The Worldwide Aluminum Economy: The Current State of the Industry

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This article provides an overview and characterization of the worldwide aluminum industry and its importance to the world economy. It reviews the current state of the industry, addressing the complete process from primary production through aluminum products to recycling. Global markets for aluminum and the future challenges and directions of the industry are also discussed, and the historical milestones in the aluminum industry are noted.

INTRODUCTION

The aluminum industry makes a substantial contribution to the global economy and to many individual national economies in more than 30 countries. Forty-five million tonnes of semi-fabricated aluminum products are produced annually, including ~14 million tonnes from recycled aluminum. The aluminum industry directly employs more than one million people worldwide and indirectly generates four times as many jobs in downstream and service industries. [1–5]

For much of the industry's history, the United States was the largest producer of primary aluminum. Since 2000, however, the United States has dropped from the first to the fourth largest producer of aluminum, with China, Russia, and Canada emerging as the three largest producers (Figure 1). Despite the drop in production, the United States remains the largest consumer of aluminum. According to the U.S. Geological Survey (USGS) Minerals Yearbook, U.S. aluminum consumption in 2005 was 6.460 million tonnes.[1]

Aluminum has established a worldwide position because of its advantages over other competitive materials, including:

- Relatively high tensile, compression, and shear strengths
- Relatively light weight, providing exceptional unit strengths (strength/density ratio)
- Very high corrosion resistance, providing low maintenance costs
- Toughness, even in Arctic environments, providing freedom from brittle fracture
- Readily joined by all commercial processes such as welding, brazing, soldering, etc.
- Readily fabricated by all commercial processes, including extrusion (a major advantage)
- Readily recycled

See the sidebar for historical milstones in the aluminum industry.

PRIMARY METAL PRODUCTION

In primary aluminum production, deposits of bauxite ore are mined and refined into alumina—the feedstock for aluminum metal. Then, alumina and electricity are combined in a cell with molten cryolite electrolyte. Direct current electricity is passed from a consumable carbon anode into the cryolite, splitting the aluminum oxide into molten aluminum metal and carbon dioxide. The molten aluminum collects at the bottom of the cell and is periodically "tapped" into crucibles and cast into ingots. Through ongoing innovative research and development (R&D) efforts, the industry is constantly searching for areas in which energy consumption and cost can be reduced and ecological concerns addressed.

Bauxite Mining

There are numerous bauxite deposits, mainly in the tropical and subtropical regions; deposits in the United States

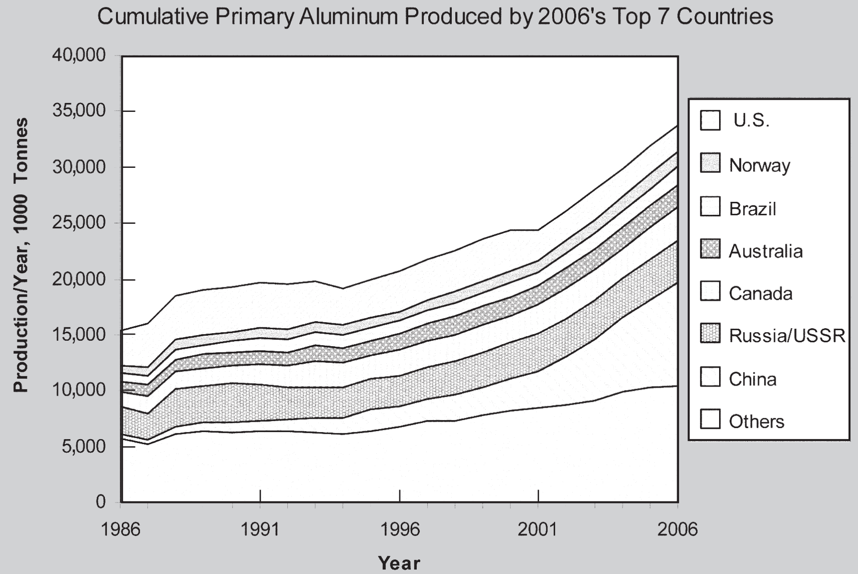

Figure 1. Primary aluminum production per year by the top seven nations in 2006.[1] In the United States, the aluminum industry operates more than 300 plants in 35 states, producing more than 10.4 million tonnes of metal annually and employing more than 145,000 people with an annual payroll of about $5 billion.

and Western Europe are now exhausted. Bauxite is generally extracted by open mining from strata, typically some 4–6-m thick under a shallow covering of topsoil and vegetation. In most cases the topsoil is removed and stored for ultimate restoration of the mine. Eighty percent of world bauxite production, mainly from large blanket-type deposits, is from surface mines; the remaining 20% is mainly from underground excavations.

