	5
Extruded shapes	68	70	65	55	60	49	32	45	44	69	64
Extruded pipe and tube(b)	3	2	2	2	1	1	1	1	1	1	1
Drawn tube(b)	...	...	...	...	1	1	1	1	1	1	1
Bare wire	...	...	...	...	...	...	...	...	...	1	1
Forgings	42	39	33	31	34	20	14	23	21	37	33
Impacts	1	1	1	1	1	1	1	1	1	1	1
Total	506	470	436	419	466	357	273	310	287	497	449
Passenger cars											
Ingot	1253	1162	1101	1109	1108	917	662	781	746	1008	1003
Total mill products	493	468	444	438	434	362	249	324	300	493	568
Sheet	313	296	286	274	284	235	156	199	180	333	392
Plate	2	2	1	1	1	1	1	1	1	1	2
Foil	56	55	47	46	43	40	26	28	24	36	41
Rod and bar(a)	22	20	22	20	18	19	9	9	10	11	11
Extruded shapes	46	49	46	53	43	34	37	59	61	73	77
Extruded pipe and tube(b)	39	33	26	27	22	18	9	13	9	10	14
Drawn tube(b)	...	...	...	...	5	3	1	4	7	12	13
Bare wire	2	2	3	3	4	1	1	1	1	1	1
Forgings	11	9	11	12	12	10	8	8	6	14	14
Impacts	2	2	2	2	2	1	1	2	1	2	3
Total(c)	1746	1630	1545	1547	1542	1279	911	1105	1046	1501	1571
Trailers and semi-trailers											
Ingot	29	32	28	30	31	20	17	20	21	33	33
Total mill products	396	418	360	356	394	281	157	191	222	355	392
Sheet	153	167	143	140	158	124	62	78	88	143	165
Plate	9	9	10	11	9	7	4	7	9	14	15
Rod and bar(a)	1	1	1	1	1	1	1	1	1	2	2
Extruded shapes	229	237	203	201	222	147	88	103	122	194	208
Pipe and tube(b)	3	3	2	2	2	1	1	1	1	1	1
Bare wire	1	1	1	1	2	1	1	1	1	1	1
Forgings	...	...	...	...	...	...	...	...	...	...	...
Total	425	450	388	386	425	301	174	211	243	388	425

(a) Extruded rod and bar combined with rolled and continuous cast and rod bar. (b) Drawn tube combined with extruded pipe and tube. (c) Shipments to passenger cars cover new domestic automobile production, spare parts, accessories and after-market parts. Shipments for light trucks and vans are included in the trucks and buses classification. Source: Aluminum Association, Inc.

ance. 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 alloys are used in medium and heavy-duty gasoline and diesel engines for connecting-rod and main bearings. Cast and wrought bearings may be composite with a steel backing and

babbited or other plated overlay. Bearing alloys are further discussed in the article "Aluminum Foundry Products" in this Volume.

Railroad Cars. Aluminum is used in the construction of railroad hopper cars, box cars, refrigerator cars, and tank cars (Fig. 10). Aluminum is also used extensively in passenger rail cars, particularly those 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, 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 about 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 may 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. Ad-

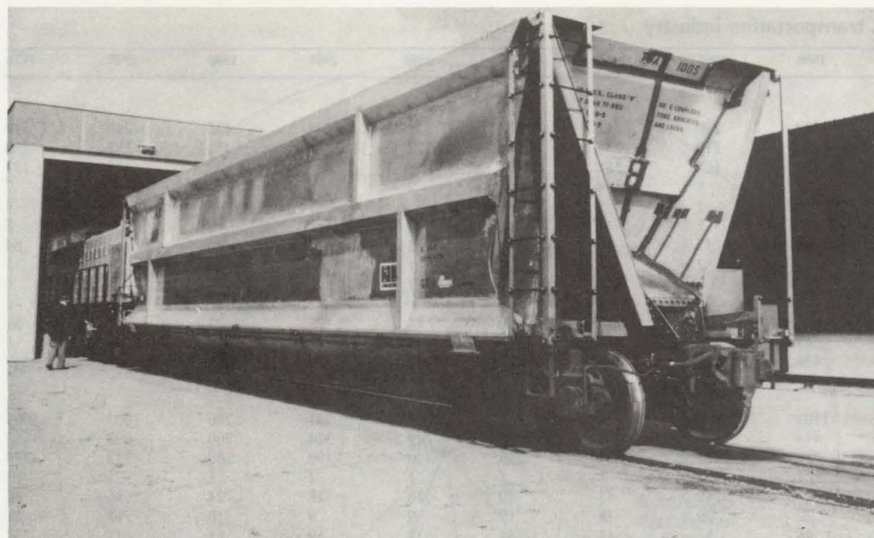


Fig. 10 The intensive use of aluminum in all transportation systems minimizes dead weight and reduces operating and maintenance costs. Courtesy of Alcan International

