Rolling Aluminum: From the Mine Through the Mill
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HOW TO USE THIS PUBLICATION

This publication enlarges upon the information presented in The Aluminum Association DVD “Rolling Aluminum: From the Mine Through the Mill”.

The expanded explanations of various aspects of aluminum production and rolling appear where they are mentioned in the DVD.

The user who wants to learn the general features of aluminum production and rolling will find them summarized in the DVD and the early paragraphs of each section of the manual and in its Self-Test Questions and Answers.

For readers who want to understand these subjects more thoroughly, the full text of the manual provides more detailed explanations.

The manual may also be used as a ready-reference, by consulting its subheaded Table of Contents and/or alphabetical index.

Metric values of the US customary units in the manual have been included for the convenience of the reader and are not intended as precise arithmetic conversions. Where the products (foil / sheet / plate) are defined by their thickness range, the actual metric gauge definition has also been included for reference.

Finally, the loose-leaf format permits the easy insertion of product information, additional notes or future informational updates.

ABOUT THE ALUMINUM ASSOCIATION

The Aluminum Association is an industry-wide trade organization representing US and foreign producers of aluminum, leading manufacturers of semi-fabricated aluminum products, secondary smelters and suppliers to the aluminum industry.

The Association’s aims are to increase public and industrial understanding of aluminum and the aluminum industry and — through its technical, statistical, marketing and information activities — to serve industries, consumers, financial analysts, educators, government agencies and the public generally.

For the aluminum industry and those industries that use aluminum, The Association helps develop standards and designation systems, helps prepare codes and specifications involving aluminum products and studies technical problems of the industry.

The Association maintains and periodically issues industry-wide statistics and records which are used as an authoritative source.

Association members also join together on a number of commodity and end-market committees to conduct industry-wide market development programs.
# INTRODUCTION

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## PRODUCTION OF ALUMINUM AND ITS ALLOYS

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## PREPARATION OF ALUMINUM ALLOYS FOR ROLLING

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Advantages of Aluminum

The properties of aluminum make it one of the most advantageous and versatile materials in use today. Aluminum is:

- **Lightweight**—Aluminum and its alloys weigh only about one-third as much as equal volumes of iron, steel or copper.

- **Strong**—Given appropriate tempers, some aluminum alloys equal or surpass the strength of some steels. Strong aluminum alloys can be as much as two or three times stronger than steel for the same weight.

- **Cryo-tolerant**—In contrast to steel, titanium and many other materials that become brittle at very low (cryogenic) temperatures, aluminum remains ductile and even gains strength as temperature is reduced. This property makes aluminum highly useful in very cold climates and for transporting extremely cold materials such as liquefied natural gas (-260°F [-162°C]).

- **Ductile and workable**—Aluminum alloys can be readily formed and fabricated by all standard metalworking methods.

- **Joinable**—Aluminum alloys can be joined by all appropriate major methods, including welding, mechanical connections, and adhesive bonding.

- **Reflective**—Aluminum alloys with standard commercial finishes typically reflect more than 80 percent of visible light and more than 90 percent of infrared radiation, making aluminum an effective reflector of, or shield against, light, radio waves and radiant heat.

- **Heat-conducting**—Aluminum is an excellent heat conductor suitable for cooking ware and for heat exchangers; it is more efficient, pound for pound, than copper.

- **Electrical conductivity**—Aluminum is also an excellent conductor of electricity, commonly used in such heavy-duty applications as high-voltage transmission lines, bus bars and local and building distribution systems.

- **Corrosion resistant**—Aluminum, exposed to air, forms a transparent natural oxide film which seals its surface against further reactions and protects it from corrosion from normal weather exposure. Specific aluminum alloys, treatments and/or coatings may be selected to maximize corrosion resistance in particular applications.

- **Non-toxic**—Rolled aluminum alloys are non-toxic, easily cleaned, and non-absorbent. For these reasons, they are widely used in food preparation and packaging.

- **Non-combustible**—Rolled aluminum does not burn, and it generates no hazardous emissions when exposed to heat. It is safer than many other materials where fire is a potential hazard.

- **Recyclable**—Aluminum’s resistance to corrosion and to reaction with most common materials keeps it in good condition throughout the lifetime of most products. Scrap aluminum is widely recycled, reducing demands for waste disposal and the environmental impacts of new material production.
Flat-Rolled Aluminum

Flat-rolled products — sheet, plate and foil — have, for many years, made up by far the largest volume of aluminum products shipped annually in the United States, outstripping other forms such as castings, extrusions, wire, rod and bar, forgings and impacts, and powders and paste.

Consumption of aluminum sheet and plate in North America has generally increased over the past 45 years. In 1960, sheet and plate consumption in domestic markets added up to 1.42 billion pounds (645 million metric tons), or about 34.6% of total aluminum product shipments.

By 1980, in a rapidly growing market for aluminum, sheet and plate consumption was 5.56 billion pounds (2,523 million MT) or 46.7%.

In 2005, domestic consumption of sheet and plate was 9.59 billion pounds (4,349 million MT), 41.5% of the total; including foil, flat-roll products accounted for just under half (47.7%) of all aluminum products shipped that year.

Aluminum Sheet Applications

Aluminum sheet is a remarkably versatile material, not only because of the custom-tailored characteristics that it can be given in the rolling mill, but also because of its suitability to a wide range of finishing, fabrication and joining processes.

It can be given a wide variety of surfaces: patterned, painted, plated, polished, colored, coated, laminated, anodized, etched or textured. It can be machined in different ways: sheared, sawed and drilled. It can be easily formed: bent, corrugated, drawn or stamped. It can be readily jointed to itself or to other materials: riveted, bolted, clinched, brazed, soldered, welded and adhesively bonded.

Its applications are too many to list completely. They include such familiar products as: light bulb bases, beverage and food cans, cooking utensils; home appliances; awnings and Venetian blinds; siding, roofing, flashing, gutters and curtainwall panels for residential, commercial, industrial and utility buildings; highway signs, license plates; heat exchangers; automobile structures and exteriors; truck, trailer and van panels; small boat hulls and aircraft skins.

Aluminum Plate Applications

Aluminum plate can be formed directly into strong shapes with uniform thickness. It can also serve as a “blank” from which complex large-area parts can be machined, such as the ribbed wing plates of advanced aircraft. It can be welded into large, strong, durable structures.

Among many other applications, aluminum plate is used to make railroad gondola and tank cars, battle armor for military tanks and vehicles, superstructures of large merchant and military ships and offshore oil rigs, tanks for storing and transporting super-cold liquefied natural gas, aircraft structural parts, and spacecraft components.

Aluminum Foil Applications

Aluminum foil is familiar to most people in the popular form of soft, very thin (0.00065 inch [0.0165 mm] thick) household kitchen foil: it’s easy to fold, impenetrable by water and vapor, fire resistant, both heat-conductive and heat-reflective, and inhospitable to molds.

But aluminum foil is also made of harder, stronger alloys whose strength may approach that of steel.

The variety of properties available in aluminum foils make them useful in applications ranging from the protective packaging of foods, pharmaceuticals and many other consumer products, to laminated vapor-barriers and insulation-backing in buildings, to artificial Christmas trees, sound transducer/receiver diaphragms, rigid containers and adhesive-bonded structural honeycomb.

Specialty Products

Special types of sheet and plate may be produced for particular applications. Some examples include:

- Anodizing sheet
- Armor plate
- Brazing sheet
- Decorative panel sheet
- Industrial roofing sheet
- Lithography sheet
- Painted sheet
- Patterned sheet
- Porcelain enameling sheet
- Reflector sheet
- Rural roofing sheet
- Tapered sheet and plate
- Tooling plate
- Trailer roof sheet
- Tread plate
- Vinyl-coated sheet
Just a few of the hundreds of applications of rolled aluminum.
DEFINITIONS

All three are aluminum products that are rolled flat with a rectangular cross-section. They differ mainly in thickness.

- **Plate** is aluminum rolled one-quarter inch (6.3 mm) thick or more.
  Aluminum plate is a product that is rectangular in cross-section and form, and 0.250 inch (6.3 mm) or more thick. It may have sheared or sawed edges. It is usually produced in flat form (but can be coiled) or in a variety of special shapes or fabrications. Some aluminum plate producers can perform additional processing or apply special surface treatments so that the plate product is suitable for the desired application. (Note: When products are ordered to metric specifications using metric dimensions, plate is defined as being >6 mm thick; however, the common US customary reference thickness for 0.250" is 6.3 mm.)

- **Under one-quarter inch (6.3 mm) down to eight-thousandths of an inch (0.20 mm) thick, it’s called “sheet.”**
  Aluminum sheet is a product that is rectangular in cross-section and form, and of >0.0079" (0.20 mm) thickness through 0.249" (6.3 mm) thickness. It may have sheared, slit or sawed edges. It may be produced in coiled or flat form, or in a variety of special shapes or fabrications. Some aluminum sheet producers can perform additional processing or apply special surface treatments so that the sheet product is suitable for the desired application. (Notes: When products are ordered to metric specifications using metric dimensions, sheet is defined as being >0.20 mm to ≤6 mm thick. Sheet was previously defined as ≥0.006" (0.15 mm) through 0.249" (6.3 mm).)

- **Thinner than that, it’s “foil.”**
  Plain aluminum foil is a rolled product that is rectangular in cross section and ≤0.0008" (0.20 mm) thick. It is available in coiled form or in flat sheets. Some aluminum foil producers can perform additional processing or apply special surface treatments so that the foil product is suitable for the desired application. (Notes: When products are ordered to metric specifications using metric dimensions, foil is defined as being ≤0.20 mm thick. Foil was previously defined as <0.006" (0.15 mm) thick.)

ROLLING ALUMINUM: GENERAL DESCRIPTION

Sheet, plate and foil are usually made by rolling thick aluminum between rolls that reduce the thickness and lengthen it, the way a baker rolls out pie crust. But rolling aluminum is a lot more complicated than rolling dough.

The actual passage of aluminum through a rolling mill is only one step — although the central one — in a comprehensive sequence. Each flat-rolled product owes its final properties not just to the rolling process itself but to its vital interactions with: the preparatory steps of alloying, casting, scalping and pre-heating; intermediate annealing; and such later finishing steps as solution heat treatment or final annealing, stretching, leveling, slitting, edge trimming and aging.

Modern aluminum rolling plants conduct many, or all, of these operations, selecting, adjusting and coordinating them scientifically to produce flat-rolled products with the precise dimensions, properties and other characteristics specified by each customer.

Aluminum Rolling: A Capsule History

Aluminum is a modern metal — discovered in 1807, first isolated in 1825, produced in tiny amounts as a precious metal in 1845, and widely commercialized only after the invention of the Hall-Heroult production process in 1886. Since then, aluminum has rapidly grown to become the second most heavily used metal in the world after iron/steel.
By the time aluminum arrived on the scene, mankind had thousands of years’ experience cast- ing and forging metals and several hundred years of learning to roll them into sheets, plates and even foils. Metal rolling may have been practiced in developed countries as early as the beginning of the 16th century. These familiar metal working techniques were all adapted and applied to alu- minum.

The first aluminum stew pan was stamped in 1890, and most of the aluminum produced before 1900 was used in cooking utensils.

Aluminum hulled boats were built in the 1890s, including the U.S. racing yacht “Defender”, with aluminum plates, in 1895.

By 1903, some 6.5 million pounds (3 million kg) of aluminum was consumed annually, about one-third of it in the form of sheet.

In that same year aluminum foil was first rolled, in France; aluminum foil-rolling in the United States began in 1913, for wrapping candy and chewing gum.

Thin aluminum skins appeared on aircraft as early as 1917 (on the Junkers J-4 monoplane and the Dornier DO-1 biplane, forerunner of today’s “stressed-skin” aircraft structures).

A practical method to produce Alclad sheet — strong aluminum alloy clad with a thin layer of a different aluminum alloy for enhanced corrosion resistance — was developed, in the United States, in 1926. Since then, many other clad aluminum products have been developed for such purposes as corrosion protection, surface appearances, or ease of brazing.

**Technological Advances**

The fundamental principles and designs of metal rolling mills had been established by the end of the 19th century, but improvements in their technology and metallurgy have continued throughout the 20th century.

Aluminum rolling has gained steadily in both quality and efficiency through advances in its own specific technology as well as improvements applied to metal rolling in general.
Hot and cold continuous sheet rolling mills came into operation in the United States in 1926. The maximum speed of the first U.S. cold “strip” mill was reported to be only about 200 feet per minute (60 m/min.); modern cold mills operate about 35 times faster!

The rolling industry switched from steam engines to electric power; it built specialty mills, and bigger multi-purpose mills.

The standard “two-high” and “four-high” mill configurations that were brought into early use, with mill rolls “stacked” vertically, are still basic to the rolling industry. They were later supplemented, however, by various “cluster” designs with work rolls supported by two or more back-up rolls each, as explained in Section 4.

Over the decades, safety, efficiency, cost and product quality were improved by the introduction of automatic material handling devices, manipulators, guides, guards, lifting and tilting tables; automatic roll changers, compact load-measuring cells on roll bearings, gauge control feedbacks, load equalization and overload protection; programmed coolant/lubricant application; and many other technical advances.

In recent years, aluminum rolling mills have been introducing computerized process control, quality control and inventory tracking, and advanced gauge and shape controls, to achieve even higher product quality and consistency. Computerization, in turn, is pointing the way to such further developments as Computer Integrated Manufacturing (CIM), Statistical Process Control (SPC), and Just-In-Time (JIT) production schedules. These recent advances are designed to increase product quality and delivery reliability and to reduce production costs.

Aluminum that starts out two feet (0.6 m) thick may travel a mile (1.6 km) through large rolling mills, furnaces, cutters and stretchers, to emerge as thin sheet only a few hundredths of an inch (a few tenths of millimeters) thick... And it’s had a long journey before it even reaches the rolling mill.
SELF-TEST QUESTIONS
SECTION 1: INTRODUCTION

1.1 Name any five important advantages of rolled aluminum products.

1.2 Aluminum resists atmospheric corrosion because:
   a. It is always painted or coated.
   b. It has a naturally stable oxide film.
   c. It is a good heat conductor.
   d. It is non-combustible.

1.3 Aluminum weighs about as much as an equal volume of iron, steel or copper.
   a. Three-quarters.
   b. One-half.
   c. One-third.
   d. One-quarter.

1.4 High-strength aluminum alloy can be...
   a. up to half as strong as
   b. up to 90% as strong as
   c. just about as strong as
   d. stronger than
   ...an equal weight of steel.

1.5 As temperature is reduced, the strength of aluminum...
   a. decreases.
   b. remains the same.
   c. increases.

1.6 The largest volume of aluminum products shipped annually in the United States consists of...
   a. castings.
   b. rolled products.
   c. forgings and impacts.
   d. wire, rod and bar.

1.7 Name five applications of aluminum sheet.

1.8 Name five applications of aluminum plate.

1.9a In US customary units “plate” means a rolled product...
   a. less than 6 inches thick.
   b. greater than one-tenth inch thick.
   c. greater than or equal to one-quarter inch thick.
   d. exactly 0.250 inch thick.

1.9b In metric units “plate” means a rolled product...
   a. greater than 6 mm thick.
   b. greater than 2.5 mm thick.
   c. less than 150 mm thick.
   d. exactly 6 mm thick.

1.10a In US customary units “sheet” means a rolled product...
   a. from .010 to .200 inch thick.
   b. from .008 to .249 inch thick.
   c. from .001 to .249 inch thick.
   d. from .006 to .490 inch thick.

1.10b In metric units “sheet” means a rolled product...
   a. from 0.25 to 5 mm thick.
   b. from 0.025 through 6 mm thick.
   c. from 0.20 through 6 mm thick.
   d. greater than 0.20 up to 12 mm thick.

1.11 Air conditioner fin stock produced as a coil product, for example, .0045-inch (0.115 mm) thick falls into the category of...
   a. sheet.
   b. plate.
   c. foil.

Why?
1.12 The existence of aluminum as a metal was first discovered...
   a. in prehistoric times.
   b. around 700 B.C.
   c. in 1725 (A.D.).
   d. in 1807.
   e. in 1903.

1.13 The Hall-Heroult process was invented...
   a. in 1807.
   b. in 1825.
   c. in 1845.
   d. in 1886.

1.14 Most of the aluminum produced before 1900 was used in:
   a. Military armor.
   b. Vehicles.
   c. Cooking utensils.
   d. Architecture.
   e. Boat hulls.

1.15 Aircraft skins made of aluminum sheet appeared as early as...
   a. 1903.
   b. 1917.
   c. 1931.
   d. 1942.

1.16 The basic principles and designs of metal rolling mills had been established by...
   a. the end of the Roman Empire.
   b. the end of the Renaissance.
   c. the end of the 19th century.
   d. the middle of the 20th century.
Aluminum is one of the most abundant elements on earth. It is estimated that the solid portion of the earth’s crust to a depth of ten miles is about 8% aluminum, surpassed only by oxygen (47%) and silicon (28%). Aluminum is a major constituent of clay and almost all common rocks.

Aluminum is never found as a pure metal in nature, but only in chemical compounds with other elements — and especially with oxygen, with which it combines strongly.

Feldspars, micas and clay contain aluminum oxide (Al$_2$O$_3$), also known as alumina, in concentrations ranging roughly between 15 and 40 percent by weight.

Most aluminum is produced from an ore called bauxite (named after the town of Les Baux in southern France where it was discovered in 1821), which may contain 40 to 60 percent impure hydrated aluminum oxide — that is, aluminum oxide to which water molecules have become attached. The other components of bauxite typically include various amounts of iron oxide, silicon oxide, titanium oxide and water. Its texture can range from crumbly to something like limestone, and its color varies from off-white to rusty-red, depending on its iron oxide (rust) content.

The richest and most economical bauxite ores are often found close to the earth’s surface in tropical and subtropical areas. Worldwide reserves of bauxite ore are estimated to be very large: enough high grade ore to last perhaps 300 to 500 years, and enough lower-grade ore for another 500 years at recent consumption rates. Clays and other minerals could, if necessary, provide an almost limitless source of alumina.

Mining methods may vary, but most bauxite is mined in open pits by conventional digging machinery, and then is crushed, washed and dried in preparation for separation of the alumina from the other, undesirable components. Subsequent to the mining operation, the aluminum industry spends considerable effort to the restore the land and its flora and fauna back to their original condition.

ALUMINUM REFINING

Most alumina is refined from bauxite by the Bayer process, patented in Germany by Karl Josef Bayer in 1888. This process is carried out in four steps:

1. The crushed, washed and dried bauxite is “digested” with caustic soda (sodium hydroxide) at high temperatures and under steam pressure, dissolving the alumina in a mixture with undissolved impurities called “red mud.”
2. This mixture is filtered to remove the red mud, which is discarded. The clarified alumina solution is transferred to tall tanks called “precipitators.”

3. In the precipitator tank, the hot solution is allowed to cool with the addition of a little aluminum hydroxide to “seed”—that is, stimulate—the precipitation of solid crystals of aluminum hydroxide and sodium hydroxide. The aluminum hydroxide settles to the bottom and is removed from the tank.

4. The separated aluminum hydroxide is washed to remove residues of caustic soda and then is heated to drive off excess water in long rotating kilns called “calciners.” Aluminum oxide (alumina) emerges as a fine white powder that looks like granulated sugar but is hard enough to scratch glass. The widely-used abrasives corundum and emery are forms of alumina. Refined alumina consists of about equal weights of aluminum and oxygen, which must be separated in order to produce aluminum metal.

**ALUMINUM REDUCTION: THE HALL-HEROULT PROCESS**

A practical way of breaking down the aluminum oxide — the Hall-Heroult process — was invented in 1886. Another mineral, cryolite, is melted, and the aluminum oxide is dissolved in it.

Electric current passed through the bath attracts the oxygen to carbon anodes. The carbon and oxygen form carbon dioxide, which bubbles out of the bath.

Molten aluminum is left behind at the bottom of the reducing cell, or “pot.” It is siphoned into a crucible for transport to the casting foundry.

The process is continuous, and a typical pot may produce about 1400 pounds of aluminum daily. Hundreds of cells on the same electrical circuit form a potline.

A luminum and oxygen form such a strong chemical bond that it takes a very large amount of energy to separate them by “brute force” methods like heating. Although aluminum as a pure metal melts at about 1220°F (660°C); aluminum oxide requires a temperature of about 3660°F (2015°C) before it will melt.

Chemical methods of breaking down aluminum oxide were developed in the mid-19th century but were so expensive that metallic aluminum cost as much as silver. The small amounts of aluminum that were produced were used mainly for jewelry and other luxury items.

Early researchers thought of using electricity to
separate aluminum from its oxide in solution but were frustrated by seemingly high energy requirements; the inadequacy of their only sources of electricity — batteries; and the insolubility of alumina in water.

The invention of the rotary electric generator, the dynamo, in 1866 solved part of that problem. The other part was not solved until 1886 when Charles Martin Hall in the United States and Paul L.T. Heroult in France discovered the answer almost simultaneously. Hall and Heroult found that alumina would dissolve in a molten mineral called cryolite (a sodium aluminum fluoride salt) at about 1742°F (950°C). In solution, the aluminum oxide is readily separated into aluminum and oxygen by electric current.

Other solvents might have worked in theory. Cryolite, however, has the practical advantages of stability under process conditions and a density lower than that of aluminum, allowing the newly-forming metal to sink to the bottom of the “reduction cell.”

The Hall-Heroult process takes a lot of electricity but only a low voltage, so it is practical to connect many reduction cells, or “pots”, in series along one long electrical circuit, forming a “potline.” Modern cells are operated with currents of around 250,000 amperes but at only four or five volts each. Such cells use about six or seven kilowatts of electricity per pound of aluminum produced.

The heat generated by electrical resistance keeps the solution molten.

Oxygen atoms, separated from aluminum oxide, carry a negative electrical charge and are attracted to the positive poles in each pot. These poles, or anodes, are made of carbon which immediately combines with the oxygen, forming the gases carbon dioxide and carbon monoxide. These gases bubble free of the melt, leaving behind the aluminum which collects at the bottom of the pot.

The process, therefore, steadily consumes the carbon anodes, which must be renewed either by regular replacement or by continuous feeding of a self baking paste (Soderberg anode). About one-half pound (225 g) of carbon is consumed for every pound (455 g) of aluminum produced. Most aluminum reduction plants include their own facilities to manufacture carbon anodes, each of which may weigh 600 - 700 pounds (270 - 320 kg) and must be replaced after about 14 days of service.

The negative electric pole, or cathode, forms the inner lining of each pot. It is also made of carbon. As a cathode it does not react with the melt, so it has a long service life.

As alumina is reduced to aluminum and oxygen, fresh alumina is added to the molten bath to continue the process. Aluminum fluoride is also added when necessary to maintain the bath's chemical composition, replacing aluminum fluoride lost by reactions with caustic soda residues and airborne moisture. Modern smelters capture and recycle fluorides and other emissions.

When sufficient molten aluminum has collected at the bottom of a pot, it is siphoned into a crucible for transport to alloying and casting facilities. The aluminum produced by the Hall-Heroult process is more than 99 percent pure.
Main steps in the Bayer alumina-refining process and the Hall-Heroult aluminum-reduction process.
**ALLOYING**

In the melt house, the aluminum is poured into a remelt furnace for alloying and fluxing.

Adding small amounts of other elements to pure aluminum produces strong alloys, which can be further conditioned by heating, cooling and deformation treatments called “tempering.”

Alloying requires the thorough mixing of aluminum with other elements in liquid — molten — form. This may be done in different ways, depending on the sources of aluminum used.

Newly-produced aluminum may be transferred, still liquid, from the Hall-Heroult reduction cells into a “holder” or reservoir furnace where solid alloying elements are added, to dissolve and mix into the melt.

Solid scrap aluminum, from fabrication operations or recycled products, must be melted in a “remelt” furnace before its alloy composition is adjusted as necessary. Then the recycled, re-alloyed scrap is transferred to a holder.

Often, new aluminum is alloyed with scrap aluminum of known composition. The solid scrap is added to the molten new aluminum, and then further alloying elements are added to the mixture as needed to adjust its final composition.

Most melting furnaces are large (capacity as much as 200,000 pounds (90,000 kg) or more) and are oil- or gas-fired. They can accept molten metal and alloying ingredients in addition to scrap at a temperature around 1400°F (760°C). For certain melting needs, the furnace is smaller, has a lower melting rate and may be electrically heated to minimize oxidation of light gauge (thin) scrap or to control emissions. The molten metal is then transferred to a holder.

After alloying, the molten metal is cleaned and fluxed to remove impurities and hydrogen gas before being transferred to the casting pit.