Alumina Refining

The aluminum industry relies on the Bayer process to produce alumina from bauxite. It remains the most economic means of obtaining alumina, which in turn is vital for the production of aluminum metal—about 2 tonnes of alumina are required to produce 1 tonne of aluminum.

Bauxite is washed, ground, and dissolved in sodium hydroxide at high pressure and temperature. The resulting liquor contains a solution of sodium aluminate and undissolved bauxite residues containing iron, silicon, and titanium. These residues sink gradually to the bottom of the tank and are removed as red mud. Red mud is also removed by filtration.

The clear sodium aluminate solution is pumped into a chain of tanks known as precipitators. Fine seed particles of alumina are added to aid the precipitation of alumina particles as the liquor cools. The particles sink to the bottom of the tank, are removed, and are then passed through a rotary or fluidized calciner at 1,100°C to drive off the chemically combined water. The result is a white powder—alumina. The process for producing metallurgical-grade alumina from bauxite (known as the Bayer process) has changed little since the first plant opened in 1893, except for the enormous scale and process control sophistication.

Aluminum Smelting

The basis for all modern primary aluminum smelting plants is the Hall–Héroult process. Alumina is dissolved in an electrolytic bath of molten cryolite (sodium aluminum fluoride) within a large carbon- or graphite-lined steel container (electrolytic cell) known as a "pot." An electric current is passed through the electrolyte at low voltage but very high current, typically 180,000 amperes, although some modern cells operate at up to 500,000 amperes. The electric current flows between a carbon anode (positive), made of petroleum coke and pitch, and a cathode (negative), formed by the thick carbon or graphite lining of the pot.

Between the anode and the cathode is a space filled by an electrolyte composed of cryolite and other stable fluoride salts. This mixture must be heated to ~965°C, at which point it melts and the refined alumina is added; this then dissolves in the molten electrolyte. Molten aluminum is deposited at the bottom of the pot and is siphoned off periodically, taken to a holding furnace, often but not always blended to an alloy specification, cleaned, and then cast. Increasingly, molten aluminum is directly transported to a foundry to retain the incorporated heat energy.

Aluminum smelting is energy intensive, which is why smelters are located in areas that have access to abundant power resources (hydroelectric, natural gas, coal, or nuclear). Many locations are remote, and the electricity is generated specifically for the aluminum plant. However, between materials recovery and ongoing innovative R&D efforts, the aluminum industry is constantly searching for areas where energy and costs can be reduced. In the past two decades, the energy efficiency of the metal production has improved by about 20%. It takes ~16 kWh of electricity to produce 1 kg of aluminum from alumina.

FABRICATION PROCESSES AND PRODUCTS

Aluminum alloys are melted for conversion into casting finished or near-finished parts and ingots for subsequent fabrication by various processes. Accordingly, aluminum fabricated products can be divided into two major categories:

HISTORICAL MILESTONES IN THE ALUMINUM INDUSTRY

Aluminum is the third most abundant element in the earth's crust and constitutes 7.3% by mass. In nature, however, it only exists in very stable combinations with other elements (particularly as silicates and oxides) and it was not until 1808 that its existence was first established. It took many years of painstaking research to unlock the metal from its ore and many more years to produce a viable, commercial production process.

Aluminum has only been produced commercially for 146 years and is still a very young metal. Humans have been using copper, lead, and tin for thousands of years, and yet today more aluminum is produced than all other nonferrous metals combined. Key milestones of aluminum discovery and industrialization are given below.

1808

Sir Humphrey Davy in Britain was the first to produce small quantities of the metal and named the new element "aluminum." This term was then altered further to "aluminium" to agree with the "-ium" spelling that ended most of the element names. Today, the metal is called aluminium virtually everywhere in the world, except in the United States where it is called aluminum.

1821

P. Berthier in France discovered a hard, reddish, clay-like material containing 52% aluminum oxide near the village of Les Baux in southern France. He called it bauxite, the highest grade aluminum-containing ore produced by weathering clay-like minerals.

1886

Two unknown young scientists, Paul Louis Toussaint Héroult (Paris, France) and Charles Martin Hall (a student at Oberlin College, Ohio), working separately and unaware of the other's work, simultaneously invented a new electrolytic process, the Hall–Héroult process, which is the basis for all aluminum production today. They discovered that by dissolving aluminum oxide (alumina) in a bath of molten cryolite and passing a powerful electric current through it, molten aluminum is deposited at the bottom of the bath.