ditional 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 (Fig. 11)—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 in salt water and other atmospheres is secured

through the use of alclad alloys or anodic coatings. The exterior of aircraft exposed to salt water environment is usually fabricated from clad alloys. Anodized bare stock successfully resists corrosion when only occasional exposure to salt water is encountered. Corrosion resistance may be further enhanced by organic finishes or other protective coatings. Extensive reviews on the uses and corrosion properties of aluminum for aircraft and aerospace vehicles can be found in Volume 13, *Corrosion*, of the 9th Edition of *Metals Handbook* (see pages 1019 to 1106).

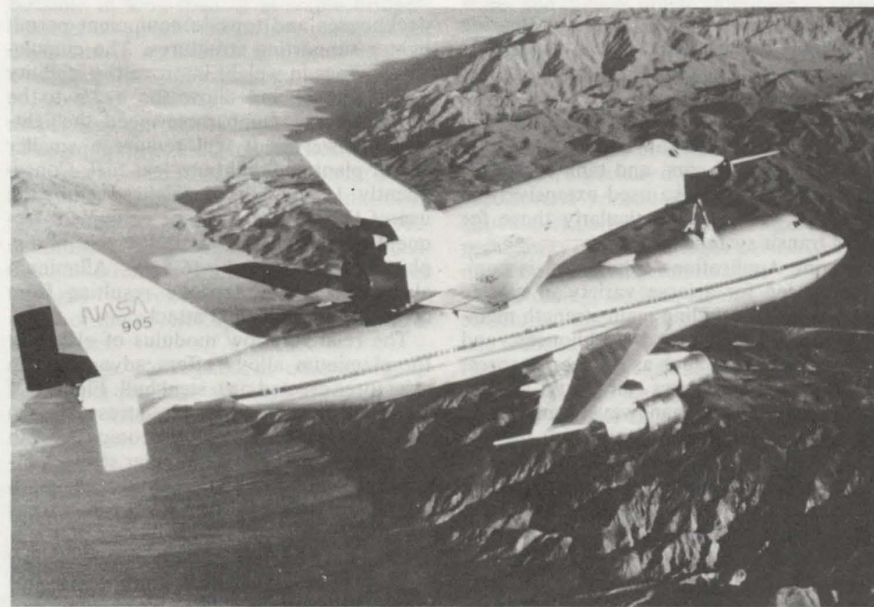


Fig. 11 Aluminum is used extensively in aircraft/aerospace vehicles such as the space shuttle shown in this figure.

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 a basis of mass instead of volume, minimum conductivity of hard drawn aluminum 1350 is 204.6%. Other alloys are used in bus bar, for 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 may 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 about 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, are often 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 extensively 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 name plates, and hardware such as bolts, screws, and nuts. In addition, finned shapes are used in electronic components to facilitate heat removal. Aluminum may 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, wrapped into the coil, mechanically sepa-

rates 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 may 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 its other desirable characteristics aluminum's brazability 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 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, ice cube trays, 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 may 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. The use of aluminum for each of the aforementioned industries is described in more detail in Volume 13, *Corrosion*, of the 9th Edition of *Metals Handbook*.

Textile Equipment. Aluminum is used extensively in textile machinery and equip-

ment in the form of extrusions, tube, sheet, castings, and forgings. It is resistant to many corrosive agents encountered in textile mills and in the manufacture of yarns. A high strength-to-weight ratio reduces the inertia of high-speed machine parts. Permanent dimensional accuracy with light weight improves the dynamic balance of machine members running at high speeds, 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 and 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 hydro-press 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 assure 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.

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 may 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 powders and pastes include printing inks, pyrotechnics, floating soap, aerated concrete, thermite welding, and energy-enhancing fuel additives. Additional information can be found in Volume 7, *Powder Metallurgy*, of the 9th Edition of *Metals Handbook*.

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. See the article "Cathodic Protection" in Volume 13, *Corrosion*, of the 9th Edition of *Metals Handbook* for additional information.