### Aluminum Alloy Series

Aluminum alloys are registered according to their composition. For most of the world, aluminum alloy formulations are registered with the Aluminum Association under a numerical classification system.

Each alloy is assigned a four-digit number, in which the first digit identifies a general class, or “series”, characterized by its main alloying elements:

- **1xxx Series alloys** include aluminum of 99 percent or higher purity. They have excellent corrosion resistance and thermal and electrical conductivity.

- **2xxx Series alloys** have copper as their principal alloying element, often with smaller amounts of manganese and magnesium, and can be strengthened substantially by heat treatment.

- **3xxx Series alloys** have manganese as their major alloying element, sometimes with smaller amounts of magnesium, and are generally non-heat-treatable.

- **4xxx Series alloys**, alloyed mainly by silicon, are usually non-heat-treatable.

- **5xxx Series alloys** contain magnesium as their main alloying element, often with smaller amounts of manganese and/or chromium. These alloys are generally non-heat-treatable.

- **6xxx Series alloys** contain silicon and magnesium in proportions that will form magnesium silicide and are heat-treatable.

- **7xxx Series alloys** are alloyed mainly by zinc, often with smaller amounts of magnesium and sometimes copper, resulting in heat-treatable alloys of very high strength.

- **The 8xxx Series** of alloy numbers is reserved for alloys of various other compositions.

The aluminum alloy designation system is explained in greater detail in Section 10, Appendix A. Section 10, Appendix C contains tables of typical mechanical properties, physical properties, and comparative characteristics and applications.
HEAT-TREATABLE ALLOYS
Some alloys, usually in the 2xxx, 6xxx, and 7xxx series, are “solution heat treatable”. They can be strengthened by heating and then quenching, or rapid cooling. They may be further strengthened by “cold working” controlled deformation at room temperature.

Some aluminum alloys can be significantly hardened and strengthened by controlled heating and quenching sequences known as “heat treatment” followed by natural or artificial aging (“precipitation hardening”). Such alloys are called “heat-treatable.”

Most heat-treatable aluminum alloys contain magnesium, plus one or more other alloying elements such as copper, silicon and zinc. In the presence of those elements, even small amounts of magnesium promote precipitation hardening. These alloys respond to heat treatment because their key alloying elements show increasing solubility in aluminum with increasing temperature.

The increase of strength induced by heat treatment can be dramatic. For example, in the fully annealed O-temper, aluminum alloy 2024 has an ultimate yield strength of about 27,000 pounds per square inch (185 MPa). Heat treatment and cold working followed by natural aging (T3 temper) increases its strength 2 1/2 times, to 70,000 pounds per square inch (480 MPa). As strength is increased by heat-treating, formability is affected in the other direction: for example, alloy in the T3 temper is less formable than “fully soft” alloy in the O-temper.

NON-HEAT-TREATABLE ALLOYS
“Non-heat-treatable” alloys can be tempered only by cold working and annealing operations.

Alloys which will not gain strength and hardness from heat treatment are called “non-heat-treatable.”

The initial strength of these alloys, usually in the 1xxx, 3xxx, 4xxx, and 5xxx series, is provided by the hardening effect of their alloying elements. Additional strengthening can be created by cold working — deformation which induces strain-hardening, denoted by the “H” tempers. Strain-hardened alloys containing appreciable amounts of magnesium are usually given a final elevated temperature treatment to stabilize their properties.

Cold-working can increase strength significantly in non-heat-treatable alloys. For example, the ultimate tensile strength of alloy 3003 is increased from about 16,000 pounds per square inch (110 MPa) in the O-temper to 29,000 pounds per square inch (200 MPa) in the H18 strain hardened temper. The ultimate tensile strength of alloy 3004 is increased from about 26,000 psi (180 MPa) in its O-temper to about 41,000 psi (280 MPa)in the H38 temper (strain-hardened and stabilization heated).

Both heat-treatable and non-heat-treatable alloys may be deliberately softened and made more formable by annealing.

Aluminum for rolling must be alloyed to exacting specifications. It must be suitable for the planned rolling, for tempering, and for its intended end use.

Equally important is freedom from impurities that might weaken the alloy, cause mechanical defects, or damage mill rolls.
Recycled beverage cans are not only a large source of aluminum scrap but also a particularly convenient one because of the known uniformity of their alloy composition. They can be recycled right back into new sheet ingot for canstock, as well as other products. Some specialized plants produce aluminum sheet ingot only from used aluminum beverage cans, providing very efficient, energy-saving “closed-loop” recycling.

Aluminum scrap generated within the rolling plant itself is also returned to the melting hearths; this in-house scrap is also very convenient because its alloy composition is exactly known. Similarly, scrap returned from fabricators often consists of uniform loads of identified alloys.

Other scrap from various recycled products is also used for alloying, taking into account its alloy composition, determined by testing.

Addition of alloying elements

Next, selected elements — such as magnesium, silicon, manganese, zinc or copper — are mixed in to achieve the correct alloy composition.

Magnesium, silicon and zinc are usually added as pure ingredients. Chromium, manganese and iron are usually added as briquettes containing up to 85% pure metal, balance being aluminum foil and binders, to facilitate mixing with the melt. Copper is added in either pure (shot / chopped wire / etc.) or alloyed forms. Titanium and zirconium are typically added as either 5-10% alloy or as compacted, 95% pure “hockey pucks”.

Recycled scrap makes up more than half of the aluminum alloy processed in the United States; and recycling uses 95 percent less energy than making new aluminum.
SELF-TEST QUESTIONS
SECTION 2: PRODUCTION

2.1 Aluminum makes up about_____of the earth’s crust.
   a. 8%
   b. 15%
   c. 28%
   d. 47%

2.2 Aluminum is_____found as a pure metal in nature.
   a. always
   b. sometimes
   c. never

2.3 Economically mined bauxite contains what percentage of aluminum oxide?
   a. 40-60%
   b. 25-40%
   c. 15-25%

2.4 Most bauxite is mined...
   a. in deep tunnels.
   b. in open pits.
   c. in rock quarries.
   d. in shallow river bottoms.

2.5 “Alumina” is another name for...
   a. aluminum.
   b. bauxite.
   c. aluminum oxide.
   d. aluminum alloy.

2.6 Most alumina is refined by...
   a. the Karl process.
   b. the Hall process.
   c. the Heroult process.
   d. the Hall-Heroult process.
   e. the Bayer process.

2.7 Refined alumina contains what proportion of aluminum by weight?
   a. about two-thirds
   b. about one-half
   c. about one-quarter
   d. None.

2.8 Pure aluminum melts at about...
   a. 660°F
   b. 660°C
   c. 1220°F
   d. 1220°C

2.9 Aluminum oxide melts at about...
   a. 212°F (100°C).
   b. 660°F (350°C).
   c. 1000°F (540°C).
   d. 3660°F (2015°C).

2.10 The main factor which induces the release of metallic aluminum from aluminum oxide is...
   a. heat.
   b. electricity.
   c. water.
   d. None of the above.

2.11 The modern Hall-Heroult reduction process utilizes...
   a. heat.
   b. dissolving medium.
   c. electric current.
   d. a, c
   e. b, c
   f. a, b, and c.

2.12 In the Hall-Heroult reduction process, what substance combines with the oxygen in Al₂O₃ to leave molten aluminum?
   a. Feldspar
   b. Cathode
   c. Carbon
   d. Hydrogen

2.13 Cryolite is...
   a. a popular aluminum alloy.
   b. a sodium aluminum fluoride salt.
   c. the material of aluminum reduction anodes.
   d. None of the above.

2.14 A typical modern Hall-Heroult cell uses about how many kilowatts of electricity to produce one pound (455 g) of aluminum?
   a. One or two
   b. Six or seven
   c. Ten or twenty
   d. Trick question: no electricity.
2.15 The cathodic lining of an aluminum reduction pot has a long service life because...
   a. it is made of brick.
   b. it is not in direct contact with the melt.
   c. it does not react with the melt.
   d. it plays no role in the reduction process.

2.16 Molten aluminum is removed from a reduction “pot” by...
   a. siphoning.
   b. pouring.
   c. ladling.
   d. pumping.

2.17 Aluminum produced by the Hall-Heroult process is...
   a. a high-strength alloy.
   b. about 75% pure aluminum.
   c. exactly 89% pure aluminum.
   d. more than 99% pure aluminum.

2.18 “The most important reason for having remelt furnaces in a rolling facility is to recycle generated process scrap.” This statement is:
   a. True.
   b. False.

2.19 What is the approximate temperature in a melting furnace?
   a. 1000°F (540°C).
   b. 1400°F (760°C).
   c. 1800°F (980°C).

2.20 Wrought aluminum alloy series numbers always have how many digits?
   a. Three.
   b. Four.
   c. Five.
   d. As many as necessary.

2.21 The different aluminum alloy series are characterized by...
   a. alloy strength.
   b. aluminum content.
   c. alloy composition.
   d. (None of the above).

2.22 “Solution heat-treatable” alloys are those which...
   a. can stand high temperatures without melting.
   b. can be brightened by heating.
   c. can be dissolved at high temperatures.
   d. can be strengthened by heating and quenching.

2.23 Solution heat-treatable alloys are usually in the...
   a. 2xxx, 6xxx and 7xxx series.
   b. 2xxx, 4xxx and 5xxx series.
   c. 1xxx, 5xxx and 6xxx series.
   d. 2xxx series only.

2.24 “Non-heat-treatable” alloys are those which...
   a. can be strengthened only by low temperatures.
   b. can be strengthened only by cold working.
   c. can be strengthened by annealing.
   d. risk cracking when heated.

2.25 Non-heat-treatable alloys are usually in the...
   a. 1xxx series.
   b. 3xxx series.
   c. 4xxx series.
   d. 5xxx series.
   e. All of the above.

2.26 An element which never plays a major part in the precipitation hardening of heat-treatable aluminum alloys is...
   a. copper.
   b. manganese.
   c. zinc.
   d. silicon.
   e. magnesium.

2.27 “Only solution-heat-treatable alloys can be made more formable by annealing.” This statement is:
   a. True.
   b. False.
2.28 Remelting and alloying scrap aluminum uses about as much energy as smelting new aluminum.
   a. 5%
   b. 50%
   c. 100%
   d. 150%

2.29 The melt is transferred into a holding furnace before casting in order to...
   a. add more scrap.
   b. adjust alloy composition.
   c. remove hydrogen.
   d. a and b.
   e. b and c.
   f. a and c.
Materials charged into an alloying furnace often carry with them some unavoidable foreign matter, and other non-metallic materials may be generated by chemical reactions. These substances, which could otherwise cause problems in later operations and impair product quality, are removed from the alloy by fluxing and filtration.

**Fluxing**

“Fluxing” refers primarily to the removal of dissolved hydrogen gas from molten aluminum alloy by bubbling gases through it. However, the bubbling gases also “sweep” some solid impurities to the surface where they collect as a frothy dross which is removed.

Hydrogen gas — derived from airborne water vapor, from materials added to the melt, or from furnace walls, tools, or anything else that comes in contact with the melt — dissolves readily in molten aluminum. But it is only about 5% as soluble in solid aluminum. If it were allowed to remain while the molten metal is cast, it would emerge during solidification to form tiny bubbles: blisters which mar the surface, or internal pores which weaken the product.

Before casting, dissolved hydrogen is removed by bubbling dry, hydrogen-free gases through the molten aluminum. Hydrogen dissolved in the aluminum diffuses into these other gases and is carried out of the melt by the rising bubbles. Inert (nonreactive) gases, chiefly nitrogen, are used for this purpose to avoid altering the chemical composition of the alloy. However, small amounts of chlorine or other reactive gases, typically less than 10 percent, may be mixed with the inert gases in order to react with certain impurities such as sodium, calcium or lithium and form compounds which can be removed by skimming or filtration. Even though chlorine will have a tendency to react and preferentially remove magnesium, it does offer the most efficient way to remove hydrogen through a chemical reaction in contrast to a much slower diffusion process inherent to inert gases. Due to environmental and other concerns the use of chlorine is being reduced, and in some regions its use is prohibited.

Typical fluxing techniques include porous plugs located in the bottom of the furnace, spinning rotors and fluxing wands (ceramic coated metal tubes which incorporate porous plugs at the end of the tube). All of these techniques are designed to promote uniform distribution of fine bubbles which enhance diffusion and chemical reaction processes.

Fluxing may be done in the holding furnace or in a special in-line device between the furnace and the casting station, separately or in conjunction with filtration.

In-line degassing can be used as the only means of hydrogen removal, or it can be a part of a comprehensive approach which includes furnace fluxing and ceramic foam or other rigid media filtration.

**ALLOY SAMPLE ANALYSIS**

Now a small sample of the alloy is cast and is analyzed within minutes by the lab.

At the holding hearth and during casting, a small amount of molten alloy is scooped up with a ladle and poured into a small mold where it cools and hardens in about 15 to 20 seconds into a solid disk about two inches (50mm) in diameter, called a “button”.

This “button” is identified with the number of its alloy batch and is sent to the plant laboratory
for analysis. Laboratory analysis may be done automatically by a device called a spectrometer or quantometer. The alloy button is placed in a chamber in the device. Then a high-voltage spark instantly vaporizes a tiny amount of material from the surface of the sample and momentarily excites, or energizes, the atoms in this alloy vapor. The excited atoms immediately radiate away the excess energy, returning to their normal state. Each atom radiates excess energy in a pattern, a spectrum, unique to its element. By detecting and measuring the emitted energy patterns, the spectrometer identifies each element present and its proportion in the alloy sample.

A single “shot” in the high voltage spark spectrometer is usually completed in about 25 seconds including the set-up time. A series of four shots on one sample can be completed in two or three minutes.

The analyzer may be linked with a computer which automatically registers the batch number and its specified alloy composition, compares it with the actual sample analysis, and issues a “pass” message when the alloy is within specifications or an “off-analysis” message if it is not.

The results may be returned automatically to the hearth operator by instantaneous electronic communication. Thus, a “rush” request for analysis can be answered within a few minutes from the time the button sample leaves the hearth area. If the alloy is found to be “off analysis”, elements may be added to correct its composition. It will then be retested for approval. If batch correction is not practical, off analysis alloy is recycled.

If its composition is correct, the alloy moves to a holding furnace for casting; if not, it is corrected and retested.

FILTRATION

Before casting, aluminum flows through a filter to remove any remaining particles.

Any foreign particles or inclusions that have escaped the fluxing process or have developed afterward must be removed from the molten aluminum alloy before it is cast into rolling ingot. Inclusions, hard or soft, might weaken the final product, show up as streaks or flaws in its surface, or damage work roll surfaces. Filtration is performed to remove these potentially harmful particles. Filtration is sometimes performed in combination with the fluxing step, within the same process unit.

Filtration may utilize deep bed filters which are used for multiple casts and typically consist of 5 to 15" (125 – 380 mm) layers of media such as sintered high density alumina flakes or spheres with diameters in the range of .25 to .75" (6 – 19 mm). Molten aluminum flows through the deep bed which captures and retains nonmetallic and similar fine particulates.

Another method utilizes disposable rigid media filters which have the morphology of a sponge. They are typically 16" (400 mm), 20" (500 mm) or 24" (600 mm) square and approximately 2" (50 mm) thick. These filters have pore sizes which range from 20 per inch (8 per cm) for capturing coarse impurities to 70 per inch (30 per cm) for removal of very fine particulates.

During the past 25 years another group of filters was developed. They use spinning nozzle technology. Each of these filters consists of two or three chambers. Each chamber is equipped with a spinning nozzle which delivers a fine dispersion of gas bubbles. It is very similar to the fluxing process in the holding furnace except that argon with up to approximately 3% chlorine is used for flotation (removal) of small particulates and hydrogen. While the material is flowing through the chambers, particulates are captured and float to the surface while at the same time hydrogen is also removed. Some of the more commonly used types are SNIF, ALPUR and LARS.
The addition of small amounts of titanium (usually in combination with either boron or carbon) to molten aluminum alloy as a grain-refiner is widely practiced in the rolling industry. Dissolved in the alloy, titanium carbide or titanium diboride particles provide numerous “nucleation points” where solidification begins during cooling. This enhances uniformity, disperses stresses throughout the solidifying aluminum, and reduces stress-induced cracking.

From its holding hearth, molten aluminum is poured through a trough into the ingot-casting mold. The grain refiner is usually added immediately before casting, and the most commonly used additive form is 3/8" (10 mm) diameter rod. Typical grain refiners are 5%Ti /0.3% Boron or 5% Ti/0.15% C alloys. For example, a solid rod of these grain refiners may be fed into the molten stream of aluminum at a controlled rate en route to casting. The addition levels are quite low, typically less than 0.01 weight percent.

Grain refiner is added “at the last minute” because it is most effective if its first five minutes in the aluminum alloy take place during alloy solidification. Longer residence in molten alloy would give the grain refiner time to coalesce into larger particles, reducing its effectiveness.

CONTINUOUS CASTING OF SHEET OR PLATE

Aluminum sheet can be continuously cast for a variety of applications. This production method reduces the steps to produce the sheet. The continuous casting process is used for a variety of common aluminum applications. Currently about 20% of the North American sheet and plate production is produced by this method.

Continuous casting takes molten metal and solidifies it into a continuous strip. A variety of methods are used to solidify the metal, including roll casters, belt casters and block casters. The common feature for all of these methods is that sheet is taken directly from molten metal, solidified, and coiled in one operation. In many cases, the strip is run through a hot mill (which may have more than one stand).

Three significant differences between continuous casting and the more traditional DC ingot casting (see next section) are:

- Significantly reduced hot working in continuous casting compared to DC ingot casting.
- No homogenization between casting and hot rolling.
- No scalping between casting and hot rolling.

The reduction in hot working is a result of the reduced casting thicknesses seen in continuous casting. Although actual thicknesses vary by method and producer, “as-cast” continuous cast strip is less than 1 inch (25 mm) thick, compared to the 30+ inch (760+ mm) thick ingot produced via the DC ingot process.

Because it is much thinner than ingot, continuously cast strip cools and solidifies much faster than DC ingot; this may produce greater supersaturation of alloying elements and less segregation of these elements within metal grains. In effect, continuously cast strip is partly pre-homogenized.

In addition, the rapid cooling of continuously cast strip minimizes the tendency of alloying elements to concentrate at the surfaces and makes scalping unnecessary, so these products can move directly to rolling.

The lack of homogenization and reduced hot working does result in different metallurgical structures even in similar alloys. As a result,
continuously cast alloys may have different capabilities than their DC counterparts.

Producers of continuous cast sheet have established practices to ensure comparable performance in their chosen markets. In some applications, however, efforts to make continuous cast products as formable as their DC ingot counterparts may significantly reduce the advantages of the continuous casting process.

There are many markets where continuous cast products are found, including (but not limited to):

- Building and Construction Applications
- Foil and Fin Stock
- Food and Beverage Containers
- Truck and Trailer applications
- General Distribution

Types of Continuous Casters

Continuous casters are generally described by the type of product they yield (“strip” or “slab” casters), or by the type of equipment used (for example — roll, belt or block casters).

Both strip (continuous sheet) and slab (continuous plate) casters have been in use since the 1950s. They are less versatile in product thicknesses and characteristics than conventional mills which flat-roll aluminum ingot, but they require lower capital investment and have found economical application primarily in conjunction with limited-purpose “minimills.” There, one of their main advantages — particularly in slab casting — is the ability to produce a continuous band, which can move immediately through a hot-rolling mill for transformation into thinner wrought products in an unbroken flow.

Continuous casting processes are undergoing further technical development aimed at increasing their speed and versatility.

Strip (Continuous Sheet) Casters

Strip casters can produce continuous aluminum sheet thin enough to be coiled immediately after casting, without additional rolling. This coiled sheet may be re-rolled later into thinner sheet gauges. Alternatively, the cast sheet may be fed immediately through a hot-rolling mill for thickness reduction before the product is coiled.

Roll Casters

The roll caster is the most common form of strip casting: molten aluminum flows from nozzles between a pair of water-cooled rolls. In contact with the rolls, it solidifies at a cooling rate between 100 and 1,000°F per second (55 – 555°C/sec.). In addition, the newly solidified metal undergoes some hot deformation as it passes through the roll gap.

Typical roll casters can produce continuous sheet in the range of 30 to 80 inches (760 – 2030 mm) wide, at linear speeds ranging from about 6 to 10 feet per minute (2 – 3 m/min.). Their productivity rates are generally in the range of 60 to 100 pounds of product per hour, per inch of width (10 – 18 kg per hour per cm of width).

Slab Casters

Slab casters produce continuous aluminum products in the plate thickness range. These products do not undergo any hot deformation in the caster. They emerge with as-cast metallurgical characteristics and must be rolled by hot mills to achieve wrought aluminum properties and a sheet gauge that can be coiled.

They produce slab typically between 10 and 80 inches (255 – 2030 mm) wide, at linear speeds around 20 feet per minute (6 m/min.), yielding productivities in the range of 1,000 to 1,300 pounds of product per hour, per inch of width (180-225 kg per hour per cm of width).

Slab casters cool and solidify molten aluminum at rates ranging from 1 to 10°F per second (1/2 to 5°C); solid slab emerges at a temperature of about 1,000°F (540°C), requiring little or no reheating before hot rolling.

The two main commercial types of slab casters are belt and block casters.

Belt Casters

In the belt caster, molten aluminum flows between two almost-horizontal, continuous, thin metal belts that are in constant motion. Metal side dams moving with the belts contain the aluminum while it solidifies. The belts are usually inclined at an angle of 5 to 9 degrees from horizontal, to minimize turbulence in the pool of molten aluminum, and belt speed is synchronized with the metal flow rate.

The hot metal transfers its heat through films of
lubricant to the metal belts, which are water-cooled on their outer sides, producing slabs typically in the range of 1/2 to one inch (12 – 25 mm) thick. This continuous slab is usually fed directly into low-speed in-line rolling mills which reduce it to coils of thinner sheet stock for eventual re-rolling.

As this loop belt rotates around its drive gears, each block takes its turn lining up with its neighbors to contain the flow of molten aluminum from a nozzle. The blocks above and below the aluminum absorb enough heat to solidify the alloy as they travel along with it. Then, as they reach the farther drive gears, each block lifts away from the aluminum and moves around to the far side of its loop where a cooling system removes the heat before the block swings back for another turn in the traveling mold wall.

As with belt casters, the continuous slab produced by the block caster is usually hot-rolled immediately into thinner sheet stock.

Block Casters

The block caster operates on the same general principle as the belt caster: that is, the aluminum slab is formed between upper and lower traveling walls. In place of continuous flat belts, however, the block caster’s traveling walls consist of thick blocks of metal lined up side-by-side so that the exposed surfaces which contact the aluminum form flat walls about six feet long. The sides of the blocks away from the aluminum are attached to a jointed loop belt, like “caterpillar” vehicle treads.
**DC INGOT CASTING**

But most sheet and plate is rolled from thick slabs called “Ingots”, cast by the “direct chill” or DC method.

Aluminum is poured into a mold that is only about six inches (150 mm) deep. Progressive cooling while in contact with the mold and bottom block provides a solidified shell around the still-molten core of the ingot.

Once this solid shell forms, the bottom block is lowered along with the aluminum shell, while more aluminum is poured in, hardening at the walls and extending the shell.

The ingot emerges at about a speed of 1 1/2 to 4 inches per minute (40-100 mm/min.) and is chilled by a water spray to complete its cooling.

This direct-chill method permits mold walls only six inches (150 mm) deep to produce a retangular ingot over 30 feet (9 m) long, seven-and-a-half feet (2300 mm) wide and over two-and-a-half feet (760 mm) thick, weighing about 30 tons(27 metric tons).

“Hot metal” (molten aluminum alloy) is stored before casting in a holding hearth at a temperature ranging from ~1290 to 1345°F (~700 – 730°C). Its temperature decreases by about 40 to 50°F (22 – 28°C) upon transfer to the casting pit or station.

Direct-chill ingot casting takes place in a “DC casting pit” and each casting of ingot(s) is called a “drop”. Modern casting operations utilize multiple, commonly 4 – 6, rectangular DC molds typically 16 to 30” (40 – 75 mm) thick and 45-80” (1.1 – 2 m) wide.

The walls of the mold collar are water cooled to speed the solidification of the ingot shell. The solid shell cools to a temperature in a range of about 570 to 930°F (300 – 500°C) and contracts as it cools, separating from the mold wall before it emerges. The cooling rate is sharply reduced where wall contact is interrupted by this separation, called the shrinkage gap. This effect may permit an unwanted enrichment of alloying elements in a narrow zone near the surface. The enrichment zone is usually removed before rolling, a procedure called “scalping.”