Large-scale industrial production of aluminum began in 1888 at about the same time in France, Switzerland, and the United States Because aluminum itself does not occur in nature as a metal, aluminum processing took a giant leap forward with the advent of large sources of economical electric power. The global production grew from 0.18 million tonnes in 1918 to 2 million tonnes in 1952 and reached 32 million tonnes in 2005.

aluminum cast products and wrought products, in which the majority are rolled, extruded, or forged. Challenges and opportunities for the aluminum fabricated products were discussed at the 2006 TMS Annual Meeting.[6]

Castings

Aluminum castings have played an integral role in the growth of the aluminum industry since their inception more than 100 years ago. The first commercial aluminum products were castings, such as cooking utensils and decorative parts, which exploited the novelty and utility of the new metal. They were used to replace the silver or gold cutlery to serve the royal families in ancient Europe. In the United States, an aluminum casting was selected as the capstone of the Washington Monument because it was the most precious metal at that time.

Today, aluminum alloy castings are produced in hundreds of compositions by all commercial casting processes, including sand casting, investment casting, and pressure die casting. In general, casting alloys contain larger amounts of alloying elements such as silicon and copper, which provide excellent cast fluidity, and, together with other elements like copper, magnesium, and zinc, provide high strength and high toughness.

The automotive industry is the largest market for aluminum castings, and cast products comprise about 75% of the aluminum used in cars. Cast aluminum transmission housing and pistons have been virtually universal in cars and trucks throughout the world for years.

Flat-Rolled Products

Shipments of flat-rolled sheet and plate account for 58% of the total 8.07 million tonnes of mill product in 2005. Flat-rolled products include sheet, plate, and foil. They are manufactured by combinations of hot and cold rolling, in which the metal passes through single or multiple stands of large rolling mills. The rolling process is used to reduce the thickness as well as to achieve the desired physical and mechanical properties by controlling proper thermomechanical parameters.

Rolled-aluminum Al-Mn sheet for beverage can packaging accounts for 1.85 million tonnes, ~16% of total aluminum consumption. This is the single largest-volume aluminum product and is highly engineered with metallurgical and manufacturing techniques. State-of-the-art technology is applied to achieve extremely high productivity and superior quality control. The original thickness of the cast ingot is reduced from 760 mm to 0.25 mm, with a precision of ±0.005 cm for a coil as long as 10 km.

Extrusions

Extrusion is second only to rolling for making semi-fabricated products. The process consists of subjecting a confined billet to high pressure in an extrusion press that forces the metal through an opening in a die to form a profile with a constant cross section.

To many designers and materials scientists, extruded aluminum is the material of choice for countless applications. Experts choose aluminum extrusions because they offer so many design options:

- Alloys can be readily formed into complex shapes, placing the metal where it is most needed to carry the maximum design stress
- Extrusion tooling is relatively inexpensive
- Lead times for custom shapes or prototypes are relatively brief
- Many finishes are available
- The life cycle value of the product remains high because of the recyclability of aluminum

A range of different process variants and equipment types has been developed for extrusion operation. Two significant processes are direct extrusion and indirect extrusion. In direct extrusion, the billet is pushed from behind and the metal forced through the die by the rear pressure. For indirect extrusion, the billet is held stationary and the die is pushed back toward and through the billet, forcing the metal to flow through the die by backward pressure.

Aluminum extrusions are made in a variety of alloys and tempers to meet a broad spectrum of needs. Principal applications include parts for the aircraft and aerospace industries, pipe, wire, rods, bars, tubes, hollow shapes, cable sheathing, architectural and structural sections, and automotive trim. The selection is made to meet the specific requirements in strength, weldability, forming characteristics, finish, corrosion resistance, and machinability. The Al-Mg-Si aluminum alloys are selected for nearly 75% of extrusion applications. As an example of the use of extruded shapes, the all-aluminum bridge structure in Foresmo, Norway, was prefabricated in a shop and erected on the site in days.

Forgings

Aluminum alloys can be forged into a variety of shapes and types of forging with a range of performance design criteria based on the intended application. Selection of the optimal forging method for a given forging shape is based on the desired forging shape, the sophistication or complexity of the forging shape, and cost. Most aluminum alloy forgings are produced in closed dies. Open-die forging is frequently used to produce small quantities of aluminum-alloy forgings for which the construction of relatively expensive closed dies is not justified.