As the bottom block is lowered and the solidifying ingot emerges from the mold, the surface is further cooled by water from openings around the inside of the mold. The water is recirculated through cooling towers to maintain a correct temperature for effective ingot cooling.

Sensors linked to a computer coordinate the rate of water flow, molten metal levels, the rate of molten metal addition, and the bottom block speed. Casting speeds may range from one-and-a-half to four inches per minute (37 to 100 mm/min.),
depending on the aluminum alloy and mold size involved.

Since it is very important to provide a continuous distribution of molten metal, fiberglass socks, screens and distribution bags are placed in the ingot head within the confines of the mold. These provide uniform molten metal distribution and temperature through the entire perimeter of the mold thus minimizing surfaces defects such as cold folds or molten metal breakouts.

At two inches per minute (50 mm/min.), it takes about 2-1/2 hours to cast a 290-inch (7365 mm) long ingot. An aluminum ingot 24 inches thick, 55 inches wide and 290 inches long (about 2 x 4.5 x 24 feet [610 x 1400 x 7365 mm]) weighs about 20 tons (18 metric tons) and contains enough aluminum, for example, to produce more than 1.5 million beverage can bodies.

DC casting has been used to produce ingots as much as 37 feet (11.25 m) long or longer.

Electromagnetic Casting

Electromagnetic casting (EMC) is a DC ingot casting variation in which a strong magnetic field confines the molten aluminum while its shell initially solidifies. Continuous cooling and elimination of the liquated zone inherent to the DC process eliminates the zone of enrichment thus minimizing the need for scalping. The aluminum does not contact mold walls, so there is no “shrinkage gap” effect and surface enrichment of alloying elements is avoided.

Therefore, EMC casting can produce ingots with smoother, metallurgically more homogenous surfaces that need little or no scalping and/or edge trimming on the hot line. A number of sheet products, such as 3xxx and 5xxx beverage stock alloys, have been cast and rolled without the need for scalping.

SCALPING

To create high quality surfaces for rolling, the broadest sides of the ingot are shaved by a machine with rotating blades called a “scalper.”

Sometimes all four of the sides are scalped.

Scalping is performed on an ingot to remove any irregularities or undesirable chemical compositions, such as excess oxides or concentrated alloying elements, left in its surface by the casting process. By providing smooth, metallurgically homogenous surfaces, scalping promotes high quality rolling and avoids the rolling of “slivers” into the surface of plate or sheet.

The scalper itself is a specialized milling machine with horizontal blades spanning about five feet (1.5 m) or more and rotating on a vertical axle.

The scalper generally mills the rolling faces of the ingot—that is, its widest surfaces, scalping one side and then turning the ingot over to scalp the other side. Some operations utilize two sets of cutters permitting simultaneous scalping of both
rolling surfaces. Edges and ends which are trimmed during the rolling operation need not be scalped. Recently, more emphasis is being placed on minimizing downstream operations such as intermediate trimming. Therefore, based on ingot profile, edges may also be scalped, thus eliminating the need for intermediate trims or sawing operations.

**PREHEATING**

The scalped ingot must be preheated for hot rolling. The temperature and time is controlled to promote specified ingot properties. There are a variety of methods of preheating ingots. These include “walking-beam” or “pusher” furnaces, car-bottom furnaces and soaking pits.

**Purposes of preheating**

Preheating the ingot before hot rolling serves several important purposes, including:

1. Raising the alloy’s temperature above the recrystallization temperature to prevent cold-working (strain-hardening) from taking place during rolling. This avoidance of strain-hardening is the key characteristic which differentiates hot rolling from cold rolling.

2. Homogenization — that is, putting all soluble alloy constituents into a more complete and uniform solid solution. During direct-chill casting solidification alloying elements tend to segregate inside alloy grains, in low concentrations at grain centers and increasing concentrations toward grain boundaries. This concentric stratification is also known as “coring.” At elevated pre-heating temperatures, these alloying elements redistribute themselves more uniformly within grains by diffusion, reducing segregation and coring.

3. Spheroidizing insoluble constituents. Homogenization pre-heating causes undissolved precipitates to coalesce into fewer particles and to lose their sharp comers and take on rounder, more compact shapes which significantly improve the alloy’s formability.

4. Softening the ingot and thereby minimizing the mechanical force necessary to reduce its thickness by rolling.

5. Relieving stresses in the ingot.

**Preheating methods**

Ingots are preheated in temperature-controlled furnaces. Several variations of preheating procedure are available to serve different ingot dimensions or treatment requirements:

- Ingots may be stacked up, lying flat and separated by spacers, on cars which convey them into and out of the furnace (“car-bottom” furnace).
- They may be stood on their long edge and pushed through the furnace on a slide (“pusher” furnace) or carried through it by “walking beams.”
- They may be inserted, standing on end, into a furnace called a soaking pit.

The temperature inside the furnace follows a controlled cycle which governs the rate of temperature increase; the stabilized temperature; the time spent at each temperature level; the rate of temperature decrease; and the final temperature at which the ingot is delivered for rolling.

Temperature cycles vary according to alloys and intended metallurgical results. For example, in one case, ingot temperature may be raised directly to a rolling temperature of perhaps 850°F (455°C) and held at that level right through to ingot delivery. In a different case, the temperature might be raised above rolling temperature, held there for a specified time, and then reduced by the use of cooling fans to the rolling temperature.

Then the hot ingot is laid flat on a conveyor and checked.

If its temperature is within the desired range, the carefully engineered ingot is sent to the rolling line.
SELF-TEST QUESTIONS
SECTION 3: PREPARATION

3.1 “Fluxing” means...
   a. pouring molten aluminum.
   b. removing impurities from molten aluminum.
   c. mixing in alloying elements.
   d. cleaning the walls of a reduction cell.

3.2 The main target of fluxing is...
   a. solid impurities.
   b. water vapor.
   c. dissolved hydrogen gas.
   d. undissolved aluminum particles.

3.3 The gases usually used for fluxing are...
   a. hydrogen and chlorine.
   b. nitrogen, argon and chlorine.
   c. oxygen and carbon dioxide.
   d. All of the above.

3.4 In a modern aluminum rolling plant, a sample of alloy can be sent to the lab and analyzed and the results reported back to the mill operators within...
   a. a few seconds.
   b. a few minutes.
   c. a few hours.
   d. a few days.

3.5 Aluminum alloy which is found to be “off analysis” is...
   a. rolled into product more carefully.
   b. thrown away.
   c. corrected or recycled.
   d. stored to await a matching customer order.

3.6 If inclusions are not removed from molten aluminum alloy before it is cast and rolled, they might...
   a. weaken the final product.
   b. cause streaks or flaws in the product surface.
   c. damage work roll surfaces.
   d. None of the above.
   e. All of the above.

3.7 “Final filtration of molten metal is done only when the end user demands minimal inclusions.” This statement is:
   a. True.
   b. False.

3.8 Name a grain refining element used in aluminum alloys.

3.9 Grain refiner is added to aluminum alloy...
   a. in the Hall-Heroult reduction cell.
   b. with the other alloying elements.
   c. just before ingot casting.
   d. during solution heat-treating.

3.10 “Continuous casters”...
   a. produce ingots two feet (610 mm) thick and 24 feet (7.3 m) long.
   b. operate 24 hours a day.
   c. produce unbroken slabs or strips.
   d. are used to cast large volume parts.

3.11 A roll caster...
   a. produces high-precision work rolls.
   b. solidifies molten metal between chilled rolls.
   c. applies absolutely no hot deformation.
   d. None of the above.

3.12 The product emerging from belt casters or block casters is usually...
   a. set aside to cool slowly before rolling.
   b. used, as-is, in commercial products.
   c. chilled quickly for immediate cold rolling.
   d. hot-rolled immediately into sheet stock.

3.13 In casting, the term DC or Direct Chill refers to the fact that...
   a. the molten metal comes in contact with the mold directly.
   b. there is water circulating inside the mold.
   c. water flows over the emerging slab or billet.

3.14 In DC casting, the mold...
   a. is the size of a finished ingot cross section.
   b. consists of two parts, one stationary and one moveable.
   c. must be discarded after one use.
   d. a and b.
   e. b and c.
   f. a and c.
3.15 “Electromagnetic casting is capable of producing ingots which, for some products, need no scalping and no hot mill edge trim.” This statement is:
   a. True.
   b. False.

3.16 Scalping is applied...
   a. to remove the enrichment zone.
   b. to remove surface irregularities.
   c. to obtain uniform slab thickness.
   d. a and b
   e. a and c
   f. a, b and c.

3.17 Scalping equipment can be described accurately as...
   a. a grinder.
   b. a lathe.
   c. a vertical or horizontal milling machine.

3.18 Pre-heating ingot for hot rolling serves several purposes. One is to soften the ingot for hot rolling. Another is...
   a. to oxidize the surface.
   b. to homogenize the alloy.
   c. to anneal the metal.
The work rolls, which actually contact and shape the aluminum, lie at the heart of a massive assembly of scientifically designed and precision manufactured parts that make up a modern rolling mill. The mill’s main mechanical components also include:

- **The mill stand**: the strong structure which supports various parts and withstands the enormous tensions imposed by rolling.
- **Back-up rolls**, whose function is to support the work rolls against excessive flexing and vibration.
- **Drive motors**, which provide the power that turns work rolls and forces aluminum through the roll gap.
- **Gearboxes**, which convert the rotation rates of the motors into the appropriate rotation rates and torque (turning force) for the work rolls.
- **Drive spindles**, which transmit the turning force of the motors to the work rolls.
- **Roll bending machinery**, capable of inducing slight, controlled flexing in the rolls to compensate for thermal expansion or other distortion and, thereby, control product flatness.

- **Gap adjustment machinery**, to set the gap between work rolls accurately and then to maintain it against the resistance of the alloy undergoing thickness reduction.

- **Coolant systems**, to apply liquid coolant/lubricant to the rolls.

And, for sheet mills, coil and core handling machinery to install, remove and transport heavy coils of rolled sheet.

The components which directly apply the mechanical force that reduces the aluminum thickness must be both strong and precise, capable of applying forces up to millions of pounds with uniform accuracy of a few hundredths or thousandths of an inch.

Rolls with appropriate diameters and surfaces must be used. Automatic roll-changing machinery makes it relatively easy to adapt a mill to changing product requirements.

No less important than the large mechanical components are the control systems, which sense product thickness and shape, and the computers which analyze the data and control the mill’s adjustment systems to maintain product tolerances while the mill is running.
A number of rolling mill parameters are controlled, either by the operator or by computer. They may include: roll gap, roll force, roll torque, roll cooling, roll bending, roll tilting and sheet tensions.

At many mills today, the operator may preset such parameters and then let the computer automatically run the mill through the prescribed process.

Main features of a four-high rolling mill.
A mill roll is basically just a long smooth steel cylinder with an axle shaped to be gripped and rotated by powerful motors. The apparent simplicity of its shape masks a lot of complex engineering.

It must be a near-perfect cylinder with a smooth but hard surface. It must also be stiff enough not to bend excessively with the high force needed to flatten an ingot or plate of aluminum alloy.

The aluminum product receives its specified surface directly from contact with the work rolls, which must therefore have the intended type of surface. Roll surface finish is also very important both for rolling efficiency and for product quality. Depending on specifications, flat rolled aluminum may be produced with a relatively rough “mill finish” surface, or with smoother surfaces up to and including “bright sheet” with a mirror-smoothness. At the same time, the roll’s degree of roughness largely determines how effectively it can “bite” into the aluminum and, by friction, force it through the roll gap. A rougher roll applies more friction and a stronger bite than a smoother roll, so the rougher roll can apply greater thickness reduction per pass — an important factor in mill efficiency. In order to provide sufficient friction with a smooth roll surface, it may be necessary to reduce the application of coolant/lubricant. This, in turn, reduces the rate of heat removal and necessitates compensating changes in the rolling plan.

Because of such considerations, it is economically important to use rolls with surfaces appropriate to the type of product to be produced. A customer who would be satisfied with mill finish aluminum might be just as satisfied with a smooth finish. The unnecessarily smooth rolls, however, might impose equally unnecessary penalties on the mill operation.

It is also important to maintain work roll surface quality in service. On hot work rolls, even the smallest blemishes must be avoided, to prevent aluminum from sticking locally and creating surface flaws in the rolled product. Hot work rolls often pick up tiny amounts of aluminum oxide or even aluminum metal, a phenomenon known as “roll coating.” Within limits, this can be advantageous because it tends to increase friction and make the rolls more efficient. Care must be taken to avoid excessive build-up, which can result in product surface flaws through imprinting or oxide detachment.

Work roll surface quality is closely monitored for excessive wear, deterioration or damage, to assure high quality products. Chrome plating of the work rolls was adopted to improve surface hardness, improve surface finish and extend the life of the work rolls.

Rolling solution, roll coolants or oil emulsions is another closely controlled parameter. Computer controls provide optimum addition of the coolant
to the work rolls. Controlled application of coolant improves control of the work roll temperature, thus improving shape control and ultimately yielding a flatter plate or sheet.

In addition, roll design is intimately connected with total mill design, because important trade-offs occur when roll size and properties are varied.

Roll diameter and roll stiffness are two of the most important factors. Other things being equal, a mill’s efficiency in reducing product thickness depends on work roll diameter. Product flatness depends largely on roll stiffness which, in turn, depends on both the diameter of the roll and the steel from which it is made.

Work rolls with a relatively small diameter can reduce aluminum thickness by a greater proportion in one pass than rolls with a larger diameter. On the other hand, smaller-diameter rolls bend more easily than those with larger diameters, making it harder to maintain uniform, accurate product flatness. Overall roll flexibility increases with length. The wider the rolled product must be, the longer the roll must be and the more the roll is likely to deflect without support.

Roll deflection can be counteracted to some extent by “crowning” the roll: i.e., making it slightly larger in diameter by a few thousandths of an inch (tenths of a millimeter) at the middle than at the ends. Because crowning is a fixed dimension, it can compensate accurately only for a matching, fixed amount of roll deflection. This implies that any one crowned roll is fully suitable only for specific rolling regimes with appropriate alloys and thickness reductions. It will not have exactly the right shape for other rolling tasks. Moreover, it will fail to compensate or can even distort the product, if roll deflection is allowed to become greater or smaller than intended.

Alternatively, in some circumstances work rolls may be “concaved” — made slightly smaller in diameter at the center than at the ends — to compensate for anticipated thermal expansion which would otherwise cause undesired crowning.

Smaller-diameter rolls are also more vulnerable to horizontal deflection in the pass-through direction. The friction of the aluminum passing between rolls tends to drag them in the same direction and may cause a roll to deflect until its elasticity overcomes the friction and snaps it straight again. Such deflections must be prevented by appropriate choice of roll size, and/or provision of horizontally stabilizing back-up rolls.

Because of their larger mass, larger work rolls can absorb or surrender a given amount of heat with less overall change in temperature than smaller ones. Thus larger-diameter rolls have greater thermal stability.

Larger, more massive work rolls also have more physical inertia — more resistance to changes of motion. Therefore, it takes more energy to accelerate and decelerate their rotation, a consideration that may substantially affect mill design and economics, especially for reversing mills and other start-stop rolling mills.

**ROLL CONFIGURATIONS**

But most aluminum plate and sheet rolling requires so much force that it is difficult to avoid excessive flexing with only the two work rolls. So each work roll is backed up by a larger roll, pressing against it to keep it straight.

Rolls are positioned one above the other. A stand with two rolls is called a “two-high” mill. A stand with two work rolls plus two back-up rolls is called a “four-high.”

Some two-highs are used, mostly to roll foil or in laboratories. And mills with three-, five- or six-roll combinations are also operated. But the four-high mill is the most widely used for rolling aluminum.

Some mills are designed to roll in only one direction; others, called “reversing mills” can roll aluminum back and forth.
Common roll configurations: a) two-high, b) four high, c) cluster.
In principle, it takes only two work rolls to reduce aluminum to any desired thickness. In commercial practice, however, work rolls are usually supported by “back-up rolls” that press against the work rolls and turn with them but never touch the product. Either the work roll or the back-up roll may be driven directly by the mill's motors. The other roll becomes an idler, turned by the friction of the driven roll.

The most common arrangement is the “four-high” mill in which the two work rolls are placed one above the other and each is supported by a backup roll, above the top work roll and below the bottom one, in a vertically stacked configuration “four (rolls) high.”

In this configuration, the chief purpose of the backup rolls is to maintain accurate, uniform product flatness by preventing excessive vertical deflection in the work rolls. Thus, the main requirement of a back-up roll is strength, achieved by sufficient diameter to withstand the “separating force” applied by the aluminum’s resistance to deformation.

A larger-diameter back-up roll can permit the use of a smaller-diameter work roll and, at the same time, increase the thermal stability of the unit by acting as a heat sink or source for the work roll. However, a more massive backup roll also increases the inertia of the rolling mill and demands more energy for acceleration and deceleration.

Thermal stability and inertia may influence backup roll selection, but the dominant consideration is always its ability to control work roll deflection.

Backup rolls are also applied in other configurations to combat horizontal work roll deflection as well as vertical deflection. This is accomplished by positioning the back-up rolls off the vertical axis of the work roll stack, so that their force against the work rolls is directed both vertically and horizontally.

Configurations using multiple back-up rolls are generally termed “cluster mills” and are usually used to roll thin products.

The combination of work rolls and back-up rolls in forceful contact with each other introduces the possibility that the very small variations from perfect roundness which would be acceptable in either roll alone could add up to an unacceptable deviation for the entire stack. In addition, small acceptable amounts of “give” in the bearings which support each roll can also add up to unacceptable deviations from perfect rotation as more rolls (and more bearings) are involved.

So roll grinding and roll bearings must be precise enough to keep the “eccentricity” (off center deviations) of the entire roll stack, as a unit, within the limits required for accurate, smooth product thickness.

Roll diameters must be accurate to within 2.5 ten-thousandths of an inch (0.006 mm). Total roll-stack eccentricity may be held within limits as small as 4 ten-thousandths of an inch (0.01 mm) or less.

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**HOT OR COLD ROLLING**

Rolling is done either “hot”—with hot, softened aluminum—or “cold”, with aluminum at room temperature.

In aluminum rolling terms, “hot” and “cold” have more technical definitions than their common meaning. “Hot” rolling means rolling at a metal temperature high enough to avoid strain-hardening (work-hardening) as the metal is deformed.

“Cold” rolling means rolling the metal at a temperature low enough for strain-hardening to occur, even if the alloy would feel hot to human senses.

In practice, hot-rolling temperatures may decline enough during rolling to permit some strain-hardening to occur.

It takes more energy, of course, to roll cold metal than metal which is softened by a high enough temperature. Cold rolling can provide a smoother final surface and different tempers than hot rolling. The thinnest products must be cold rolled to their final thickness.

Hot mills currently roll sheet at rates approaching 2,000 feet per minute (600 m/min).

Cold mills can roll sheet at rates up to 7,000 feet per minute (2135 m/min) or more.
**Hot Rolling – Metallurgical Effects**

Hot rolling has at least two significant metallurgical effects:

1. It welds pores left by casting, creating a denser, stronger metal.

2. It breaks up and distributes hard constituents of iron and silicon which have formed at grain boundaries. This action transforms brittle cast alloy into ductile wrought alloy, because fragmented and distributed constituents offer less resistance to the internal metal flow necessary to ductility. Reduction schedule or reduction per pass and directionality of rolling has a very important impact on some of the damage characteristics of the high strength aircraft alloys.

Rolling temperature also influences the appearance and structure of the final product. Lower hot-rolling temperatures yield relatively brighter product surfaces and elongated alloy grains, while higher hot-rolling temperatures can induce recrystallization in the metal. The rolling temperature is selected according to the product properties that are to be achieved.

Too high a temperature can weaken grain boundaries and cause boundary cracking. Consequently, rolling temperature is kept 20 to 90°F (10 to 50°C) below a certain limit — the “solidus” or solidification temperature — of each alloy.

**Cold Rolling – Metallurgical Effects**

On the atomic level, solid metals have a “crystal lattice” structure: its atoms are arranged in a regular pattern which can be considered, ideally, as a stack of flat planes.

When the metal is deformed, as it is in flat rolling, regions of the crystal “slip” past each other along these “glide planes”; such “slip lines” are sometimes visible on the metal surface. The lattice planes are never ideal. There are breaks and offsets in them, called “dislocations”, which tend to block slippage and so resist deformation.

Rolling, or other cold deformation, tends to break and offset the lattice planes, thereby increasing the number of dislocations which resist force and making the metal stronger and harder. This effect is deliberately induced as “work hardening” (work hardening) to strengthen aluminum alloy products. Various applications of strain hardening are included in the “H-tempers” and some of the “T-tempers” of aluminum.

The same hardening effect can occur prematurely, before rolling is completed; it is undesirable if a soft product is ordered. In such cases, annealing is performed to undo the work hardening that has occurred.

Work hardening has a natural limit for each alloy because it is, in fact, straining the alloy toward its strength limit. The number of dislocations which a crystal lattice can develop is limited and, therefore, so is its maximum strength. As work hardening increases, the metal can withstand increasing force without breaking; but it retains less reserve against additional force.

Metal cold worked to its maximum limit can be broken by only a slight additional deformation.

Thus, cold working, or strain-hardening, is applied to the degree required by product specifications which involves a trade-off between maximum strength and maximum ductility.

The heat of annealing relieves the distorted, dislocated lattice structure and allows it to reform in relatively undislocated planes again, restoring ductility at the cost of the acquired strength.
SELF-TEST QUESTIONS
SECTION 4: ROLLING MILL

4.1 The parts of a rolling mill that apply thickness reductions by direct contact with the product are called...
a. the mill stand.
b. the drive spindles.
c. the work rolls.
d. the backup rolls.
e. the gap adjustment machinery.

4.2 "The purpose of backup rolls is to permit the use of smaller-diameter work rolls." This statement is:
a. true.
b. false.

4.3 What type of work roll surface can be used efficiently for all rolled products and specifications?
a. mirror-smooth.
b. smooth.
c. mill finish.
d. extra rough.
e. none of the above.

4.4 Which of the following factors affect the amount of roll deflection during rolling?
a. roll width.
b. roll diameter.
c. product width.
d. product ductility.
e. amount of applied thickness reduction.
f. all of the above.

4.5 The most common roll-configuration for rolling aluminum is the...
a. two-high.
b. four-high.

4.6 Which of the following affects the roll gap?
a. roll crown.
b. roll bending.
c. coolant/lubricant sprays.
d. all of the above.

4.7 Roll bending is the equivalent of...
a. smoother finish.
b. changing the roll crown.
c. more reduction.

4.8 "Hot rolling" means rolling aluminum...
a. when it is too hot to touch bare-handed.
b. with pre-heated work rolls.
c. hot enough to avoid strain-hardening.
d. hot enough to induce full annealing.

4.9 Which, if any, of the following are significant effects of hot rolling?
a. making the metal smoother.
b. making the metal more dense.
c. making the metal more ductile.
d. making the metal more weldable.
e. none of the above.

4.10 "Cold rolling" means rolling aluminum...
a. at or near room temperature.
b. after refrigeration.
c. at any temperature which avoids strain hardening.

4.11 In general, cold deformation of aluminum...
a. increases its strength.
b. decreases its strength.
c. does not affect its strength.
d. changes its strength unpredictably.
e. causes it to break immediately.

4.12 Cold deformation of aluminum is effective because...
a. it twists the shape of the crystal lattice.
b. it makes lattice planes slip past each other.
c. it breaks and offsets lattice planes.
d. it rearranges alloying elements in the lattice.

4.13 In general, as strain-hardening increases, a metal’s ductility...
a. increases.
b. stays the same.
c. becomes unstable.
d. decreases.

4.14 The amount of strain-hardening that can be achieved in aluminum alloy...
a. is the same for all alloys.
b. is unlimited.
c. has a natural limit depending on the alloy.
d. has a limit depending on product thickness.
The first rolling mill encountered by an aluminum ingot entering the rolling line is called the “breakdown mill.” It is usually a single-stand four-high reversing hot rolling mill. Its main function is to “break down” the ingot, reducing its thickness to the dimensions of plate. For some purposes the breakdown mill alone can produce final product thickness. For others, the product of the breakdown mill is fed through additional rolling mills (hot or cold) for further thickness reduction and/or surface finishing.

In a breakdown mill, the work rolls are powered and their back-up rolls are turned by contact with the work rolls. A typical breakdown mill may apply 5,000 horsepower (3730 kilowatts) to each work roll, for a total of 10,000 working horsepower (7460 kilowatts) to drive the ingot through the gap, where it undergoes a compression force of about 8 million pounds (3,635 metric tons) along the contact line.

Breakdown mills are often described by the length of the work rolls they can accommodate (and consequently the maximum width of product they can roll): for example, a “120-inch mill” (“3-meter mill”) or a “168-inch mill” (“4.25-meter mill”).

### BREAKDOWN MILL PARAMETERS

*Its operator, in an elevated control room called the pulpit, raises the upper rolls from their last setting and sets the gap for the first pass — perhaps two or three inches (50-75mm) less than the ingot thickness.*

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Since it must reduce an ingot as much as 30 inches thick (760 mm), the typical breakdown mill is a large, powerful assembly. Its lower work roll and back-up roll are fixed in position. Its upper work roll and back-up roll are raised or lowered by screw-threaded or hydraulic mountings in the mill stand’s side columns, so the operator can continuously vary the gap between the working rolls.

As indicated previously, the roll gap for each pass is only one of several mill parameters that are set to achieve the desired product properties. Rolls with appropriate diameters and surfaces must be in place. Roll acceleration and speed are controlled as required for the alloy and the intended reduction. In many modern mills the entire rolling sequence is computer-controlled, once the operator feeds in appropriate instructions.
A prepared ingot is sent into the mill at a carefully adjusted rolling temperature. The rolling process itself generates additional heat: from friction between the ingot and the work rolls; and from the severe deformation of the metal — in effect, internal friction — as its thickness is reduced.

This additional heat must be removed to maintain temperature control. This is necessary not only to prevent excessive thermal distortion of the mill rolls but also to control alloy temper throughout the rolling sequence.

In addition, the work rolls must be lubricated, to prevent the hot aluminum from sticking to the rolls and causing surface flaws on the product. Both the quantity and application pattern of lubrication must be appropriately controlled.

Therefore, a system of hoses feeds liquid coolant/lubricant through the nozzles of spray bars installed in front of the rolls.

Lubricant is generally suppressed when the ingot enters the workroll gap, to promote a good friction “bite” by the rolls, and then is applied while the ingot passes through. There must be enough lubricant to prevent sticking but not too much. Either too little or too much lubricant can impair the product surface.

Both of these functions — heat removal and lubrication — are performed in a breakdown mill by application of a single liquid coolant/lubricant, typically an emulsion of water with about five percent oil which is continuously filtered and recirculated.

Other types of rolling mills may use different coolant/lubricant formulations suited to their functions and products.
The ingot is positioned and fed to the work rolls by a set of conveyor rollers in the “feed table” divided into right and left segments (table rolls) which are independently powered and controlled. By matching or varying the right and left conveyor speeds, the mill operator can maintain ingot alignment or turn the ingot to reposition it. Thus, ingot can be “cross-rolled”, i.e., run through the work rolls “sideways”, instead of in its normal lengthwise orientation, to roll it into a product wider than the original ingot.

The table rolls push the ingot into contact with the work rolls, but it is the work rolls themselves that “bite” the ingot by friction and force it through their gap.

The ingot is reduced in a number of passes to a slab a few inches (centimeters) thick. For example, a 15-inch-thick (380 mm) ingot may be reduced to about 13 inches (330 mm) on the first pass. Then the roll gap is reset, the direction is reversed, and the ingot is passed through again and is reduced to perhaps 11 inches (280 mm). The gap is repeatedly narrowed for each pass until the desired breakdown thickness is reached.

The operator in the control pulpit may read the roll separation directly from a digital display inside his booth, or he may monitor the roll gap settings from a large dial or indicator atop the mill. In some modern mills the rolling sequences are controlled automatically with sensors providing feedback to the rolling program while the operator monitors the operation.

When the ingot is rolled in its usual lengthwise position, the reduction in its thickness is compensated almost entirely by a corresponding increase in its length. Friction along the line of contact between the work rolls and the ingot is generally enough to prevent the ingot from widening significantly.

The edges of the ingot may also be rolled by work rolls on vertical axles at one end of the roll tables, to prevent edge cracking and control width spread.

### INTERMEDIATE HOT ROLLING

*If it is to be made into sheet, it is usually conveyed to another single-stand hot mill and is rolled down to a plate thickness of about one inch (25 mm).*

Some rolling mills apply intermediate hot rolling, but most of the newer rolling mills transfer plate-thickness slabs directly from the breakdown mill to a tandem sheet-rolling mill.
**Sheet Hot Rolling: The Single Stand Reversing Mill**

Some mills utilize a single stand reversing hot mill. This type of hot mill also includes one or two coilers, one on each side of the mill. Starting with a standard size ingot, the metal is rolled back and forth through the reversing mill. Once the strip is rolled to the desired thickness, generally less than .500” (12 mm), the metal can then be coiled. The mill has rewind capabilities on both sides, and the slab is generally coiled one or three times before the rolling is completed.

**Sheet Hot Rolling: The Tandem Mill**

The plate is rolled down to sheet thickness in a tandem, or multiple-stand, hot-rolling mill. There, several thickness reductions take place simultaneously as the sheet passes between several sets of work rolls with smaller and smaller gaps.

The stands of a tandem mill must be closely coordinated. From each stand, the sheet emerges thinner and longer — and so, faster — than it went in. Multiple-stand rolling speeds must be coordinated to accommodate sheet acceleration.

In fact, some sets of rolls must have a little extra power and speed, to keep just the right amount of tension on the sheet. Too little tension would let the sheet buckle; too much would tear it.

A modern multi-stand hot-rolling mill is computer-controlled to meet batch specifications. Sensors automatically measure sheet tensions, roll speeds and roll power relationships, and the computer adjusts them.

In a multiple-stand mill, roll power relationships, roll gaps and sheet tension are all interrelated and must be coordinated.

When plate or sheet is reduced in thickness, the total volume of metal, of course, remains the same but is redistributed. Since the width of the piece is essentially unchanged, any reduction in thickness must be compensated by a proportional lengthening to maintain constant volume. For example, if a plate 1.2 inches (30 mm) thick is rolled down to sheet 0.2 inch (5 mm) thick, it is reduced in thickness by a factor of six. This product emerges from the rolls six times longer and, therefore, six times faster than it entered.

This principle applies to each stand in a tandem mill. Since each stand except the last feeds its output into the next stand, the roll speeds must be progressively higher from stand to stand,

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A four-stand tandem rolling mill with take-up coil (schematic drawing).
to accommodate the accelerating sheet. Each speed increase must be large enough to keep tension on the sheet and prevent buckling, but not large enough to tear the sheet.

Furthermore, the larger the reduction of thickness imposed by any single stand, the more turning power it requires. Power differentials between stands also affect sheet tension, so roll speeds and turning power must be coordinated.

The roll gap is another influence which can be adjusted to maintain correct sheet tension. Since gap changes are relatively slow, tension is controlled more quickly by adjusting roll speed.

Tension-measuring devices are located between the stands of a tandem mill. The rolled sheet passes over each device at a slight angle, generating a downward force which is measured by load-cells in the bearing supports. An automatic feedback system adjusts roll speeds and gaps as necessary to maintain correct sheet tension.

Proper composition and application of coolant/lubricant is also crucial to tandem mill sheet-rolling to remove excess heat; avoid dulling the product surface or causing undesirable reduction marks or “herringbone” and prevent aluminum from sticking to work rolls. Mill lubricants may include various additives which increase their load-bearing capacity — their ability to prevent direct contact between the aluminum and the steel even under high pressures.

Also, the coolant/lubricant formulation must remain chemically stable under rolling conditions.

COILING AND EDGE TRIMMING

As sheet emerges from the hot mill, it is rolled up into a coil which may be as much as 8 feet (2.4 m) in diameter.

After rolling, this sheet is edge-trimmed on its way to coiling.

A tension reel wraps the emerging sheet into a tight coil, typically with an inside diameter of about 20 or 24 inches (500-600 mm) and an outside diameter in excess of 90 inches (2285 mm). Sometimes the ends of the sheet are secured by welding at the inside and outside of the coil. Otherwise, the coil is wrapped with a confining band. The mandrel on which the coil is wound contracts for removal of a full reel.

Coils of rolled aluminum awaiting further processing (right).
ANNEALING

If additional rolling is needed, it may be done at room temperature in single- or multiple-stand cold rolling mills. They operate on the same basic principles as hot rolling mills.

Before, after, or between cold rolling operations, the sheet may be fully or partially annealed for various reasons by heating and slow cooling, to soften it and counteract the tempering that has already taken place.

Applied before or between cold rolling operations, annealing prepares the metal for rolling.

Partial annealing may be applied after rolling is completed, to stabilize some tempered properties.

Full or partial annealing may be used to prepare the sheet for later mechanical forming in product fabrication.

Or the annealed condition may simply be the final temper requested by the customer.

Purposes of Annealing

Aluminum alloys may be hardened by hot or cold rolling procedures to a degree that is not desired in the finished product or that would interfere with further rolling and the achievement of a desired temper.

Heat-treatable alloys may be sufficiently heated and cooled during hot-rolling to undergo some partial solution heat treatment and precipitation hardening.

Cold rolling, on the other hand, elongates grains and sets up internal stresses and strain. These changes create resistance to further deformation: the cold-rolled plate or sheet is said to become “work-hardened.”

Unwanted precipitation hardening or work hardening is removed before further rolling or product finishing by annealing — that is, by heating the aluminum alloy above its recrystallization temperature and holding it there long enough for the grain structures created earlier to re-crystallize and relieve the internal stresses.

Annealing can be applied at any stage in the rolling process.

Full Annealing

Full annealing heats the alloy hot enough, long enough, to soften the product completely — that is, to achieve full recrystallization. “Recrystallization temperature” is not a precise term. Recrystallization does not occur suddenly at a sharply defined temperature; instead, it begins gradually as the temperature rises into an effective range, and it progresses to completion over an extended time. The effective recrystallization temperature depends on the alloy and on the deformation and treatment it has previously undergone, as well as the annealing “soak” time.

Full annealing converts both heat-treatable and non-heat-treatable wrought alloys into their softest, most ductile, most workable condition, designated as the “O-temper.”

For full annealing of heat treatable wrought aluminum alloys, the metal is typically “soaked” for about two hours at a temperature in the range of 635 to 700°F (335-370°C) to remove cold work, or 750 to 800°F (400-425°C) to counteract heat treatment.

Then the metal is cooled slowly, at a closely controlled rate appropriate to the alloy. This per-
mits maximum coalescence of precipitating particles, minimizing hardness.

Non-heat-treatable alloys are annealed by heating for one-half hour to two hours (most often about one hour) at a temperature in the range of 635 to 765°F (335-405°C). Then they are cooled at a controlled rate.

Annealing also provides the conditions for stress-relief and may even be applied specifically for that purpose if furnace schedules and product requirements permit.

The “H1” and “H3” aluminum alloy tempers are created by applying specific amounts of strain-hardening to fully-annealed metal. These are called “rolled-to-temper” products.

**Partial Annealing**

As its name suggests, partial annealing stops short of full annealing and, instead, applies patterns of temperature and time to strain-hardened, non-heat-treatable wrought alloys in order to develop properties in between fully soft and fully work hardened. It is typically performed after the completion of cold rolling.

These intermediate tempers are formally designated as “H2X tempers”: strain-hardened and partially annealed.

A quality partially-annealed product requires sophisticated process control.

**Stabilization Annealing**

Certain non-heat-treatable aluminum-magnesium alloys, such as 5052, 5456, 5083 and 5086 and also alloy 3004 develop high strengths because of their high internal stresses after rolling. However, because of a tendency for magnesium to come out of solid solution, the initial temper of these alloys is unstable and they may suffer “age-softening” — a gradual loss of some strength over time, at room temperature. Such alloys may also undergo dimensional changes, unless stabilized.

Further age-softening is prevented and the mechanical and dimensional properties of these alloys are stabilized by heating them to a relatively low temperature, usually about 350°F (180°C). After stabilization, the strength, hardness and dimensions do not change at room temperature.

**Annealing Methods**

Annealing applies heat by convection through the atmosphere inside an annealing furnace. To avoid oxidizing any unevaporated lubricant residues or forming magnesium oxide on magnesium-bearing alloys, annealing may be carried out in a dry, inert (low-oxygen) atmosphere such as nitrogen gas. A large integrated aluminum rolling plant may have its own nitrogen generating plant for this purpose.

Annealing methods may be divided broadly into two general approaches: batch annealing and sheet annealing.

**Batch Annealing/Treatment**

Batch annealing means loading a furnace with a batch of metal, usually coiled sheet, and holding it there until the annealing process is complete. Coils of aluminum sheet are annealed as a single batch, depending on the size of the coils and the size and shape of the furnace.

In batch annealing, heat conveyed by the furnace atmosphere to the outside surfaces of the coils must be conducted through the metal to the innermost layers, and sufficient time must be allowed for all parts of each coil to absorb enough heat to achieve the planned anneal.

Batch annealing is an efficient approach and is the most commonly used method in high-production sheet mills.

**Sheet Annealing/Treatment**

In sheet annealing, uncoiled sheet is passed through a furnace so that its entire surface contacts and is heated by the hot furnace atmosphere. This heats the sheet rapidly, permitting the development of a finer alloy grain structure.

Uncoiled sheet may be annealed either as continuous sheet passed through the furnace from coil to coil or as cut sheet transported through by a conveyor.
COLD ROLLING

Cold rolling is used to give aluminum sheet a desired strength and temper; or to provide a final surface finish; or to reduce sheet to very small thicknesses. For example, aluminum beverage can stock is cold-rolled from sheet about one-tenth of an inch (2.5 mm) thick down to about one-hundredth of an inch (.25 mm). This may be done in four or five passes through a single-stand mill or in one pass through a multiple-stand mill.

Aluminum alloys can be cold rolled down to thicknesses of around 0.002 inch (0.05 mm). Pure (low-alloy) aluminum can be cold rolled into foil as thin as 0.0001 inch (0.0025 mm).

The first pass through a single-stand cold rolling mill may reduce the material thickness by about 50 percent. Subsequent passes may reduce the thickness by similar or smaller amounts.

Sheet destined for cold rolling to thicknesses under about 0.040 inch (1 mm) is usually hot rolled to about 0.120 to 0.240 inch (3-6 mm) before cold rolling begins.

As the work hardening increases, it takes more power to roll the sheet thinner. Beyond a certain degree of hardness, the metal may crack if it is rolled again. This imposes practical limits on the amount of cold rolled thickness reduction that can be achieved in an uninterrupted series of passes. When further thickness reduction is necessary, the sheet must be annealed as described above to soften the metal for further cold rolling.

The degree of cold rolling performed after (or without) annealing is calculated to produce desired properties in the rolled sheet: either its final temper or the condition required to achieve its final temper.

To produce a reflective surface on cold rolled sheet, smaller thickness reductions are rolled during the final passes. The brightest surfaces are produced by the use of highly polished work rolls.

A typical single-stand cold mill can roll sheet at a rate of about 5,000 to 6,000 feet per minute (1525 to 1830 m/min) on each pass.

Although the sheet enters the mill “cold”, at room temperature, the friction and pressure of rolling may raise its temperature to about 180°F (80°C) or more. This excess heat must be removed by an appropriate coolant/lubricant.

Cold rolling in a tandem (multiple-stand) mill is governed by the same general principles as single-stand cold rolling. The tandem mill applies several thickness reductions in a single pass and readily matches or surpasses the productivity of the single-stand.

Lubricants used for cold rolling are usually composed of a load bearing additive in a light petroleum distillate oil. Lower-viscosity oils transfer heat more efficiently and improve rolling performance. A lower limit on viscosity is imposed by oil evaporation, flash and fire points at rolling temperatures. Oil-water emulsions have been developed for high speed cold rolling and have been adopted at some mills. Rolling lubricants are filtered to remove rolling wear debris, then recirculated.

The length of sheet wrapped in a single coil depends on the coil’s diameter and on the sheet thickness. The 38 inches (965 mm) distance between an inner radius of 10 inches (255 mm) and an outer radius of 48 inches (1220 mm) (20-96-inch [510-2440 mm] coil diameters), can accommodate 760 layers of sheet rolled to a typical thickness of 0.05 inch (1.25 mm). One such coil could hold a strip of aluminum sheet over two miles (3.25 kilometers) long which started from 24 inch thick by 24-foot long (610 x 7315 mm) ingot.

(Flat-rolled metal more than one-quarter inch [6.3 mm] thick is not usually coiled but is delivered to a run-out table and is cut to specified lengths.)

Gauge and Profile Control

As technology has progressed, the requirements placed on flat-rolled aluminum products for accuracy of thickness (gauge), flatness and cross-sectional shape have become more demanding, and rolling technology has advanced to keep pace.

Initially, rolling technology concentrated mainly on achieving uniform thickness throughout the
length of the rolled product. In recent years, it has added a more sophisticated ability to control transverse (cross-width) thickness.

The cross-width thickness variation is called profile, and it can be controlled during the hot rolling process. Profile can be further described as having two main components, namely crown and wedge.

For most alloys, the edges of the sheet will be slightly thinner than the center (positive crown), as a result of slight bending or bowing of the work rolls as they work to reduce the slab thickness. The higher the rolling load, the greater the degree of bending of the work rolls, and the higher the crown. More dilute alloys (softer) are sometimes prone to having thicker edges than center, or negative crown, a condition which can have an adverse effect on flatness during subsequent cold rolling passes.

Wedge is the difference in the thicknesses of the two edges where the sheet increases in thickness across the strip, and can be caused either by work rolls that are not parallel or by an uneven temperature distribution across the roll gap.

Many applications of sheet and plate require the flattest possible cross-sectional profile, with constant thickness across the strip. On the other hand, some applications require a positive profile, a little thicker toward the middle than toward the edges.

The formation of a required strip profile is most readily achieved on thick, hot metal: that is, during single-stand hot rolling or in the entry and middle rolls of a hot-rolling tandem mill.

The flatness of the final product depends more heavily on the rolling applied by the last mill stand it passes through, its exit stand. Achieving the best possible flatness is usually one of the main objectives of cold rolling.

Thickness control, of course, is practiced at every rolling step; but it is most critical in the last reduction stand which gives the product its final thickness.

In order for thickness and profile to be effectively controlled, they must be both accurately measured and accurately corrected. Modern computerized rolling technology makes it possible to measure the thickness, flatness and profile of a product as it comes out of the mill stand, compare them with specified values, and adjust the rolling mill to make appropriate corrections while the rolling continues. Such measurement/control feedback loops make it possible to produce sheet and plate with more accurate profiles than ever before.

In some cases, feedback loops may be augmented by “feed-forward” loops in which the product is measured both approaching and leaving the work rolls, and the two measurements can signal automatic mill adjustments in time to correct the rolling of the product as it enters the work rolls.

Product thickness (gauge) may be measured during rolling by contact rolls or by non-contact sensing of X-rays or other radiation beamed through the metal.

Surface flatness may be measured by segmented contact rolls or by laser beams.

Instantaneous thickness corrections during rolling may be made by activating hydraulic pistons which move the rolls slightly upward or downward to adjust the roll gap as needed.

Thickness and profile considerations overlap when the separating force applied by the rolled product causes work rolls to deflect. A variety of techniques (called “actuators”) are available to control gauge and/or profile during rolling. They include:

- **Roll tilting:** Work rolls may be tilted out of parallel vertically to counteract and correct product surfaces which are non-parallel in the opposite direction.

- **Roll crossing:** Work rolls may be “crossed” (made slightly non-parallel horizontally) by moving their end-mountings, to alter the distribution of rolling forces. This type of adjustment is made between rolling passes.

- **Localized roll cooling:** Controlled increases or decreases of cooling application to localized segments of rolls may be used to control thermal expansion and contraction, and so control roll shape during rolling. This can be a significant control technique for cold rolling.

- **Roll-bending:** Work rolls or backup rolls may be bent in either the vertical or the horizontal plane, to compensate for rolling forces or to correct an incoming profile. Roll-bending can be controlled dynamically, during rolling.

- **Stepped backup rolls:** Backup rolls may be installed with larger-diameter cylindrical center
sections and smaller-diameter ends, to concentrate their pressure on the work rolls just over the width of the rolled product. The “step” width may be a ground-in fixed feature of the back-up roll, or it may be adjustable, created by shrink-fitting removable outer sleeves or sleeve segments on the core roll. Stepped rolls are installed or adjusted between rolling passes.

- **Axial shifting of sleeved backup rolls:** A sleeve fitted on a backup roll may be moved from side to side by sliding the sleeve along the roll, shifting the area of pressure against the work roll. The sleeves of upper and lower backup rolls may be moved in the same, or in opposite, directions depending on the type of correction needed. Because these sleeves are shrink-fitted on their cores, they can be shifted only between rolling passes.

- **Axial shifting of cylindrical work rolls:** Conventional cylindrical work rolls may, themselves, be shifted from side to side to redistribute their pressure against the product. The upper and lower work rolls may be shifted in the same or in opposite directions. Shifting is carried out between rolling passes.

- **Axial shifting of non-cylindrical work rolls:** Instead of the conventional straight cylinder, work rolls may be made with a wave-shaped profile from end to end; that is, a slightly convex form toward one end, changing smoothly into a slightly concave form toward the other. When two such work rolls are used together, the shape of the gap between them can be varied by shifting them axially in opposite directions. Moving the two concave segments opposite each other allows the product passing between them to bulge in the middle, either forming a crowned profile or correcting an undesired concavity. Moving two convex segments into opposition squeezes middle of the product and forms a concave profile or corrects unwanted crowning. Placing convex and concave segments into opposition creates a product with constant transverse thickness but a “wavy” profile which may require flattening by subsequent rolling.

- **Flexible backup rolls:** Backup rolls have been made available which can be expanded hydraulically at the center or at the ends to induce crowning or concaving dynamically during rolling, in response to sensor/computer feed-back loops. In addition, a “self compensating” backup roll, more flexible at its ends than at its middle, combats unwanted product crowning by offering elastic resistance roughly in proportion to the various degrees of separating force all across the roll gap. Flexible backup rolls also extend the effective range of work roll bending.

Some of these techniques may be applied in combination with others. The choice of measurement systems, feedback loops, and actuator systems for any specific rolling mill depends on that mill’s own products and operating conditions.

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**TEXTURING AND EMBOSsing**

*Some products — such as the aluminum tread plates of decks and steps — call for texturing or embossing during the final rolling. Instead of the usual smooth surfaces, one or both work rolls will have a pattern which is transferred to the sheet as it passes through, during rolling or subsequent finishing operations, and often by the last stand of a tandem mill.*

- **Embossing:** Coiled sheet is run through set of rolls with the purpose of transferring a special pattern from engraved rolls onto surface of the coil. Unlike during the fabricating of tread plate where a deeper pattern is extruded on one side of the metal, embossing does not appreciably reduce the metal thickness. Embossed aluminum sheet with specific patterns such as “wood grain” or “diamond” is widely used in architectural applications.
SELF-TEST QUESTIONS
SECTION 5: SHEET ROLLING

5.1 A breakdown mill...
   a. is of a vastly different design from non-breakdown mills.
   b. is the first mill to apply rolling where there are more mills than one.

5.2 The purpose of a coolant/lubricant spray system is to:
   a. remove excess heat generated during the thickness reduction.
   b. control flatness.
   c. minimize variation in the roll gap along its length.
   d. all of the above.

5.3 During ingot breakdown, a reduction in thickness of ____ per pass is not extraordinary.
   a. 0.02" (0.5 mm)
   b. 0.2" (5 mm)
   c. 2.0" (50 mm)

5.4 In a breakdown mill, the ingot or slab is positioned for rolling by the...
   a. work rolls.
   b. backup rolls.
   c. table rolls.
   d. roll gap.

5.5 When a slab is rolled normally, its width...
   a. increases by about 10x.
   b. changes little.
   c. decreases.

Why?

5.6 If an ingot is rolled to 1/2 of its original thickness, its length...
   a. becomes half the original length.
   b. remains unchanged.
   c. becomes 50% longer than the original length.
   d. becomes twice as long as the original length.

5.7 “Cross-rolling” means rolling an ingot...
   a. faster.
   b. sideways.
   c. thinner.

5.8 Cross-rolling rolling is done to increase...
   a. productivity.
   b. speed.
   c. width.

5.9 A group of two or more mill stands or ranged so that the aluminum plate or sheet is successively rolled by each stand during the same pass is called...
   a. a cold mill.
   b. a hot mill.
   c. a cluster mill.
   d. a tandem mill.
   e. a breakdown mill.

5.10 Which, if any, of these factors affects sheet tension between the stands of a tandem mill?
   a. Sheet thickness.
   b. Roll power relationships.
   c. Take-up coil diameter.
   d. Roll gaps.
   e. None of the above.

5.11 Annealing is performed for which, if any, of these reasons?
   a. To remove precipitation hardening.
   b. To strengthen the alloy.
   c. To remove impurities.
   d. To remove work hardening.
   e. To remove recrystallization.
   f. None of the above.
5.12 Recrystallization occurs...
   a. suddenly at a precise temperature.
   b. gradually over an effective temperature range.
   c. in sharp steps at several different temperatures.
   d. only after remelting.

5.13 What is the term used to signify that metal has been heated above its recrystallization temperature?

5.14 “Some recrystallization or annealing can take place during hot rolling.” This statement is:
   a. true.
   b. false.

5.15 “Full anneal”, “partial anneal”, and “stabilize” are the thermal process terms related to...
   a. the alloy.
   b. the type of furnace.
   c. the purpose and practice.

5.16 The purpose of controlled atmosphere annealing is to avoid...
   a. oxidation of the residual oils.
   b. oxidation of the Mg in some alloys.
   c. a and b.
   d. Neither.

5.17 The primary reason for stabilizing 5xxx-series alloys is to...
   a. prevent age softening.
   b. improve corrosion resistance.
   c. optimize finishing characteristics.
   d. all of the above.

5.18 Some heat-treatable alloys are sold in O-temper because...
   a. the government requires it.
   b. forming requirement is severe.
   c. the cost is lower.

5.19 Brightness of final as-rolled surface finish is most affected by...
   a. the amount of reduction.
   b. the alloy.
   c. the finish of the work roll.

5.20 The main purpose of the coolant system in the cold rolling mill is to...
   a. maintain the work roll dimensions.
   b. achieve the temper in the sheet.
   c. both.
   d. neither.

5.21 List five product characteristics that are affected by cold rolling.

5.22 The fastest cold rolling mills reach speeds of more than...
   a. 3000 ft./min. (915 m)
   b. 5000 ft./min. (1525 m)
   c. 7000 ft./min. (2135 m)

5.23 Name at least four techniques or “actuators” available to control gauge and/or profile during rolling.

5.24 Tread plate is usually produced by...
   a. hot rolling.
   b. cold rolling.
   c. a finishing operation.
Metallurgical Function of Solution Heat Treating

The atoms of every solid metal are naturally arranged in regular, repeating patterns that form crystals. Aluminum atoms tend to form repeated joined cubes that share their boundaries, just as rooms in an apartment building share walls, floors and ceilings. This arrangement of joined cubes is called the crystal’s “lattice.” Cube walls that line up with one another in any direction are said to lie in the same lattice plane.

When the shape of solid metal is changed by force — that is, deformed — its atomic lattice is rearranged. Normally, this means that parallel lattice planes are forced to slip past each other.

Any condition that resists the slipping of lattice planes stiffens the whole lattice and makes the metal mechanically stronger.

In practical metal products, crystal lattices are never perfect and their planes are not smooth and unbroken. Here and there, the repeated pattern gets out of step and the plane is “dislocated.”

Dislocations hinder lattice planes from slipping past each other, creating resistance to deformation in the bulk metal. Alloying elements are introduced to create just that effect, strengthening the alloy by further distorting the crystallographic lattice.

But a dislocation itself, if it is not locked in place, can be pushed along its plane by an applied force, like a hump in a rug that simply moves someplace else if you step on it. A dislocation can block plane slippage only if it stays in place and resists the slip instead of moving along with it.

When a molten aluminum alloy solidifies during casting, the atoms of its dissolved alloying elements tend to cluster (precipitate) into relatively large particles visible under a microscope.

Large particles are essentially separate from the metal’s crystal lattice. Dislocations can travel around them, much as waves in water can detour around an isolated rock and continue past it.

Smaller, submicroscopic particles or individual alloying atoms, however, become closely integrated with the aluminum crystal lattice. Their presence tends to “pin down” lattice dislocations in two ways.

Because they don’t fit in as neatly as the crystal’s natural element, aluminum, other elements create stressed areas that resist the movement of dislocations, because it takes more energy to move dislocations around stressed areas.

It also takes more energy to force a dislocation through a stressed area instead of around it. Both ways, dislocation migration is strongly impeded, and the metal is strengthened against deformation.
The purpose of solution heat treating, then, is to dissolve large particles and disperse them as smaller precipitates or dissolved atoms capable of pinning down dislocations and strengthening the product.

**Solution Heat Treatment: “Soaking”**

“Solution heat treatment” usually refers to a three-stage process in which solution heating is the first step. That is followed by quenching and then aging.

Solution heating consists of raising the alloy to the desired temperature and then holding it at that temperature — “soaking” it — for the necessary amount of time to dissolve alloying elements.

This dissolving (solutionizing) must take place in solid metal. Melting the alloy would only repeat the casting conditions that form large particles. The degree to which solid aluminum can hold unprecipitated elements in solution is called its “solid solubility”. When solid aluminum is heated, the solid solubility of important alloying elements in it is increased and precipitated elements can redissolve.

Therefore, the alloy is held at a temperature below its melting point but high enough to produce a nearly homogenous solid solution. The solution heat treating temperature must be selected and carefully controlled for each aluminum alloy, because the range between the solution temperature and the melting point may be quite narrow, as illustrated by these examples of three alloys, all in the 2xxx series:

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Solution Treating Temperature, °F (°C)</th>
<th>Eutectic Melting Temperature, °F (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>925-945 (496-507)</td>
<td>945 (510)</td>
</tr>
<tr>
<td>2017</td>
<td>925-950 (496-510)</td>
<td>955 (513)</td>
</tr>
<tr>
<td>2024</td>
<td>910-930 (488-499)</td>
<td>935 (502)</td>
</tr>
</tbody>
</table>

In these examples, the lowest effective solution temperature is only 20 to 25°F (11-14°C) short of the melting point. One of these alloys soaked at a temperature in the middle of its solution range would be only 15°F (8°C) below the melting temperature. Thus, temperatures must be strictly controlled during solution heat treatment.

The “soak time” required for adequate solution varies depending on the thickness of the metal and its initial microstructure. It can range from minutes to hours after the metal has reached solution temperature.

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**Quenching**

Dissolved elements can move more freely through an alloy when its lattice structure is absent (in the molten state), incomplete or weak, at high temperatures, than they can once the lattice is fully formed, cool and rigid.

If a solutionized alloy were allowed to cool slowly, its dissolved, dispersed elements would be partially squeezed out of the forming crystal lattice and would cluster together in large particles with little strengthening influence.

This is prevented by “quenching” the hot alloy; that is, cooling it in a time too short for the dissolved elements to migrate. This, in effect, freezes dissolved elements where they are, still dispersed in what becomes a “supersaturated” solid solution holding more alloying elements in solution at room temperature than would otherwise occur with a slow cool down.

To achieve this condition, the alloy must be cooled very quickly through the temperature range in which particle precipitation would otherwise occur. The aim is to retain the “supersaturated” solid solution all the way down to room temperature.

Quenching is usually accomplished by plunging heat-soaked metal into cold water or flushing water over it at high flow rates.

Milder quenching methods, such as water spray, hot or boiling water, air blast or water-mist “fog”, may be used on some alloys whose heat treated properties are less sensitive to the quenching rate. Milder quenching may minimize distortion and residual stress in the metal, reducing the need for straightening operations.

Immediately after quenching, when alloying elements are still in solution and have not had time to form small dislocation-pinning precipitates, most aluminum alloys are almost as ductile as in the annealed condition. Therefore, straightening operations are often carried out as soon as possible after quenching to take advantage of this softened condition.

Rolling or other cold working in this condition may further improve the properties of some heat treated alloys.

Modern mills use “continuous strip” heating and quenching. In this system, uncut sheet runs continuously through a tunnel-type furnace and an adjacent quenching station.
Natural Aging (Precipitation Hardening)

The increased strength which is the usual purpose of solution heat treating develops only during its final step, aging or “precipitation hardening.”

The elements dissolved in a supersaturated, solid solution can still migrate through cool metal, even at room temperature, but not as fast or as far as they could at high temperatures. As a result, atoms of dissolved alloying elements can slowly gather to form tiny precipitates with relatively short distances between them, but not large, widely-spaced particles. The large number and high density of small dislocation-pinning precipitates gives the alloy its strength and hardness.

Aging means allowing enough time for this to happen before the metal is used for its intended applications. Solution heat-treatment and quenching have established the necessary conditions for dislocation pinning to occur; aging allows it to take place.

This may occur during “natural aging” at room temperature. Some alloys, particularly those in the copper-alloyed 2xxx series, reach virtually maximum strength by natural aging in a short time—a few days or weeks—while others continue to gain strength appreciably by precipitation hardening for years. In alloy 2024, for example, precipitation hardening is essentially complete after about four days at room temperature, achieving the T3 or T4 temper. Alloys 2014 and 6061, sometimes used in the T4 temper, reach fairly stable precipitation conditions after about one month at room temperature.

Artificial Aging (Precipitation Heat Treatment)

Many other alloys, however, harden slowly at room temperature, continuing to strengthen appreciably for years. Those alloys are treated to accelerate precipitation by “artificial aging”: holding them for a limited time at a moderately raised temperature, which increases the mobility of dissolved elements and allows them to precipitate more rapidly than at room temperature. This process is also called “precipitation heat treatment”.

Even alloys which naturally age rapidly may be artificially aged to assure the development of maximum strength. The strength of some alloys can be maximized by applying a combination of treatments: a small amount of cold working, followed by artificial aging.

Precipitation heat treatment temperatures generally range between 240 to 375°F (115-190°C), and soak times vary from about 5 hours to 48 hours. The time/temperature cycle for each alloy is selected to achieve the most suitable compromise between the conflicting demands of product strength and ductility, and other required characteristics such as corrosion resistance.

Artificial aging can be deliberately carried beyond the point of maximum alloy strength. By promoting the controlled growth of somewhat larger precipitates and thus reducing strength and hardness, certain specified product properties are achieved. This procedure is called “over-aging.”

These variations in treatment are reflected in the different definitions of the T3, T4, T6, T7, T8 and T9 aluminum alloy tempers, and the progressively aging “W” tempers.

It should be noted that precipitation hardening can also be slowed down to some extent by reducing temperature. For some purposes and in some alloys, aging can be slowed or delayed for several days by refrigerating the metal at zero°F (-18°C) or lower.

Forming or straightening may induce desirable property changes if performed before significant aging (precipitation) has occurred. When these procedures cannot be carried out immediately after quenching, the alloy may be refrigerated to retard aging until the metal can be worked more conveniently.
SLITTING

Coiled sheet is then run through a high-speed slitter, whose circular knives trim the edges straight.

The slitter may also divide wide sheet into narrower coils of specified widths.

The slitter may be used not only to trim the edges of wide sheet, but it may also cut sheet into narrower strips down to widths as small as 1/4 inch (6.3 mm) according to the customer's specifications. The slit sheet is recoiled as it emerges from the slitter.

A high-speed slitter applying a surface lubricant electrostatically may process sheet at a rate up to 4000 feet per minute (1220 m/min.). A laser scanner simultaneously checks for surface defects.

TENSION-LEVELING

Before or after slitting, the sheet may also go through a tension-leveler. There, it passes over sets of rolls that flex and stretch the metal to remove any buckling and give it a uniform flatness.

The tension-leveler flattens rolled strip by stretching it to a predetermined, exactly controlled percentage of elongation. The sheet is kept in tension by the grip of entry and exit bridle rolls. In between the entry and exit bridle rolls, the sheet passes over and under a series of steel rolls. This bends and works the sheet beyond its elastic limit and produces permanent elongation which counteracts any remaining curvature and completes the straightening process, producing an alloy strip which is flat and stress-equalized.

Surface Finishes

Aluminum sheet and plate emerge from rolling with a surface largely determined by the smoothness of the work rolls employed. Various other surface finishing operations may be performed after rolling is completed, to enhance product appearance, improve surface characteristics, or increase corrosion resistance.

Most surface finishing methods fall under one of three general categories: mechanical finishes, chemical finishes, and coatings.

Configuration of tension leveler rolls (schematic drawing).
Mechanical Finishes for sheet and plate include:
- Buffing
- Polishing
- Sanding
- Scratching
- Grinding
- Burnishing
- Embossing

Chemical Finishes for sheet and plate include:
- Etching
- Anodizing
- Chemical brightening
- Conversion coating
- Zincate coating

Coatings for sheet and plate include:
- Priming
- Painting
- Porcelain enameling

Finishes and coatings may be applied singly or in combination as required for the intended product.

**Oilng**
Sheet and plate products may be coated with oil to prevent oxidation, water staining, and scratching during handling, storage, and shipping (unless they have been given a specific surface finish which should not be oiled). Sheet and plate products destined for overseas shipment are usually oiled. Customers purchasing sheet and plate sometimes request that it be given a uniform coating of oil which will ease later metal-forming operations. The oils used for these purposes usually have a mineral oil base and are formulated to provide high resistance to water while avoiding skin irritation among handlers.

**Degreasing**
Just the opposite procedure, degreasing, is applied to remove any oils remaining on sheet or plate from the rolling operation, when a customer orders an oil-free product.

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**COATINGS AND MARKINGS**

Coatings or decorations may also be applied. Paint, enamel, or other liquids are usually sprayed or rolled on. Paper, plastic or other films may be applied using adhesives, pressure and heat. Some aluminum rolling mills have their own coating lines, but this type of finishing is often done elsewhere.

**Stenciling**
When ready identification of finished sheet is essential, codes identifying the product’s specifications, alloy, temper, gauge, and manufacturer may be stenciled on it by inked rollers or other marking devices. Stenciled markings may also be required by federal or military specifications.

In recent years, systems have been developed for marking aluminum sheet and plate with bar codes that can be read automatically by computer-linked laser scanners.

**CUTTING TO LENGTH**
When separate flat sheets are required, coiled sheet is sent to a “cut-to-length” line. There, it is uncoiled and cut to the specified lengths.

Coiled sheet may be cut to length in one of two ways:
1. Sheet unrolled from a coil may be momentarily stopped and cut to a pre-set length by stationary shears.
2. It may unroll from the coil and be cut to length by “flying shears” that travel with the moving sheet while they cut it.
   A mechanical stacker using forced air or vacuum lifters lowers cut sheets onto the stack gently, to avoid scratching.
STRETCHER-LEVELING

*If necessary, cut sheets are stretched to flatten them.*

Cut sheet may be further flattened by a sheet stretcher. This device clamps the ends of the sheet between pneumatically activated jaws. Then these stretcher heads are hydraulically separated, stretching the sheet to a preset amount. Stretcher-leveled sheet is important to many applications, such as smooth truck body panels whose wide expanses would make any irregularity more noticeable.

PACKAGING AND STORAGE

*Finally, the finished sheet is packaged and stored for shipping.*

The ends of coiled sheet are sometimes welded to the inside and outside of the coil to prevent uncoiling.

Then the coils are wrapped in plastic to keep out moisture and are banded.

Coiled sheet is usually wrapped and sealed against moisture as a unit. Flat sheet is also protected, usually by separating stacked sheets (“interleaving”) with an anti-tarnish, noncorrosive craft paper.

Flat sheet surfaces may also be protected temporarily by gummed tape, which should be removed within 90 days after its application.

Another protection method for some sheet products is a thin transparent vinyl film which can be readily removed by hand or by air blown between the coating and the metal surface. This film should be removed within ~90 days or as recommended by the supplier. Leaving the film on for longer periods can result in problems with its removal.

Flat sheet may be packaged for shipping in a variety of ways, such as: bare metal in a strapped bundle; a paper-wrapped bundle; or inside a fiber or wood box or a reusable shipping container.
SELF-TEST QUESTIONS
SECTION 6: SHEET FINISHING

6.1 Solution heat treating involves dissolving...
   a. copper.
   b. lattice dislocations.
   c. alloying elements.

6.2 In solution heat treating, “soaking” means...
   a. wetting the alloy before heat-treatment.
   b. heating the alloy long enough to dissolve its alloying elements.
   c. quenching heated alloy in cold water.
   d. remelting the alloy to add new elements.

6.3 Solution heat treatment temperature may be critical because...
   a. precipitation may occur.
   b. melting temperature is close.
   c. solid solubility is limited.

6.4 The purpose of quenching is...
   a. to freeze dissolved elements where they are.
   b. to make dissolved elements cluster into large particles.
   c. to cool heat-treated metal to room temperature for ease of handling.
   d. to establish the right temperature for further rolling.

6.5 The purpose of aging after solution-treating and quenching is...
   a. to achieve specific length and width dimensions.
   b. to achieve stable precipitation conditions.
   c. to thicken aluminum’s natural oxide film.
   d. to produce a specified surface finish.

6.6 Maximum strength is not achieved in a heat treatable alloy unless it is...
   a. formed.
   b. artificially aged.
   c. naturally aged.

6.7 Tension leveling uses both tension and bending or flexing for flattening and to...
   a. prevent scratches.
   b. equalize stresses.
   c. remove coil set.

6.8 Most aluminum surface finishing methods fall under one of three general categories. Name them.

6.9 In recent years, systems have been developed to mark aluminum sheet and plate with...
   a. photo-engraved symbols.
   b. coded magnetic stripes.
   c. laser-scanned bar codes.
   d. laser-burned engraving.
PLATE ROLLING & FINISHING

Aluminum plate and sheet products are rolled and finished by essentially similar procedures.

PLATE ROLLING

A slab rolled in the breakdown mill to four to five inches (100-125 mm) is already thick plate. For some applications it is sent straight to the finishing line. Thick plate is machined by customers into more elaborate shapes.

Otherwise, the breakdown mill may continue rolling thick plate down to a thinner gauge.

Final thickness may be achieved in a second hot-rolling stand, for closer control or simply for efficiency.

Sometimes plate is also cold-rolled to increase its strength or improve flatness. Plate for boat structures or military armor may be reduced 30 percent in thickness by cold-rolling, to increase its strength.

Plate remains uncoiled and flat all through its processing. It is often transported between work stations by a crane equipped with vacuum pads.

Slab Reheating

After its initial breakdown reduction, the slab is advanced on a run-out table where its ends are trimmed square. Occasionally, slabs destined for further rolling into plate are then transferred to a furnace for reheating which may take from two to 24 hours, depending on the alloy. Restored to rolling temperature, they are moved to the intermediate rolling mill.

Intermediate Edge Trimming

Plates of some alloys may crack along the edges during rolling. Such cracks would invade the product during subsequent rolling if they were allowed to remain. Therefore, after intermediate rolling the plate’s edges are trimmed to remove such cracks, leaving it wide enough for trimming to final size when rolling is completed. Both ends are also trimmed square.

PLATE FINISHING

After rolling, heat-treatable plate goes through a horizontal or vertical furnace for solution heat treating and quenching.
Solution Heat Treating and Quenching

The solution heat treating, quenching, and precipitation hardening of aluminum plate follows the same physical laws and practical procedures as for aluminum sheet. The procedures may have to be adapted to take into account the greater thickness of plate.

Because the rate of heat transfer through metal is limited, it takes time for cooling applied at the surface of hot plate to reach its center. During that time large temperature differences can develop, setting up mechanical expansion/contraction stresses between surface and core which become frozen into the cooled plate and are permanent unless relieved by further operations.

Tests on two-inch-thick (50 mm) plate (alloy 7075) have found as much as 350ºF (195ºC) difference between surface and core, four seconds after the start of quenching.

PLATE STRETCHING

Thick plate is stretched between the gripping jaws of a hydraulic machine, to flatten it, work-harden it, and relieve stresses created by rolling and heat-treating. A large stretcher can apply as much as 15,000 tons (133 meganewtons) or more of tension!

Thinner heat-treated plate is often stretched as well. But non-heat-treated thin plate is not usually stretched unless it's necessary for flatness.

Plate may be stretched by as little as one percent, or as much as 15 percent of its original length.

The stretcher's grip imprints the ends of the plate, so they are sawed off and recycled.

Stretching has proven to be an effective means of relieving stresses introduced into plate by quenching.

For the alloys, tempers and applications that account for almost all rolled plate production, stretching is typically within the range of one to three percent. In some specialized cases, such as alloys 2024 and 2219 in the T86 and T87 work-hardened tempers produced to meet demanding aerospace requirements, stretching of as much as 15 percent may be applied.

A stretcher applying 6 million pounds (27 meganewtons) of tension can relieve and level aluminum plate up to three inches (75 mm) thick. A stretcher with 30 million pounds (133 meganewtons) capacity can stress-relieve aluminum plate up to six inches (150 mm) thick or larger.

Stress-relief stretching has made it possible to machine thick plate into complex structural aircraft parts with integral stiffeners, without the distortion that might occur if the stresses were not first relieved.

ULTRASONIC INSPECTION

At this point, aluminum plate may be ultrasonically inspected. It is submerged in water and sound waves are beamed into it. They will bounce back from hidden flaws, revealing their presence and their location. Flawed plate, of course, is not shipped but is held back for correction or recycling.
Ultrasonic testing may be required for some products, particularly under certain military specifications. On less critical products it may be used to spot-check samples for production quality. For ultrasonic testing, a slab or plate is submerged in water in a large shallow tank nicknamed the “swimming pool.” The water serves as an efficient coupling agent which aids in transmitting sound waves at frequencies above human hearing (ultrasonic) from a transducer into the tested metal.

The ultrasonic waves are reflected back to a detector from both surfaces of the plate. Since the speed of sound through the aluminum alloy is known, the time difference between the arrival of reflected waves from the two surfaces can be used to calculate the distance between them and the thickness of the plate. Hidden flaws within the metal will distort or reflect the sound waves as well. These flaws can be revealed and even located by the reflected patterns.

**ARTIFICIAL AGING**

*After stretching and inspection, some plate is further hardened by undergoing a moderately raised temperature to accelerate its natural aging. The process is called “artificial aging.”*

The natural aging and artificial aging of aluminum alloys are discussed above in the “Solution Heat Treating” section under “Sheet Finishing.” The principles of aging (precipitation hardening) are the same for sheet and plate and the procedures and temperature/time cycles are governed primarily by alloy composition and property specifications rather than product form.

**PLATE EDGE CUTTING**

*At some convenient stage, plate edges are trimmed straight by circular saws.*

Plate edges are usually trimmed square and flat. Customers may, however, specify special edge preparations such as: rabbeted, routed, machined or anodized.

**PLATE INSPECTION, SUPERFICIAL DEFECT REMOVAL AND STORAGE**

*Finally, the finished plate is inspected; any minor surface defects are removed, and the plate is stacked and stored for shipment—protected by plasticized paper and often separated by wooden spacers.*
NOTES
SELF-TEST QUESTIONS
SECTION 7: PLATE ROLLING AND FINISHING

7.1 Plate is cold rolled in order to...
   a. increase its strength.
   b. achieve special thickness tolerance.
   c. improve its flatness.
   d. all of the above.

7.2 Plate solution heat treating is normally done...
   a. in a horizontal or vertical furnace.
   b. to improve flatness.
   c. using air quench.

7.3 The quenching of solution-heated plate can set up internal stresses because the plate...
   a. cools faster on one side than the other.
   b. cools faster at the interior than at the surfaces.
   c. cools faster at the surfaces than at the interior.
   d. cools faster at the ends than at the middle.

7.4 Stretching relieves stresses by...
   a. allowing all the grains to line up.
   b. raising unequal stresses to a higher, more equal level.
   c. cold working the metal.

7.5 Plate is typically stretched...
   a. less than one percent.
   b. 1-3%
   c. 5-10%
   d. 12-16%

7.6 A hydraulic stretcher...
   a. leaves no marks on stretched plate.
   b. makes the plate ends smoother than the rest.
   c. leaves end imprints which become part of the finished product.
   d. leaves end imprints which are sawed off.

7.7 In some products, trimming is done before final rolling in order to...
   a. make the final trim easier to dispose of.
   b. remove edge cracks.
   c. inspect the product as early as possible.

7.8 Ultrasonic testing is done to...
   a. detect inclusions.
   b. satisfy OSHA requirements.
   c. check hardness or strength.

7.9 The principles of natural and artificial aging of aluminum plate...
   a. are essentially the same as for sheet.
   b. are entirely different than for sheet.
   c. depend on the shape of the finished product.
   d. None of the above.
Sheet and plate products are routinely tested and inspected in accordance with certain government and society specifications and good business practice. The testing routinely performed is frequently sufficient to ensure the quality required by the customer.

Additional tests or inspections may be arranged by agreement between the customer and the producer.

Some of the additional tests which may be ordered include:
- Squareness inspection
- Electrical conductivity testing
- Fracture toughness testing

And, for plate:
- Ultrasonic inspection
- Ballistic testing

**Tensile Strength Testing**

In the rolling mill laboratory, the tensile strength of an aluminum alloy is tested by stretching a sample, of standard thickness and shape, in a machine which measures the force required to deform and then break it. A computer automatically records these measured yield and tensile strengths and reports the results. In a computerized rolling mill, the control center may already have entered the alloy batch specifications into the computer, which immediately compares the tested strength with the specifications. If the sample is within specifications, the computer automatically transmits an alloy clearance to the appropriate plant operator. If not, it reports that the sample is out of specifications.

**Microscopic Inspection**

The surface of an alloy sample is polished, chemically etched to enhance grain boundaries and other metallurgical features, and then inspected visually under a light microscope. Such inspection can reveal grain sizes, inclusions, defect identification and other features of alloy structure, and cladding thickness.

If necessary, samples can be subjected to magnifications as high as 100,000 times or more by electron microscopy at appropriate facilities.

**Porosity Testing**

Porosity can be observed and estimated by applying to the surface of an alloy sample a penetrating liquid dye which concentrates in pores. This dye contains chemicals which fluoresce — that is, emit visible light — when exposed to invisible ultraviolet light. Thus, the treated sample reveals its porosity when inspected under UV light in a darkroom.
Coolant / Lubricant Analysis

The liquid coolants / lubricants used in rolling aluminum can be chemically analyzed automatically. In as little as five to ten minutes, such devices can detect and measure the presence of esters, acids, soaps and contaminants. They can provide information about conditions prevalent in the rolling process. In addition, viscosity and distillation curves can be determined. Such factors exert important influences on rolling speed and product surface quality.

Anodizing and Bright-Dipping Tests

If a batch of flat-rolled aluminum is eventually to be anodized or bright-dipped, samples may be given these treatments in small laboratory facilities to confirm that the metal will perform as intended.

Dimensional Tolerance Control

Standard dimensional tolerances for aluminum sheet and plate are promulgated by the American National Standards Institute and published in ANSI H35.2 (and H35.2M, the metric version).

ANSI H35.2 includes dimensional tolerances for thickness, width, length, lateral bow, squareness and flatness, and other tolerances applicable to specific types of products.

Sheet and plate are produced within these ANSI tolerances unless other tolerances are specified.

Producers may publish their own standard tolerances, which govern where they differ from the ANSI tolerances.

Nonstandard tolerance specifications may be adopted by mutual agreement between the customer and the producer.

The ANSI tolerances usually applied impose limits on dimensional deviations, which vary with alloy and with specified product thickness and width.

For example, sheet rolled from alloy 5052 or a number of other specific alloys to a specified thickness of 0.030 inch (0.75 mm) at a sheet width up through 39.37 inches (1000 mm) may deviate from its nominal thickness by no more than 0.0020 inch (0.045 mm) under the ANSI Standard Tolerance table.

If the same sheet is more than 39.37 inches (1000 mm) wide, up to 59.06 inches (1500 mm), the standard tolerance is increased to a permitted thickness deviation of no more than .0025 inch (0.06 mm).

Surface Quality Characteristics

Flat-rolled aluminum may be produced with one of a number of common types of surface qualities, including:

Mill finish:
The general-purpose surface finish, which meets most customer needs, produced by work rolls surfaced mainly for effective thickness reduction.

Skin-quality finish:
High surface quality on one side of the flat-rolled product, with mill finish on the other side.

One-side-bright mill finish:
Moderately “bright” (reflective) surface on one side, with mill finish on the other side.

Standard one-side-bright finish:
Uniformly bright surface on one side, with mill finish on the other side.

Standard bright finish:
A relatively bright surface on both sides.

Other aspects of flat-rolled aluminum surfaces are discussed and illustrated in The Aluminum Association's publication, “Visual Quality Characteristics of Aluminum Sheet and Plate” (QCA-1;2002).

This booklet identifies more than 90 characteristics of bare and Alclad sheet and plate, grouped under five general headings:

Flatness Characteristics
Metallurgical Characteristics
Surface Characteristics
Other Characteristics
Coated Sheet Characteristics.

The booklet describes and illustrates the visual appearances of various flaws which may be caused by deviations from optimal rolling conditions or by handling and storage conditions.
As computerization spreads and develops, modern aluminum rolling plants are increasingly adopting such techniques as “computer-integrated manufacturing”, “just-in-time production”, and “statistical process control” to improve efficiency, customer service and product quality.

**Computer-Integrated Manufacturing (CIM) systems** use the computer, connected to sensors and other information-inputs, to organize and control the flow of materials through the rolling plant and to automate rolling operations, improving plant efficiency and product uniformity.

**Just-In-Time (JIT) systems** coordinate plant utilization and production schedules with customer orders and product delivery timetables to reduce or eliminate unnecessary stockpiling and unanticipated production changes, and guarantee product delivery when the customer needs it.

**Statistical Process Control (SPC) systems** regularly measure key product and process characteristics; automatically analyze them in relation to product specifications; identify trends if changes start to occur; and feed back these findings to process controllers which make the necessary adjustments to keep processes and products within specifications.

Aluminum plate, sheet and foil look so simple—and it’s so easy to make so many things out of them—that it’s hard to imagine how much technology, power, and care has gone into them.

The modern rolling mill applies massive physical force with fine precision, producing flat aluminum products with accurate dimensions and with properties tailor-made to meet the customer’s needs.

In the race for product versatility, durability, performance, economy, and ease of fabrication, it’s hard to beat aluminum plate, sheet and foil—they’re really rolling!
NOTES
SELF-TEST QUESTIONS
SECTION 8: QUALITY AND PROCESS CONTROL

8.1 Every ingot “drop”, when finished into rolled product, is tested for dimensions, mechanical properties, and...
   a. anisotropy.
   b. hardness.
   c. alloy composition.
   d. all of the above.
   e. b and c.

8.2 “Analysis of used coolant / lubricant can detect contaminants, but it can not reveal anything about the rolling process itself.” This statement is:
   a. true.
   b. false.
   c. a “trick question”.

8.3 “Standard dimensional tolerances” are applied to aluminum sheet and plate products...
   a. in all cases.
   b. only when required by government specifications.
   c. only when required by individual purchasers.
   d. unless special tolerances are specified.

8.4 Among recent rolling mill developments, the acronym “CIM” stands for;
   a. Comprehensive Inventory Management.
   c. Complex-intelligence Machines.

8.5 A “JIT” system...
   a. coordinates production and delivery time tables.
   b. stockpiles product for potential future orders.
   c. automatically audits employee work-hours.
   d. forecasts market trends for rolled products.

8.6 “Statistical Process Control” (SPC)...
   a. improves the accuracy of company record-keeping.
   b. monitors rolling industry business statistics.
   c. heads off potential rolling-process problems.
   d. matches ingot production with orders for rolled products.
Aging—Precipitation from solid solution resulting in a change in properties of an alloy, usually occurring slowly at room temperature (natural aging) or more rapidly at elevated temperatures (artificial aging).

Alclad sheet—Composite sheet consisting of an aluminum alloy core having on both surfaces (if on one side only, Alclad One Side Sheet) a metallurgically bonded aluminum or aluminum alloy layer that is anodic to the core, thus electrolytically protecting the core against corrosion.

Alloy, aluminum—Aluminum to which metallic additions, known as alloying elements, have been made to impart certain properties. The most important alloying elements for aluminum include magnesium, copper, silicon, manganese and zinc.

Alumina—Aluminum oxide, $\text{Al}_2\text{O}_3$, an intermediate product extracted from bauxite and from which aluminum metal is separated by the Hall-Heroult reduction process; aluminum oxide, a very hard material, is also widely used as an abrasive.

Annealing—A thermal treatment to soften metal by removal of stress resulting from cold working or by coalescing precipitates from solid solution. See also “Full Annealing”, “Partial Annealing” and “Stabilization Annealing.”

Anode—A positive electrical pole: in the Hall-Heroult process, the positively-charged carbon pole which attracts and reacts with the oxygen from dissolved aluminum oxide.

Anodizing—A process for artificially increasing the thickness of the oxide layer on aluminum by applying a direct current while the piece is suspended in an electrolyte. The aluminum workpiece itself serves as the electrical anode; hence, the name “anodizing.”

ANSI—American National Standards Institute; verifies industry standard-setting procedures and accredits industry-adopted standards.

ANSI-H35.2—“American National Standard Dimensional Tolerances for Aluminum Mill Products”, published by the Aluminum Association; also published as ANSI-H35.2(M) in metric units.

Artificial aging—Precipitation from solid solution resulting in a change in properties of an alloy, accelerated by application of a moderately elevated temperature.

Backup rolls—In a rolling mill, supporting rolls which press against the work rolls to counteract deflection forces.

Bauxite—Aluminum ore: a mineral first discovered at Les Baux, France, containing about 40-55% alumina (aluminum oxide), with impurities such as iron oxide, silicon oxide, titanium oxide and water.

Bayer process—The process, patented in 1888, commonly used to extract alumina from bauxite as an intermediate stage in the production of aluminum metal.

Belt caster—A device which casts metal directly and continuously into the form of plate or sheet by allowing molten metal to solidify between cooled traveling belts which serve as local mold walls.

Bite—The initial contact friction from work rolls which draws the material being rolled into the roll gap.

Block caster—A device which casts metal directly in the form of plate or sheet by allowing molten metal to solidify in contact with traveling cold blocks which serve as heat-sinks and as local mold walls.

Breakdown mill—A rolling mill which first reduces aluminum ingot to slab, plate or sheet thickness.

Bright-dipping—Chemical treatment of aluminum in a special dip solution to produce diffuse bright or highly specular (mirror-bright) finishes.

Casting—Allowing a liquid material to solidify inside a shaping form; a product formed by casting.
Cold rolling—Rolling performed on metal at a temperature sufficiently low that strain-hardening (work hardening) occurs. Cold rolling may be performed at room temperature or at a moderately raised temperature.

Cold working—Plastic deformation of metal at such temperature and rate that strain hardening occurs.

Concaved roll—A work roll made to be of slightly smaller diameter toward the center than toward its ends at room temperature, to compensate for anticipated thermal expansion during rolling.

Continuous casting—Any process capable of casting a material into a continuously elongating form without interruptions as long as the process is continued. See, also, Direct Casting.

Controlled-atmosphere annealing—Annealing carried out in a dry inert atmosphere, often nitrogen gas.

Cross rolling—Rolling ingot by feeding it into the roll gap with its longest dimension parallel to the roll axes; sometimes performed to widen the material before rolling it to its intended thickness and length.

Crowned roll—A work roll made to be of slightly larger diameter toward the center than toward the ends, to compensate for anticipated roll deflection during rolling.

Cryolite—The main component and solvent of the electrolytic bath in which aluminum oxide is dissolved in the Hall-Heroult aluminum production process; a mineral containing sodium aluminum fluoride (Na₃AlF₆). It occurs naturally in Greenland, but most of the cryolite in commercial use is produced synthetically.

Direct casting—In the context of plate and sheet production, any process in which molten metal is cast directly into a flat form, of sheet or plate thickness; see also, “Roll Casting”, “Belt Casting” and “Block Casting.” Also known as “continuous casting.”

Direct-chill (D-C) casting—A process for casting ingots by pouring molten metal into a water-cooled mold collar whose floor is slowly withdrawn as the metal forms a solid shell, permitting the casting of large, elongated ingots without the complete enclosure of a full-sized mold.

Drop—The shop term for the direct-chill casting of one or more rolling ingots in a set; that is, the result of one lowering or “drop” of the hydraulic cylinder in the casting pit.

Ductility—The degree to which a metal or other material may be deformed without breaking, a property important for forming during fabrication and for impact resistance in service; the opposite of brittleness.

Electromagnetic casting—Metal casting in which an electromagnetic field is applied to contain molten metal and prevent it from physically touching mold walls while it solidifies; sometimes used in conjunction with “Direct-Chill Casting” to produce ingots with particularly smooth, uniformly alloyed surfaces.

Flat rolling—A general term for the rolling of all flat products with uniform thickness, including plate, sheet and foil.

Foil—A flat-rolled product rectangular in cross section and form of thickness ≤ 0.0079 inch (<0.20 mm). (Note: Foil was previously defined as being <0.006 inch (0.15 mm thick).)

Four-high mill—A rolling mill which employs four rolls: two work rolls, each supported by a backup roll.

Full annealing—Annealing performed above the recrystallization temperature for a long enough time to convert an alloy into its softest, most ductile, most workable condition, designated the “O-temper.”

Grain—A small region of solid metal within which the atoms are arranged in a continuous uniform “lattice.”

“As-cast” grains form during crystallization when molten metal solidifies.

“Deformed” grains, usually elongated, are formed during hot or cold working.

“Recrystallized” grains form during annealing.

Hall-Heroult reduction process—The common commercial method of separating aluminum metal from its oxide (alumina). Invented in 1886 by Charles Martin Hall in the United States and Paul L.T. Heroult in France, it is based on the principle of dissolving aluminum oxide in molten cryolite.
and separating the aluminum from oxygen by application of electric current.

**Heat-treating**—Heating and cooling a solid metal or alloy in such a way as to obtain desired conditions or properties. Commonly used as a shop term to denote a thermal treatment to increase strength. Heating for the sole purpose of hot working (preheating) is excluded from the meaning of this definition. (See also, “Aging”, “Annealing”, “Partial Annealing”, “Stress Relief” and “Solution Heat Treating.”)

**Heat-treatable alloy**—An alloy which may be strengthened by a suitable thermal treatment.

**Hot rolling**—Rolling performed on metal at a temperature high enough to avoid strain-hardening.

**Hot working**—Plastic deformation of metal at such temperature and rate that strain hardening does not occur.

**Inclusion**—Foreign material in the metal or impressed into the surface.

**Ingot, rolling**—A thick cast form suitable for rolling.

**Leveling**—The application of controlled mechanical force to remove edge waves, pockets or other flatness irregularities, yielding plate or sheet which is essentially flat.

**Mill finish**—The general-purpose surface finish, which meets most customer needs, produced by work rolls surfaced mainly for effective thickness reduction.

**Mill, rolling**—An installation consisting of a roll stand and its rolls and related equipment.

**Natural aging**—Precipitation from solid solution at room temperature, resulting in a change in properties of an alloy.

**Non-heat-treatable alloy**—An alloy which can be strengthened only by cold work.

**Nucleation**—The formation of aggregates of atoms which are stable enough to grow and form new grains upon heating following deformation; the first stage in the process of recrystallization.

**Partial annealing**—Thermal treatment given cold worked metal to reduce strain-hardening to a controlled level.

**Plate**—A rolled product rectangular in cross section and form of thickness 0.250 inch (6.3 mm) or more, with either sheared or sawed edges. (Note: When products are ordered to metric specifications using metric dimensions, plate is defined as being > 6 mm thick.)

**Pot**—A single Hall-Heroult process “cell”: a refractory container holding alumina dissolved in molten cryolite, through which electric current is passed to produce aluminum metal.

**Potline**—A number of Hall-Heroult “pots” connected in series on the same electrical circuit.

**Precipitation hardening**—See “Aging.”

**Pre-heating**—A high temperature soaking treatment to provide a desired metallurgical structure in preparation for rolling. Homogenizing is a form of preheating.

**Pure aluminum**—In common industry parlance, “pure” aluminum refers to metal which is at least 99.00 percent aluminum, as produced by standard commercial methods. Aluminum of higher purity can be produced by special processes.

**Quenching**—Cooling of a metal from an elevated temperature by contact with a liquid, a gas, or a solid.

**Recrystallization**—The transformation of a cold-worked grain structure, at sufficiently high temperatures, into a soft metal structure with new grains.

**Recrystallization temperature**—A temperature above which the formation of new grains within a deformed structure takes place; it is dependent on both the amount of previous cold working and on the annealing time.

**Refined aluminum**—Aluminum of very high purity (99.950 percent or higher) obtained by special metallurgical treatments.

**Reheating**—Heating metal to hot-working temperature. In general no changes in metallurgical structure are intended by simple reheating.
**Reversing mill**—A rolling mill which can roll plate or sheet on both directions by reversing the rotation of its rolls between passes.

**Roll caster**—A device which directly produces plate or sheet by pouring molten metal into the gap between two cooled rolls where it solidifies before emerging as a flat product. Some hot working takes place as the solidified metal is rolled through the gap, but the product thickness is achieved mainly by the casting, not the rolling, process.

**Roll gap**—The space between work rolls which determines the thickness of the rolled product.

**Rolling**—Passing a solid, ductile material between two work rolls to reduce its thickness and/or impart a desired surface finish.

**Rolls**—The round metal cylinders used for rolling.

**Scalping**—Machining the surface of an ingot to remove physical and/or metallurgical irregularities.

**Series, alloy**—In most of the world, aluminum alloys are assigned four-digit identifying numbers which group them in “series” according to their main alloying elements. Each series is identified by the first digit of the alloy number. For example, the “1xxx” (or “1000”) series includes aluminum of 99 percent or higher purity; the “2xxx” series includes aluminum alloys in which copper is the principal alloying element; and so on. The alloy series are explained in “Aluminum Standards and Data”, published by The Aluminum Association. Other alloy identification systems may be used in some other countries. (See also, Technical Appendix A.)

**Sheet**—A rolled product rectangular in cross section and form of thickness >0.0079 inch (over 0.20 mm) through 0.249 inch (6.3 mm), with sheared, slit or sawed edges. (Notes: When products are ordered to metric specifications using metric dimensions, sheet is defined as being >0.20 mm to ≤ 6 mm thick. Sheet was previously defined as being .006 to .249 inch (.15 to 6.3 mm) in thickness.)

**Single-stand mill**—A rolling mill with only one “stand” of rolls.

**Slab**—A semifinished product of rectangular cross-section hot rolled from ingot to about four inches thickness, suitable for further rolling.

**Soak**—In metallurgy, to maintain metal at a controlled elevated temperature for a sufficient time to achieve the purposes of a thermal treatment.

**Solution heat-treating**—Heating an alloy at a suitable elevated temperature for sufficient time to allow soluble constituents to enter into solid solution where they are retained in a supersaturated state after quenching.

**Special tolerance**—A tolerance other than “Standard.”

**Stabilization annealing**—Moderate-temperature heating of certain non-heat-treatable aluminum-magnesium alloys to stabilize their cold-worked mechanical and dimensional properties.

**Stand, rolling**—A structure which supports and controls a set of rolls.

**Standard Tolerances**—Tolerances broadly accepted by the aluminum industry and users of aluminum products as limits on acceptable deviations from nominal dimensions or other parameters. Standard tolerances are routinely applied unless non-standard tolerances are specified by agreement between supplier and purchaser. Standard tolerances for aluminum rolled products are presented in ANSI-H35.2, “American National Standard Dimensional Tolerances for Aluminum Mill Products”, and in “Aluminum Standards and Data”, both published by The Aluminum Association. (See also Technical Appendix D.)

**Strain**—A measure of the change in size or shape of a body under stress, referred to its original size or shape.

**Strain-hardening**—Modification of a metal structure by cold working resulting in an increase in strength and hardness with a corresponding loss of ductility.

**Stress**—Force per unit of area.

**Stress relief**—The reduction, by thermal or mechanical means, of internal residual stresses.

**Stretcher-leveling**—Flattening sheet or plate by mechanically gripping its ends and applying a controlled amount of stretching.

**Strip**—Continuous sheet.
**Table rolls**—motor-driven horizontal rollers which position an aluminum ingot or slab and transport it to a mill’s work rolls.

**Tandem mill**—Multiple rolling stands arranged in sequence and coordinated to apply successive thickness reductions to aluminum sheet during a single pass through.

**Temper**—The combination of mechanical properties, particularly strength, hardness and ductility, induced in a metal product by the thermal and/or mechanical treatments applied during its preparation.

**Tension leveling**—Flattening sheet by controlled flexing: usually by passing it in tension over an adjustable roll.

**Thermal treatment**—A very general term meaning any treatment in which heat is applied, usually to alter the mechanical properties of solid metal; it includes homogenizing or precipitation treatment of ingots to affect finished grain size or some other property.

**Tolerance**—Allowable deviation from a nominal or specified dimension or other parameter: the maximum deviation that may be expected in any individual piece.

**Two-high mill**—A rolling mill employing only its two work rolls.

**Ultrasonic inspection**—The non-destructive testing of rolled plate (or other products) by transmitting ultrasonic sound waves (frequencies above human hearing) through the tested product. Electronic comparison of the time differences between reflected waves can reveal internal flaws.

**Work-harden**—See “Strain-harden.”

**Work rolls**—In a rolling mill, the metal cylinders which grip the product, roll it between them and reduce its thickness.

**Work**—In metallurgy, to deform metal sufficiently to alter its metallurgical structure and consequently its mechanical properties.

**Wrought product**—A product which has been subjected to mechanical working. Rolling produces wrought products.
SELF-TEST QUESTIONS
SECTION 9: GLOSSARY

9.1 An anode is...
   a. a negative electrical pole.
   b. a positive electric pole.
   c. a type of natural mineral formation.
   d. an alloy which has been annealed.

9.2 In aluminum rolling, “bite” means...
   a. the clamping action of a stretcher-leveler.
   b. the cutting action of a slitter.
   c. the action of work rolls pulling metal into the roll gap.
   d. the amount of thickness reduction applied by a single mill stand.

9.3 “Controlled-atmosphere” annealing means carrying out the process...
   a. in a filtered natural-air atmosphere.
   b. in an oxygen-rich atmosphere.
   c. in a corrosive-gas atmosphere.
   d. in an inert-gas atmosphere.

9.4 “Ductility” means, roughly...
   a. tensile strength.
   b. ease of deformation.
   c. corrosion resistance.
   d. scratch-resistance.

9.5 In metallurgy, “grain” means...
   a. a hard particle trapped in an alloy.
   b. a rough pattern produced by improper rolling.
   c. a small region of uniform crystalline structure.
   d. a speck of metal that sticks to a work roll.

9.6 In rolling, “mill finish” is...
   a. the final condition of all rolled products.
   b. a general-purpose surface that meets most needs.
   c. a special surface finish requiring extra steps.
   d. rolling by a five-stand tandem mill.

9.7 “Strain” means...
   a. amount of force applied.
   b. percentage of thickness reduction.
   c. percentage of elongation.
   d. amount of change in shape per unit of stress.

9.8 “Stress” means...
   a. total amount of force applied.
   b. maximum force applied at any point.
   c. force applied per unit of area.
   d. force applied in tension.
   e. twisting force.

9.9 “Wrought” aluminum means a product which has been...
   a. cast under high pressure.
   b. solution heat treated and quenched.
   c. annealed in a controlled atmosphere.
   d. subjected to mechanical working.
   e. none of the above.
1. Scope

This standard provides systems for designating wrought aluminum and wrought aluminum alloys, aluminum and aluminum alloys in the form of castings and foundry ingot, and the tempers in which aluminum and aluminum alloy wrought products and aluminum alloy castings are produced. Specific limits for chemical compositions and for mechanical and physical properties to which conformance is required are provided by applicable product standards.

NOTE: A numerical designation assigned in conformance with this standard should only be used to indicate an aluminum or an aluminum alloy having chemical composition limits identical to those registered with The Aluminum Association and, for wrought aluminum and wrought aluminum alloys, with the signatories of the Declaration of Accord on an International Alloy Designation System for Wrought Aluminum and Wrought Aluminum Alloys.1

2. Wrought Aluminum and Aluminum Alloy Designation System1

A system of four-digit numerical designations is used to identify wrought aluminum and wrought aluminum alloys. The first digit indicates the alloy group as follows:

Aluminum, 99.00 percent and greater .................1xxx
Aluminum alloys grouped by major alloying elements 2 3 4
- Copper ......................................... 2xxx
- Manganese ..................................... 3xxx
- Silicon ....................................... 4xxx
- Magnesium ................................... 5xxx
- Magnesium and silicon ....................... 6xxx
- Zinc .......................................... 7xxx
- Other element ................................ 8xxx
- Unused series ................................ 9xxx

The designation assigned shall be in the 1xxx group whenever the minimum aluminum content is specified as 99.00 percent or higher. The alloy designation in the 2xxx through 8xxx groups is determined by the alloying element (Mg₂Si for 6xxx alloys) present in the greatest mean percentage, except in cases in which the alloy being registered qualifies as a modification or national variation of a previously registered alloy. If the greatest mean percentage is common to more than one alloying element, choice of group will be in order of group sequence Cu, Mn, Si, Mg, Mg₂Si, Zn or others.

The last two digits identify the aluminum alloy or indicate the aluminum purity. The second digit indicates modifications of the original alloy or impurity limits.
2.1 Aluminum

In the 1xxx group for minimum aluminum purities of 99.00 percent and greater, the last two of the four digits in the designation indicate the minimum aluminum percentage. These digits are the same as the two digits to the right of the decimal point in the minimum aluminum percentage when it is expressed to the nearest 0.01 percent. The second digit in the designation indicates modifications in impurity limits or alloying elements. If the second digit in the designation is zero, it indicates unalloyed aluminum having natural impurity limits; integers 1 through 9, which are assigned consecutively as needed, indicate special control of one or more individual impurities or alloying elements.

2.2 Aluminum Alloys

In the 2xxx through 8xxx alloy groups the last two of the four digits in the designation have no special significance but serve only to identify the different aluminum alloys in the group. The second digit in the alloy designation indicates alloy modifications. If the second digit in the designation is zero, it indicates the original alloy; integers 1 through 9, which are as signed consecutively, indicate alloy modifications. A modification of the original alloy is limited to any one or a combination of the following:

(a) Change of not more than the following amounts in arithmetic mean of the limits for an individual alloying element or combination of elements expressed as an alloying element or both.

<table>
<thead>
<tr>
<th>Arithmetic Mean of Limits for Alloying Elements in Original Alloy</th>
<th>Maximum Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up thru 1.0 percent</td>
<td>0.15</td>
</tr>
<tr>
<td>Over 1.0 thru 2.0 percent</td>
<td>0.20</td>
</tr>
<tr>
<td>Over 2.0 thru 3.0 percent</td>
<td>0.25</td>
</tr>
<tr>
<td>Over 3.0 thru 4.0 percent</td>
<td>0.30</td>
</tr>
<tr>
<td>Over 4.0 thru 5.0 percent</td>
<td>0.35</td>
</tr>
<tr>
<td>Over 5.0 thru 6.0 percent</td>
<td>0.40</td>
</tr>
<tr>
<td>Over 6.0 percent</td>
<td>0.50</td>
</tr>
</tbody>
</table>

To determine compliance when maximum and minimum limits are specified for a combination of two or more elements in one alloy composition, the arithmetic mean of such a combination is compared to the sum of the mean values of the same individual elements, or any combination thereof, in another alloy composition.

(b) Addition or deletion of not more than one alloying element with limits having an arithmetic mean of not more than 0.30 percent or addition or deletion of not more than one combination of elements expressed as an alloying element with limits having a combined arithmetic mean of not more than 0.40 percent.

(c) Substitution of one alloying element for another element serving the same purpose.

(d) Change in limits for impurities expressed singly or as a combination.

(e) Change in limits for grain refining elements.

(f) Maximum iron or silicon limits of 0.12 percent and 0.10 percent, or less, respectively, reflecting use of high purity base metal.

An alloy shall not be registered as a modification if it meets the requirements for a national variation.

2.3 Experimental Alloys

Experimental alloys are also designated in accordance with this system, but they are indicated by the prefix X. The prefix is dropped when the alloy is no longer experimental.

During development and before they are designated as experimental, new alloys are identified by serial numbers assigned by their originators. Use of the serial number is discontinued when the X number is assigned.

2.4 National Variations

National variations of wrought aluminum and wrought aluminum alloys registered by another country in accordance with this system are identified by a serial letter following the numerical designation. The serial letters are assigned internationally in alphabetical sequence starting with A but omitting I, O and Q.

A national variation has composition limits that are similar but not identical to those registered by an other country, with differences such as:

---

5 The aluminum content for unalloyed aluminum made by a refining process is the difference between 100.00 percent and the sum of all other metallic elements plus silicon present in amounts of 0.0010 percent or more, each expressed to the third decimal before determining the sum, which is rounded to the second decimal before subtracting; for unalloyed aluminum not made by a refining process it is the difference between 100.00 percent and the sum of all other analyzed metallic elements plus silicon present in amounts of 0.0010 percent or more, each expressed to the second decimal before determining the sum. For unalloyed aluminum made by a refining process, when the specified maximum limit is 0.0XX, an observed value or a calculated value greater than 0.0005 but less than 0.0010% is rounded off and shown as “less than 0.01”; for alloys and unalloyed aluminum made by a refining process, when the specified maximum limit is 0.XX, an observed value or a calculated value greater than 0.005 but less than 0.010% is rounded off and shown as “less than 0.01”.
(a) Change of not more than the following amounts in arithmetic mean of the limits for an individual alloying element or combination of elements expressed as an alloying element, or both:

<table>
<thead>
<tr>
<th>Alloy or Modification</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up thru 1.0 percent</td>
<td>0.15</td>
</tr>
<tr>
<td>Over 1.0 thru 2.0 percent</td>
<td>0.20</td>
</tr>
<tr>
<td>Over 2.0 thru 3.0 percent</td>
<td>0.25</td>
</tr>
<tr>
<td>Over 3.0 thru 4.0 percent</td>
<td>0.30</td>
</tr>
<tr>
<td>Over 4.0 thru 5.0 percent</td>
<td>0.35</td>
</tr>
<tr>
<td>Over 5.0 thru 6.0 percent</td>
<td>0.40</td>
</tr>
<tr>
<td>Over 6.0 percent</td>
<td>0.50</td>
</tr>
</tbody>
</table>

To determine compliance when maximum and minimum limits are specified for a combination of two or more elements in one alloy composition, the arithmetic mean of such a combination is compared to the sum of the mean values of the same individual elements, or any combination thereof, in another alloy composition.

(b) Substitution of one alloying element for another element serving the same purpose.

(c) Different limits on impurities except for low iron. Iron maximum of 0.12 percent, or less, reflecting high purity base metal, should be considered as an alloy modification.

(d) Different limits on grain refining elements.

(e) Inclusion of a minimum limit for iron or silicon, or both.

Wrought aluminum and wrought aluminum alloys meeting these requirements shall not be registered as a new alloy or alloy modification.

3. Cast Aluminum and Aluminum Alloy Designation System ¹

A system of four digit numerical designations is used to identify aluminum and aluminum alloys in the form of castings and foundry ingot. The first digit indicates the alloy group as follows:

Appended is a table showing the arithmetic mean of the limits for alloying elements.

The alloy group in the 2xx.x through 9xx.x excluding 6xx.x alloys is determined by the alloying element present in the greatest mean percentage, except in cases in which the alloy being registered qualifies as a modification of a previously registered alloy. If the greatest mean percentage is common to more than one alloying element, the alloy group will be determined by the sequence shown above.

The second two digits identify the aluminum alloy or indicate the aluminum purity. The last digit, which is separated from the others by a decimal point, indicates the product form: that is, castings or ingot. A modification of the original alloy or impurity limits is indicated by a serial letter before the numerical designation. The serial letters are assigned in alphabetic sequence starting with A but omitting I, O, Q and X, the X being reserved for experimental alloys.

A modification of the original alloy is limited to any one or a combination of the following:

(a) Change of not more than the following amounts in the arithmetic mean of the limits for an individual alloying element or combination of elements expressed as an alloying element or both:

<table>
<thead>
<tr>
<th>Alloy or Modification</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up thru 1.0 percent</td>
<td>0.15</td>
</tr>
<tr>
<td>Over 1.0 thru 2.0 percent</td>
<td>0.20</td>
</tr>
<tr>
<td>Over 2.0 thru 3.0 percent</td>
<td>0.25</td>
</tr>
<tr>
<td>Over 3.0 thru 4.0 percent</td>
<td>0.30</td>
</tr>
<tr>
<td>Over 4.0 thru 5.0 percent</td>
<td>0.35</td>
</tr>
<tr>
<td>Over 5.0 thru 6.0 percent</td>
<td>0.40</td>
</tr>
<tr>
<td>Over 6.0 percent</td>
<td>0.50</td>
</tr>
</tbody>
</table>

To determine compliance when maximum and minimum limits are specified for a combination of two or more elements in one alloy composition, the arithmetic mean of such a combination is compared...
to the sum of the mean values of the same individual elements, or any combination thereof, in another alloy composition.

(b) Addition or deletion of not more than one alloying element with limits having an arithmetic mean of not more than 0.30 percent or addition or deletion of not more than one combination of elements expressed as an alloying element with limits having a combined arithmetic mean of not more than 0.40 percent.

(c) Substitution of one alloying element for another element serving the same purpose.

(d) Change in limits for impurities expressed singly or as a combination.

(e) Change in limits for grain refining elements.

(f) Iron or silicon maximum limits of 0.12 percent and 0.10 percent, or less, respectively, reflecting use of high purity base metal.

3.1 Aluminum Castings and Ingot

In the 1xx.x group for minimum aluminum purities of 99.00 percent and greater, the second two of the four digits in the designation indicate the minimum aluminum percentage. These digits are the same as the two digits to the right of the decimal point in the minimum aluminum percentage when it is expressed to the nearest 0.01 percent. The last digit, which is to the right of the decimal point, indicates the product form: 1xx.0 indicates castings, and 1xx.1 indicates ingot.

3.2 Aluminum Alloy Castings and Ingot

In the 2xx.x through 9xx.x alloy groups the second two of the four digits in the designation have no special significance but serve only to identify the different aluminum alloys in the group. The last digit, which is to the right of the decimal point, indicates the product form: xxx.0 indicates castings, xxx.1 indicates ingot that has chemical composition limits conforming to 3.2.1, and xxx.2 indicates ingot that has chemical composition limits that differ but fall within the limits of xxx.1 ingot.

3.2.1 Limits for alloying elements and impurities for xxx.1 ingot are the same as for the alloy in the form of castings, except for the following:

Maximum Iron Percentage:

<table>
<thead>
<tr>
<th>For Sand and Permanent Mold Castings</th>
<th>For Ingot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up thru 0.15 ..........................</td>
<td>0.03 less than castings</td>
</tr>
<tr>
<td>Over 0.15 thru 0.25 ..................</td>
<td>0.05 less than castings</td>
</tr>
<tr>
<td>Over 0.25 thru 0.6 ...................</td>
<td>0.10 less than castings</td>
</tr>
<tr>
<td>Over 0.6 thru 1.0 ....................</td>
<td>0.2 less than castings</td>
</tr>
<tr>
<td>Over 1.0 .............................</td>
<td>0.3 less than castings</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>For Die Castings</th>
<th>For Ingot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up thru 1.3 ........</td>
<td>0.3 less than castings</td>
</tr>
<tr>
<td>Over 1.3 ..........</td>
<td>1.1 maximum</td>
</tr>
</tbody>
</table>

Minimum Magnesium Percentage:

<table>
<thead>
<tr>
<th>For All Castings</th>
<th>For Ingot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 0.50 ........</td>
<td>0.05 more than castings*</td>
</tr>
<tr>
<td>0.50 and greater ....</td>
<td>0.1 more than castings*</td>
</tr>
</tbody>
</table>

Maximum Zinc Percentage:

<table>
<thead>
<tr>
<th>For Die Castings</th>
<th>For Ingot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over 0.25 thru 0.6 ..........................</td>
<td>0.10 less than castings</td>
</tr>
<tr>
<td>Over 0.6 .................................</td>
<td>0.1 less than castings</td>
</tr>
</tbody>
</table>

*Applicable only if the resulting magnesium range is 0.15 percent or greater.

3.3 Experimental Alloys

Experimental alloys are also designated in accordance with this system, but they are indicated by the prefix X. The prefix is dropped when the alloy is no longer experimental.

During development and before they are designated as experimental, new alloys are identified by serial numbers assigned by their originators. Use of the serial number is discontinued when the X number is assigned.
4. Temper Designation System

The temper designation system is used for all forms of wrought and cast aluminum and aluminum alloys excepting ingot. It is based on the sequences of basic treatments used to produce the various tempers. The temper designation follows the alloy designation, the two being separated by a hyphen. Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter. These designate specific sequences of basic treatments, but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added to the designation.

4.1 Basic Temper Designations

**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.

**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.

**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 1/2 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.

4.2 Subdivisions of Basic Tempers

4.2.1 Subdivision of H Temper: Strain-hardened

4.2.1.1 The first digit following the H indicates the specific combination of basic operations, as follows:

**H1** strain-hardened only. Applies to products that are strain-hardened to obtain the desired strength without supplementary thermal treatment. The number following this designation indicates the degree of strain-hardening.

**H2** strain-hardened and partially annealed. Applies to products that are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. For alloys that age-soften at room temperature, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H3 tempers. For other alloys, the H2 tempers have the same minimum ultimate tensile strength as the corresponding H1 tempers and slightly higher elongation. The number following this designation indicates the degree of strain-hardening remaining after the product has been partially annealed.

**H3** strain-hardened and stabilized. Applies to products that are strain-hardened and whose mechanical properties are stabilized either by a low temperature thermal treatment or as a result of heat introduced during fabrication. Stabilization usually improves ductility. This
designation is applicable only to those alloys that, unless stabilized, gradually age-soften at room temperature. The number following this designation indicates the degree of strainhardening remaining after the stabilization treatment.

**H4** strain-hardened and lacquered or painted. Applies to products which are strain-hardened and which are subjected to some thermal operation during the subsequent painting or lacquering operation. The number following this designation indicates the degree of strain-hardening remaining after the product has been thermal-ly treated, as part of painting/lacquering cure operation. The corresponding H2X or H3X mechanical property limits apply.

### 4.2.1.2 The digit following the designation H1, H2, H3, and H4 indicates the degree of strain-hardening as identified by the minimum value of the ultimate tensile strength. Numeral 8 has been assigned to the hardest tempers normally produced. The minimum tensile strength of tempers HX8 may be determined from Table 1 and is based on the minimum tensile strength of the alloy in the annealed temper. However, temper registrations prior to 1992 that do not conform to the requirements of Table 1 shall not be revised and registrations of intermediate or modified tempers for such alloy/temper systems shall conform to the registration requirements that existed prior to 1992.

#### Table 1

<table>
<thead>
<tr>
<th>US Customary Units</th>
<th>Metric Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum tensile strength in annealed temper</td>
<td>Minimum tensile strength to HX8 temper</td>
</tr>
<tr>
<td>ksi</td>
<td>MPa</td>
</tr>
<tr>
<td>up to 6</td>
<td>8</td>
</tr>
<tr>
<td>7 to 9</td>
<td>9</td>
</tr>
<tr>
<td>10 to 12</td>
<td>10</td>
</tr>
<tr>
<td>13 to 15</td>
<td>11</td>
</tr>
<tr>
<td>16 to 18</td>
<td>12</td>
</tr>
<tr>
<td>19 to 24</td>
<td>13</td>
</tr>
<tr>
<td>25 to 30</td>
<td>14</td>
</tr>
<tr>
<td>31 to 36</td>
<td>15</td>
</tr>
<tr>
<td>37 to 42</td>
<td>16</td>
</tr>
<tr>
<td>43 and over</td>
<td>17</td>
</tr>
</tbody>
</table>

Tempers between O (annealed) and HX8 are designated by numerals 1 through 7.

—Numeral 4 designates tempers whose ultimate tensile strength is approximately midway between that of the O temper and that of the HX8 tempers;

—Numeral 2 designates tempers whose ultimate tensile strength is approximately midway between that of the O temper and that of the HX4 tempers;

—Numeral 6 designates tempers whose ultimate tensile strength is approximately midway between that of the HX4 tempers and that of the HX8 tempers;

—Numerals 1, 3, 5 and 7 designate, similarly, tempers intermediate between those defined above.

—Numeral 9 designates tempers whose minimum ultimate tensile strength exceeds that of the HX8 tempers by 2 ksi or more. (For Metric Units by 10 MPa or more).

The ultimate tensile strength of the odd numbered intermediate (-HX1, -HX3, -HX5, and HX7) tempers, determined as described above, shall be rounded to the nearest multiple of 0.5 ksi. (For Metric Units when not ending in 0 or 5, shall be rounded to the next higher 0 or 5 MPa.)

### 4.2.1.3 The third digit, when used, indicates a variation of a two-digit temper. It is used when the degree of control of temper or the mechanical properties or both differ from, but are close to, that (or those) for the two-digit H temper designation to
which it is added, or when some other characteristic is significantly affected. (See Appendix for assigned three-digit H tempers.) NOTE: The minimum ultimate tensile strength of a three-digit H temper must be at least as close to that of the corresponding two-digit H temper as it is to the adjacent two-digit H tempers. Products in the H temper whose mechanical properties are below H__1 shall be variations of H__1.

4.2.2 Subdivision of T Temper: Thermally Treated

4.2.2.1 Numerals 1 through 10 following the T indicate specific sequences of basic treatments, as follows:

T1 cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition. Applies to products that are not cold worked after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T2 cooled from an elevated temperature shaping process, cold worked, and naturally aged to a substantially stable condition. Applies to products that are cold worked to improve strength after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T3 solution heat-treated, cold worked, and naturally aged to a substantially stable condition. Applies to products that are cold worked to improve strength after solution heat-treatment, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T4 solution heat-treated and naturally aged to a substantially stable condition. Applies to products that are not cold worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T5 cooled from an elevated temperature shaping process and then artificially aged. Applies to products that are not cold worked after cooling from an elevated temperature shaping process, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T6 solution heat-treated and then artificially aged. Applies to products that are not cold worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.

T7 solution heat-treated and overaged/stabilized. Applies to wrought products that are artificially aged after solution heat treatment to carry them beyond a point of maximum strength to provide control of some significant characteristic. Applies to cast products that are artificially aged after solution heat-treatment to provide dimensional and strength stability.

T8 solution heat-treated, cold worked, and then artificially aged. Applies to products that are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

T9 solution heat-treated, artificially aged, and then cold worked. Applies to products that are cold worked to improve strength.

T10 cooled from an elevated temperature shaping process, cold worked, and then artificially aged. Applies to products that are cold worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in mechanical property limits.

APPENDIX B 10B-3

7 Numerals 1 through 9 may be arbitrarily assigned as the third digit and registered with the Aluminum Association for an alloy and product to indicate a variation of a two-digit H temper (see note Y).

8 A period of natural aging at room temperature may occur between or after the operations listed for the T tempers. Control of this period is exercised when it is metallurgically important.

9 Solution heat treatment is achieved by heating cast or wrought products to a suitable temperature, holding at that temperature long enough to allow constituents to enter into solid solution and cooling rapidly enough to hold the constituents in solution. Some 6xxx series alloys attain the same specified mechanical properties whether furnace solution heat treated or cooled from an elevated temperature shaping process at a rate rapid enough to hold the constituents in solution. In such cases the temper designations T3, T4, T6, T7, T8, and T9 are used to apply to either process and are appropriate designations.

10 For this purpose, characteristic is something other than mechanical properties. The test method and limit used to evaluate material for this characteristic are specified at the time of the temper registration.
4.2.2.2 Additional digits, the first of which shall not be zero, may be added to designations T1 through T10 to indicate a variation in treatment that significantly alters the product characteristics that are or would be obtained using the basic treatment. (See Appendix for specific additional digits for T tempers.)

4.3 Variations of O Temper: Annealed

4.3.1 A digit following the O, when used, indicates a product in the annealed condition having special characteristics.

NOTE: As the O temper is not part of the strain-hardened (H) series, variations of O temper shall not apply to products that are strain-hardened after annealing and in which the effect of strain-hardening is recognized in the mechanical properties or other characteristics.

A1 Three-Digit H Tempers

A1.1 The following three-digit H temper designations have been assigned for wrought products in all alloys:

H_11 Applies to products that incur sufficient strain hardening after the final anneal that they fail to qualify as annealed but not so much or so consistent an amount of strain hardening that they qualify as H_1.

H112 Applies to products that may acquire some temper from working at an elevated temperature and for which there are mechanical property limits.

A1.2 The following three-digit H temper designations have been assigned for pattern or embossed sheet fabricated from:

<table>
<thead>
<tr>
<th>Pattern or Embossed Sheet</th>
<th>Fabricated From</th>
</tr>
</thead>
<tbody>
<tr>
<td>H114</td>
<td>O temper</td>
</tr>
<tr>
<td>H124, H224, H324</td>
<td>H11, H21, H31 temper, respectively</td>
</tr>
<tr>
<td>H134, H234, H334</td>
<td>H12, H22, H32 temper, respectively</td>
</tr>
<tr>
<td>H144, H244, H344</td>
<td>H13, H23, H33 temper, respectively</td>
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<td>H154, H254, H354</td>
<td>H14, H24, H34 temper, respectively</td>
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<td>H15, H25, H35 temper, respectively</td>
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<td>H174, H274, H374</td>
<td>H16, H26, H36 temper, respectively</td>
</tr>
<tr>
<td>H184, H284, H384</td>
<td>H17, H27, H37 temper, respectively</td>
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<tr>
<td>H194, H294, H394</td>
<td>H18, H28, H38 temper, respectively</td>
</tr>
<tr>
<td>H195, H295, H395</td>
<td>H19, H29, H39 temper, respectively</td>
</tr>
</tbody>
</table>

A1.3 The following three-digit H temper designations have been assigned only for wrought products in the 5xxx series, for which the magnesium content is 3% nominal or more:

H116 Applies to products manufactured from alloys in the 5xxx series, for which the magnesium content is 3% nominal or more. Products are strain hardened at the last operation to specified stable tensile property limits and meet specified levels of corrosion resistance in accelerated type corrosion tests. They are suitable for continuous service at temperature no greater than 150°F (66°C). Corrosion tests include inter-granular and exfoliation.

H321 Applies to products from alloys in the 5xxx series, for which the magnesium content is 3% nominal or more. Products are thermally stabilized at the last operation to specified stable tensile property limits and meet specified levels of corrosion resistance in accelerated type corrosion tests. They are suitable for continuous service at temperatures no greater than 150°F (66°C). Corrosion tests include inter-granular and exfoliation.

A2 Additional Digits for T Tempers

A2.1 The following specific additional digits have been assigned for stress-relieved tempers of wrought products:

Stress relieved by stretching.

T_51 Applies to plate and rolled or cold-finished rod or bar, die or ring forgings and rolled rings when stretched the indicated amounts after solution heat treatment or after cooling from an elevated temperature shaping process. The products receive no further straightening after stretching.

Plate ........... 1.5% to 3% permanent set.

Rolled or Cold-Finished Rod and Bar ......... 1% to 3% permanent set.

Die or Ring Forgings and Rolled Rings ......... 1% to 5% permanent set.

T_510 Applies to extruded rod, bar, profiles (shapes) and tube and to drawn tube when stretched the indicated amounts after solution heat treatment or after cooling from an elevated temperature shaping process. These products receive no further straightening after stretching.

Extruded Rod

Bar, Profiles (Shapes) and Tube ........... 1% to 3% permanent set.

Drawn Tube ........ 1/2% to 3% permanent set.

Additional digits may be arbitrarily assigned and registered with The Aluminum Association for an alloy and product to indicate a variation of tempers T1 through T10 even though the temper representing the basic treatment has not been registered (see note 6). Variations in treatment that do not alter the characteristics of the product are considered alternate treatments for which additional digits are not assigned.
A2.2 Temper Designations for Producer/Supplier Laboratory Demonstration of Response to Heat-treatment:

The following temper designations have been assigned for wrought products test material, furnace heat-treated from annealed (O, O1, etc.) or F temper, to demonstrate response to heat-treatment.

T42 Solution heat-treated from annealed or F temper and naturally aged to a substantially stable condition.

T62 Solution heat-treated from annealed or F temper and artificially aged.

T7.2 Solution heat-treated from annealed or F temper and artificially overaged to meet the mechanical properties and corrosion resistance limits of the T7.2 temper.

A2.3 Temper Designations for Producer/Supplier Demonstration of Response to Temper Conversion:

Temper designation T2 shall be used to indicate wrought product test material, which has undergone furnace heat-treatment for capability demonstration of temper conversion. When the purchaser requires capability demonstrations from T-temper, the seller shall note “Capability Demonstration” adjacent to the specified and ending tempers. Some examples are:

- “-T3 to -T82 Capability Demonstration for response to aging”;
- “-T4 to -T62 Capability Demonstration for response to aging”;
- “-T4 to -T762 Capability Demonstration for response to overaging”;
- “-T6 to -T732 Capability Demonstration for response to overaging”;
- “-T351 to -T42 Capability Demonstration for response to re-solution heat-treatment”.

A2.4 Temper Designation for Purchaser/User Heat-treatment

Temper designation T2 should also be applied to wrought products heat-treated by the purchaser/user, in accordance with the applicable heat treatment specification, to achieve the properties applicable to the final temper.

A3 Assigned O Temper Variations

A3.1 The following temper designation has been assigned for wrought products high temperature annealed to accentuate ultrasonic response and provide dimensional stability.

O1 Thermally treated at approximately same time and temperature required for solution heat treatment and slow cooled to room temperature. Applicable to products that are to be machined prior to solution heat treatment by the user. Mechanical property limits are not applicable.
A4 Designation of Unregistered Tempers

A4.1 The letter P has been assigned to denote H, T and O temper variations that are negotiated between manufacturer and purchaser. The letter P immediately follows the temper designation that most nearly pertains. Specific examples where such designation may be applied include the following:

A4.1.1 The use of the temper is sufficiently limited so as to preclude its registration. (Negotiated H temper variations were formerly indicated by the third digit zero.)

A4.1.2 The test conditions (sampling location, number of samples, test specimen configuration, etc.) are different from those required for registration with The Aluminum Association.

A4.1.3 The mechanical property limits are not established on the same basis as required for registration with The Aluminum Association.

A4.1.4 For products such as Aluminum Metal Matrix Composites which are not included in any registration records.
Metallurgical Aspects

In high-purity form aluminum is soft and ductile. Most commercial uses, however, require greater strength than pure aluminum affords. This is achieved in aluminum first by the addition of other elements to produce various alloys, which singly or in combination impart strength to the metal. Further strengthening is possible by means that classify the alloys roughly into two categories, non-heat-treatable and heat-treatable.

Non-heat-treatable alloys—The initial strength of alloys in this group depends upon the hardening effect of elements such as manganese, silicon, iron and magnesium, singly or in various combinations. The non-heat-treatable alloys are usually designated, therefore, in the 1xxx, 3xxx, 4xxx, or 5xxx series. Since these alloys are work-harden, further strengthening is made possible by various degrees of cold working, denoted by the “H” series of tempers. Alloys containing appreciable amounts of magnesium when supplied in strain-hardened tempers are usually given a final elevated-temperature treatment called stabilizing to ensure stability of properties.

Heat-treatable alloys—The initial strength of alloys in this group is enhanced by the addition of alloying elements such as copper, magnesium, zinc, and silicon. Since these elements singly or in various combinations show increasing solid solubility in aluminum with increasing temperature, it is possible to subject them to thermal treatments that will impart pronounced strengthening.

The first step, called heat treatment or solution heat treatment, is an elevated-temperature process designed to put the soluble element or elements in solid solution. This is followed by rapid quenching, usually in water, which momentarily “freezes” the structure and for a short time renders the alloy very workable. It is at this stage that some fabricators retain this more workable structure by storing the alloys at low freezing temperatures until they are ready to form them. At room or elevated temperatures the alloys are not stable after quenching, however, and precipitation of the constituents from the super-saturated solution begins. After a period of several days at room temperature, termed aging or room-temperature precipitation, the alloy is considerably stronger. Many alloys approach a stable condition at room temperature, but some alloys, particularly those containing magnesium and silicon or magnesium and zinc, continue to age-harden for long periods of time at room temperature.

By heating for a controlled time at slightly elevated temperatures, even further strengthening is possible and properties are stabilized. This process is called artificial aging or precipitation hardening. By the proper combination of solution heat treatment, quenching, cold working and artificial aging, the highest strengths are obtained.

Clad alloys—The heat-treatable alloys in which copper or zinc are major alloying constituents are less resistant to corrosive attack than the majority of non-heat-treatable alloys. To increase the corrosion resistance of these alloys in sheet and plate form, they are often clad with high-purity aluminum, a low magnesium-silicon alloy, or an alloy containing 1 percent zinc. The cladding, usually from 2.5 percent to 5 percent of the total thickness on each side, not only protects the composite due to its own inherently excellent corrosion resistance but also exerts a galvanic effect, which further protects the core material.

Special composites may be obtained such as clad nonheat-treatable alloys for extra corrosion protection, for brazing purposes, or for special surface finishes. Some alloys in wire and tubular form are clad for similar reasons, and on an experimental basis extrusions also have been clad.

Annealing characteristics—All wrought aluminum alloys are available in annealed form. In addition, it may be desirable to anneal an alloy from any other initial temper, after working, or between successive stages of working such as in deep drawing.

Effect of Alloying Elements

1xxx series—Aluminum of 99 percent or higher purity has many applications, especially in the
electrical and chemical fields. These compositions are characterized by excellent corrosion resistance, high thermal and electrical conductivity, low mechanical properties and excellent workability. Moderate increases in strength may be obtained by strain-hardening. Iron and silicon are the major impurities.

2xxx series—Copper is the principal alloying element in this group. These alloys require solution heat-treatment to obtain optimum properties; in the heat treated condition mechanical properties are similar to, and sometimes exceed, those of mild steel. In some instances artificial aging is employed to further increase the mechanical properties. This treatment materially increases yield strength, with attendant loss in elongation; its effect on tensile (ultimate) strength is not so great. The alloys in the 2xxx series do not have as good corrosion resistance as most other aluminum alloys, and under certain conditions they may be subject to intergranular corrosion. Therefore, these alloys in the form of sheet are usually clad with a high-purity alloy or a magnesium-silicon alloy of the 6xxx series, which provides galvanic protection to the core material and thus greatly increases resistance to corrosion. Alloy 2024 is perhaps the best known and most widely used aircraft alloy.

3xxx series—Manganese is the major alloying element of alloys in this group, which are generally non-heat-treatable. Because only a limited percentage of manganese, up to about 1.5 percent, can be effectively added to aluminum, it is used as a major element in only a few instances. One of these, however, is the popular 3003, which is widely used as a general purpose alloy for moderate-strength applications requiring good workability.

4xxx series—The major alloying element of this group is silicon, which can be added in sufficient quantities to cause substantial lowering of the melting point without producing brittleness in the resulting alloys. For these reasons aluminum-silicon alloys are used in welding wire and as brazing alloys where a lower melting point than that of the parent metal is required. Most alloys in this series are non-heat-treatable, but when used in welding heat-treatable alloys they will pick up some of the alloying constituents of the latter and so respond to heat treatment to a limited extent. The alloys containing appreciable amounts of silicon become dark grey when anodic oxide finishes are applied, and hence are in demand for architectural applications.

5xxx series—Magnesium is one of the most effective and widely used alloying elements for aluminum. When it is used as the major alloying element or with manganese, the result is a moderate to high strength non-heat-treatable alloy. Magnesium is considerably more effective than manganese as a hardener, about 0.8 percent magnesium being equal to 1.25 percent manganese, and it can be added in considerably higher quantities. Alloys in this series possess good welding characteristics and good resistance to corrosion in marine atmosphere. However, certain limitations should be placed on the amount of cold work and on the safe operating temperatures permissible for the higher magnesium content alloys (over about 3.5 percent for operating temperatures above about 150°F) to avoid susceptibility to stress corrosion.

6xxx series—Alloys in this group contain silicon and magnesium in approximate proportions to form magnesium silicide, thus making them heat-treatable. The major alloy in this series is 6061, one of the most versatile of the heat-treatable alloys. Though less strong than most of the 2xxx or 7xxx alloys, the magnesium-silicon (or magnesium-silicide) alloys possess good formability and corrosion resistance, with medium strength. Alloys in this heat-treatable group may be formed in the T4 temper (solution heat-treated but not artificially aged) and then reach full T6 properties by artificial aging.

7xxx series—Zinc is the major alloying element in this group, and when coupled with a smaller percentage of magnesium results in heat-treatable alloys of very high strength. Usually other elements such as copper and chromium are also added in small quantities. The outstanding member of this group is 7075, which is among the highest strength alloys available and is used in air-frame structures and for highly stressed parts.
2. Typical Properties

The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

### TABLE 2.1 Typical U.S. Mechanical Properties

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<tr>
<th>ALLOY AND TEMPER</th>
<th>TENSION</th>
<th>HARDNESS</th>
<th>SHEAR</th>
<th>FATIGUE</th>
<th>MODULUS OF ELASTICITY</th>
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<td>STRENGTH ksi</td>
<td>ELONGATION percent in 2 in.</td>
<td>BRINELL NUMBER</td>
<td>ULTIMATE SHEARING STRENGTH ksi</td>
<td>ENDURANCE Limit ksi</td>
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<td>YIELD</td>
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<td>1/4 in. Diameter Specimen</td>
<td>500 kg load 10 mm ball</td>
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The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

### TABLE 2.1 Typical U.S. Mechanical Properties

The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

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For all numbered footnotes, see page 10C-6.
TABLE 2.1 Typical U.S. Mechanical Properties\(^1\) (continued)

The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

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For all numbered footnotes, see page 10C-6.
TABLE 2.1 Typical Mechanical Properties

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1. The mechanical property limits are listed by major product in the “Standards Section” of this manual.
2. The indicated typical mechanical properties for all except 0 temper material are higher than the specified minimum properties. For 0 temper products typical ultimate and yield values are slightly lower than specified (maximum) values.
3. Based on 500,000,000 cycles of completely reversed stress using the R.R. Moore type of machine and specimen.
4. Average of tension and compression modulus. Compression modulus is about 2% greater than tension modulus.
5. 1350-O wire will have an elongation of approximately 23% in 10 inches.
6. 1350-H19 wire will have an elongation of approximately 1½% in 10 inches.
7. Temper T631 and T651 were formerly designated T36 and T96, respectively.
8. Based on 1/4 in. thick specimen.
9. Based on 10⁷ cycles using flexural type testing of sheet specimens.
10. T7451, although not previously registered, has appeared in literature and in some specifications as T73651.
11. 5xxx products in the +H16 and +H32X tempers have similar properties and have the same testing requirements, but are produced by different practices. The -H16 and -H321 tempers are typically used in marine and other applications requiring demonstrations of intergranular and exfoliation corrosion resistance. Products in the -H32 temper have similar tensile properties and while production methods may be similar, corrosion testing requirements are different, therefore, -H32 temper products shall not be substituted for +H16 or +H321 products.
TABLE 2.3 Typical Physical Properties

The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

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<th>THERMAL CONDUCTIVITY AT 77°F</th>
<th>ELECTRICAL CONDUCTIVITY AT 68°F</th>
<th>ELECTRICAL RESISTIVITY AT 68°F</th>
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For all numbered footnotes, see page 10C-8.
### TABLE 2.3 Typical Physical Properties (concluded)

The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

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<th>MELTING RANGE APPROX.</th>
<th>TEMPER</th>
<th>THERMAL CONDUCTIVITY AT 77°F</th>
<th>ELECTRICAL CONDUCTIVITY AT 68°F Percent of International Annealed Copper Standard</th>
<th>ELECTRICAL RESISTIVITY AT 68°F</th>
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<td>单位</td>
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① Coefficient to be multiplied by 10-6. Example: 12.2 × 10-6 = 0.0000122.
② Melting ranges shown apply to wrought products of ¼ inch thickness or greater.
③ Based on typical composition of the indicated alloys.
④ English units = btu-in./ft2hr°F.
⑤ Eutectic melting is not eliminated by homogenization.
⑥ Eutectic melting can be completely eliminated by homogenization.
⑦ Homogenization may raise eutectic melting temperature 20–40°F but usually does not eliminate eutectic melting.
⑧ Although not formerly registered, the literature and some specifications have used T736 as the designation for this temper.
The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

### TABLE 2.1m Typical Metric Mechanical Properties\(^1,2\)

For all numbered footnotes, see page 10C-12.

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<th>ALLOY AND TEMPER</th>
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<th>ELONGATION Percent</th>
<th>HARDNESS</th>
<th>SHEAR STRENGTH</th>
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<th>MODULI OF ELASTIC MPa x 1</th>
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The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

### TABLE 2.1m Typical Metric Mechanical Properties

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For all numbered footnotes, see page 10C-12.
TABLE 2.1m Typical Metric Mechanical Properties\(^{(1,2)}\) (continued)

The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

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For all numbered footnotes, see page 10C-12.
The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

### TABLE 2.1m Typical Metric Mechanical Properties\(^1,2\) (continued)

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1. The mechanical property limits are listed by major product in the “Standards Section” of this manual.
2. The indicated typical mechanical properties for all except 0 temper material are higher than the specified minimum properties. For 0 temper products typical ultimate and yield values are slightly lower than specified (maximum) values.
3. Based on 500,000,000 cycles of completely reversed stress using the R.R. Moore type of machine and specimen.
4. Average of tension and compression modulus. Compression modulus is about 2% greater than tension modulus.
5. 1350-O wire will have an elongation of approximately 23% in 250 mm.
6. 1350-H19 wire will have an elongation of approximately 15% in 250 mm.
7. Tempers T361 and T861 were formerly designated T36 and T86, respectively.
8. Based on 6.3 mm. thick specimen.
9. Based on 10^7 cycles using flexural type testing of sheet specimens.
10. T7451, although not previously registered, has appeared in literature and in some specifications as T73651.
11. 3xxx products in the -H116 and +H321 tempers have similar properties and have the same testing requirements, but are produced by different practices. The -H116 and +H321 tempers are typically used in marine and other applications requiring demonstration of intergranular and exfoliation corrosion resistance. Products in the +H32 temper have similar tensile properties and while production methods may be similar, corrosion testing requirements are different; therefore, +H32 temper products shall not be substituted for -H116 or +H321 products.
The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

**TABLE 2.3m Typical Metric Physical Properties**

The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

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For all numbered footnotes, see page 10C-14.
The following typical properties are not guaranteed, since in most cases they are averages for various sizes, product forms and methods of manufacture and may not be exactly representative of any particular product or size. These data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

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1. Coefficient to be multiplied by 10⁻⁶. Example: 23.6 × 10⁻⁶ = 0.0000236.
2. Melting ranges shown apply to wrought products of 6 mm thickness or greater.
3. Based on typical composition of the indicated alloys.
4. Eutectic melting is not eliminated by homogenization.
5. Eutectic melting can be completely eliminated by homogenization.
6. Homogenization may raise eutectic melting temperature 10–20°C but usually does not eliminate eutectic melting.
7. Although not formerly registered, the literature and some specifications have used T736 as the designation for this temper.
8. MS/m = 0.58 × IACS.
# APPENDIX A 10C-16

## TABLE 3.3 Comparative Characteristics and Applications

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<th>BRAZABILITY</th>
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# TABLE 3.3 Comparative Characteristics and Applications (continued)

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For all numbered footnotes, see page 10C-18.
# TABLE 3.3 Comparative Characteristics and Applications (continued)

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<td>A</td>
<td>Electrical conductors</td>
</tr>
</tbody>
</table>

For all numbered footnotes, see page 10C-18.
## TABLE 3.3 Comparative Characteristics and Applications (concluded)

### Notes for Table 3.3

1. Ratings A through E are relative ratings in decreasing order of merit, based on exposures to sodium chloride solution by intermittent spraying or immersion. Alloys with A and B ratings can be used in industrial and seacoast atmospheres without protection. Alloys with C, D, and E ratings generally should be protected at least on faying surfaces.
2. Stress-corrosion cracking ratings are based on service experience and on laboratory tests of specimens exposed to the 3.5% sodium chloride alternate immersion test.
   - A = No known instance of failure in service or in laboratory tests.
   - B = No known instance of failure in service; limited failures in laboratory tests of short transverse specimens.
   - C = Service failures with sustained tension stress acting in short transverse direction relative to grain structure; limited failures in laboratory tests of long transverse specimens.
   - D = Limited service failures with sustained longitudinal or long transverse areas.
   - These ratings are neither product specific nor test direction specific and therefore indicate only the general level of stress-corrosion cracking resistance. For more specific information on certain alloys, see ASTM G64.
3. In relatively thick sections the rating would be E.
4. This rating may be different for material held at elevated temperature for long periods.
5. Ratings A through D for Workability (cold), and A through E for Machinability, are relative ratings in decreasing order of merit.
6. Ratings A through D for Weldability and Brazability are relative ratings defined as follows:
   - A = Generally weldable by all commercial procedures and methods.
   - B = Weldable with special techniques or for specific applications that justify preliminary trials or testing to develop welding procedure and weld performance.
   - C = Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties.
   - D = No commonly used welding methods have been developed.
7. T74 type tempers, although not previously registered, have appeared in various literature and specifications as T736 type tempers.
8. Soxx products in the -H116 and H32X tempers have similar properties and have the same testing requirements, but are produced by different practices. The -H116 and +H321 tempers are typically used in marine and other applications requiring demonstrations of intergranular and exfoliation corrosion resistance. Products in the +H32 temper have similar tensile properties andwhile production methods may be similar, corrosion testing requirements are different, therefore, +H32 temper products shall not be substituted for -H116 or -H321 products.
To ensure high-quality products with dependable properties and dimensions, the aluminum industry has developed and adheres to standard limits and tolerances which are routinely applied to aluminum plate, sheet, and foil (and other wrought products).

These standards represent, for each of the tolerated characteristics, the range within which the relevant product is to be produced. In most instances, actual deviation from nominal dimensions is even smaller than the standard tolerances would allow.

If non-standard tolerances are desired, they must be negotiated specifically between vendor and purchaser.

Adherence to these product standards is voluntary, but they are broadly accepted by both the aluminum industry and its customers and often form the basis of tolerances incorporated in government, technical society and other specifications.

**Standard Dimensional Tolerances**

The Aluminum Association developed the industry’s first standard dimensional tolerances, for extruded and tubular products, in 1949 and then expanded its efforts, publishing its first standards for aluminum mill products in 1955.

In 1970, at the request of the Aluminum Association, the American National Standards Institute (ANSI) authorized establishment of Standards Committee H35 on Aluminum and Aluminum Alloys, which was redesignated in 1983 as the Accredited Standards Committee on Aluminum and Aluminum Alloys H35. It includes representatives of various branches of the aluminum industry, aluminum-using industries and the United States Government.

ANSI itself does not develop or interpret such standards; it accredits standards and revisions after verifying that they have been developed through appropriate consensus procedures.

The standard dimensional tolerances applied to aluminum sheet and plate include:

- **Length**, sheared flat sheet and plate.
- **Width**, slit coiled sheet.
- **Lateral bow**, coiled sheet.
- **Lateral bow**, flat sheet and plate.
- **Squareness**, flat sheet and plate.
- **Diameter**, sheared or blanked sheet and plate circles.
- **Diameter**, sawed sheet and plate circles.
- **Flatness**, flat sheet.
- **Flatness**, sawed or sheared plate.
- **Thickness**, for sheet and plate for aerospace alloys.

Standard tolerances are also provided for aluminum duct sheet, commercial roofing and siding, tread plate, and foil.


**Standard limits on Non-Dimensional Properties**

The Aluminum Association also issues “Standard Limits” applied voluntarily to non-dimensional properties of aluminum sheet, plate, and other wrought products, in its publications “Aluminum Standards and Data” and “Aluminum Standards and Data Metric SI” (Technical Publication #1).

These standards include:

- Chemical composition limits of wrought aluminum alloys.
- Ultrasonic discontinuity limits.
- Lot acceptance criteria for corrosion resistant tempers.
- Location for electrical conductivity measurements.
Fracture toughness limits.
Corrosion resistance test criteria.
Mechanical property limits- non-heat-treatable alloys (sheet and plate).
Mechanical property limits- heat-treatable alloys (sheet and plate).
Mechanical property limits- brazing sheet.
Weights per square foot (by sheet thickness).
Weight (/density) conversion factors (by alloy)
Recommended minimum bend radii for 90-degree cold forming of sheet and plate.

**Always Refer to Most Recent Revisions**

Both the US customary and metric editions of “Aluminum Standards and Data” (ASD) are periodically updated, revised and republished by The Aluminum Association. In addition to The Aluminum Association’s non-dimensional standards for wrought aluminum, ASD reprints the ANSI standard dimensional tolerances which may, however, be revised between updates of ASD; in those circumstances, the latest official ANSI-H35 standards take precedence over any earlier versions still in circulation.

Therefore, readers who wish to make use of the standards currently in effect are advised to refer to the most recent editions of “American National Standard Dimensional Tolerances for Aluminum Mill Products (ANSI-H35.2)” (or the metric version ANSI-H35.2M) for sheet, plate and foil dimensional tolerances; and “Aluminum Standards and Data” for non-dimensional wrought aluminum standards.

These publications are available from The Aluminum Association’s on-line bookstore at www.aluminum.org.
10.1 “Wrought aluminum alloys and cast aluminum alloys share the same alloy designation numbering system.” This statement is:
   a. true.
   b. false.

10.2 The aluminum temper designation system uses...
   a. only letters of the alphabet.
   b. only numbers.
   c. letters followed by numbers.
   d. numbers followed by letters.

10.3 The initial symbols of aluminum temper designations are...
   a. 1, 2, 3, 4, 5
   b. A, B, C, D, E
   c. A, S, D, F, G
   d. F, O, H, W, T
   e. the last line of a doctor's eye chart.

10.4 Alloy 1199 contains a minimum of...
   a. 99.00% aluminum.
   b. 99.90% aluminum.
   c. 99.99% aluminum.

10.5 Typical yield strength of alloy 2024-O is...
   a. 11 ksi (76 MPa)
   b. 20 ksi (138 MPa)
   c. 26 ksi (179 MPa)

10.6 Name five Standard Dimensional Tolerances applied to aluminum sheet and plate.

   ________________________________
   ________________________________
   ________________________________
   ________________________________
### SECTION 1: INTRODUCTION

1.1 Lightweight; strong; cold-resistant; ductile and workable; joinable; reflective; heat-conducting; electrically conducting; corrosion resistant; nontoxic; noncombustible; recyclable.

1.2 b.
1.3 c.
1.4 d.
1.5 c.
1.6 b.

1.7 See Sec.1
1.8 See Sec.1
1.9a c.
1.9b a.
1.10a b.
1.10b c.
1.11 c. Because flat-rolled aluminum products less than .008-inch thick are defined as foil.

1.12 d.
1.13 d.
1.14 c.
1.15 b.
1.16 c.

### SECTION 2: PRODUCTION

2.1 a.
2.2 c.
2.3 a.
2.4 b.
2.5 c.
2.6 c.
2.7 b.
2.8 b and/or c.
2.9 d.
2.10 b.
2.11 f.
2.12 c.
2.13 b.
2.14 b.
2.15 c.
2.16 a.
2.17 d.
2.18 a.
2.19 b.
2.20 b.
2.21 c.
2.22 d.
2.23 a.
2.24 b.
2.25 e.
2.26 b.
2.27 b.
2.28 a.
2.29 e.

### SECTION 3: PREPARATION

3.1 b.
3.2 c.
3.3 b.
3.4 b.
3.5 c.
3.6 e.
3.7 b.
3.8 Titanium, or boron salts.
3.9 c.
3.10 c.
3.11 b.
3.12 d.
3.13 c.
3.14 d.
SECTION 4: ROLLING MILL

4.1 c.
4.2 a.
4.3 e.
4.4 f.
4.5 b.
4.6 d.
4.7 b.
4.8 c.
4.9 b and c.
4.10 a.
4.11 a.
4.12 c.
4.13 d.
4.14 c.

5.18 b.
5.19 c.
5.20 a.
5.21 Strength, temper, thickness, finish, flatness, and profile.
5.22 c.
5.23 Roll tilting; roll crossing; localized roll cooling; roll-bending; stepped backup rolls; axial shifting of sleeved backup rolls; axial shifting of cylindrical work rolls; axial shifting of non-cylindrical work rolls; flexible backup rolls.
5.24 a.

SECTION 5: SHEET ROLLING

5.1 b.
5.2 d.
5.3 c.
5.4 c.
5.5 b. Because friction in the roll gap prevents the slab from spreading.
5.6 d.
5.7 b.
5.8 c.
5.9 d.
5.10 b and d.
5.11 a and d.
5.12 b.
5.13 Annealed.
5.14 a.
5.15 c.
5.16 c.
5.17 a.
5.18 b.
5.19 c.
5.20 a.
5.21 Strength, temper, thickness, finish, flatness, and profile.
5.22 c.
5.23 Roll tilting; roll crossing; localized roll cooling; roll-bending; stepped backup rolls; axial shifting of sleeved backup rolls; axial shifting of cylindrical work rolls; axial shifting of non-cylindrical work rolls; flexible backup rolls.
5.24 a.

SECTION 6: SHEET FINISHING

6.1 c.
6.2 b.
6.3 b.
6.4 a.
6.5 b.
6.6 b.
6.7 b.
6.8 Mechanical finishes, chemical finishes, and coatings.
6.9 c.

SECTION 7: PLATE ROLLING AND FINISHING

7.1 d.
7.2 a.
7.3 c.
7.4 b.
7.5 b.
7.6 d.
7.7 b.
7.8 a.
7.9 a.

SECTION 8: QUALITY AND PROCESS CONTROL

8.1 c.
8.2 b.
8.3  d.
8.4  d.
8.5  a.
8.6  c.

SECTION 9: GLOSSARY
9.1  b.
9.2  c.
9.3  d.
9.4  b.
9.5  c.
9.6  b.
9.7  d.
9.8  e.
9.9  d.

SECTION 10: TECHNICAL APPENDICES
10.1  b.
10.2  c.
10.3  d.
10.4  c.
10.5  a.
10.6  See Appendix D.
REFERENCES


Bachowiski, Ronald; O’ Mally, R.J.; and Mohajery, M.M., “Continuous Casters for Aluminum Mini-Sheet Mills-an Alcoa Perspective”, Light Metal Age, August 1989.


the Fourth Int’l Aluminum Extrusion Technology Seminar, 1988, pp. 79-84.
Church, Fred L., “Rolling mill improvements groomed for quality not tons”, Modern Metals, April 1989.
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