Aluminum forgings have been the top choice of many automotive and aerospace applications that require the combination of light weight, high strength, and high toughness. The aircraft airframe has been the most demanding application for aluminum alloys; to chronicle the development of the high-strength alloys is also to record the development of airframes. Forged Al-Zn alloy airframe sections more than 7.62 cm thick were introduced in the United States in 1954, providing high strength and great transverse ductility.

RECYCLING

It is estimated that worldwide annual production of primary aluminum from bauxite is 32 million tonnes. Of the 780 million tonnes of primary aluminum produced since the beginning of the industry, there are still 400 million tonnes of the metal in use that will eventually be available for recycling.[1,2,5] Today, the secondary aluminum stream is becoming an even more important component of aluminum production and is attractive because of its economic and environmental benefits, which can significantly improve the sustainability of the aluminum fabrication industry.

Energy Resources and Climate Change

Aluminum has been referred to as an "energy bank" in that once the energy has been invested in it through the smelting process it can be effectively drawn upon again through recycling. It requires 16 kWh to produce 1 kg of primary aluminum from alumina and 23.8 kWh per kilogram from bauxite ore. The same amount of secondary aluminum produced from recycled metal requires approximately 5% of the energy as compared to primary aluminum production. Recycling aluminum saves 95% of the energy to produce virgin aluminum.

Primary aluminum production consumes 2% of the global electricity supply, and one third of the total energy consumption in primary aluminum production comes from coal-generated electricity. Air pollution from primary smelting and the production of the necessary electrical power includes hundreds of thousands of tonnes of carbon dioxide, nitrogen oxide, hydrogen fluoride, and particulates. Reducing these levels can be achieved by maximizing the use of state-of-the-art environmental control systems and environmentally friendly practices such as recycling.

Recycling aluminum scrap results in the production of only 5% of the carbon dioxide produced in making new primary metal. Thus, the energy savings of recycling aluminum also translates into reduced environmental emissions.

Economic Benefits

Recycling aluminum alloys provides major economic benefits. In the United States, shipments of aluminum in the form of wrought and cast products have increased from 8 million tonnes in 1992 to 10 million tonnes in 2002, whereas primary aluminum production has been shrinking. Although imports have increased, secondary aluminum has become an increasingly important component of metal supply. To survive in this competitive market of high energy and raw material costs and relatively low finished goods prices, producers must minimize conversion costs while maximizing the recoverable metal units.

In the case of the aluminum beverage can, the significant economic advantages of aluminum recycling have also been demonstrated in a joint study by Secat, the Center of Aluminum Technology, and the Sloan Industry Center for a Sustainable Aluminum Industry, which showed that for each 1% increase in the amount of aluminum cans recycled, the savings to the U.S. economy is $20 million per year. This value could approach $1 billion if all available cans were recycled.

Despite the benefits of recycling aluminum cans, the industry is facing a new challenge as recycling rates decline. Whereas aluminum recycling in sectors such as transportation and construction is about 95% in North America, only 52% of recovered beverage cans were recycled in 2005 as compared with 67% in 1992. By comparison, the global recycling rate averages 63%.

Existing Recycling Technology

The reclamation of aluminum scrap is a complex interactive process involving collection centers, remelt facilities, metal processors, and consumers. The scrap can be divided into two types according the sources of scrap: post-consumer scrap and industry scrap. The initial reprocessing of post-consumer scrap takes place in remelt facilities. Several dedicated facilities have been set up to remelt used beverage cans (UBCs) for beverage can sheet manufacturers. Scrap incurred in the processing or fabrication represents another source of recyclable aluminum. Traditionally, this form of new scrap has been returned to the supplier for recycling or sold into the general market.

The traditional flow of scrap through the primary, consuming, and secondary industries is dominated by three major scrap streams: UBCs, automotive scrap, and municipal scrap. The alloy compatibility of the components of the can makes it uniquely suitable for the closed-loop recycling concept and is responsible for the consistently high value of UBCs.

The greatest challenge for the recycling community is finding the most economical way to acquire, separate, and prepare scrap for melting to keep the metal from significantly degrading. Each product has its own specific demands. The can recycling loop is totally dedicated to a single product of two compatible aluminum alloys. Automotive recyclers, on the other hand, have to deal with a number of fractions with different destinations and relatively low values. A summary of the technologies used by these two industries is shown in Table I.

Table I. A Summary of Recycling Technologies for Cans and Automotive Scrap

Step	Description
Can Recycling Technology	
Collection	Shredding bales or briquettes and removing ferrous contaminants through an air knife.
De-Lacquering	Employing a rotary kiln with a sophisticated re-circulating system for products of combustion gases.
Alloy Separation	Screening out can lid from can body in thermo-mechanical chamber by the onset of incipient melting.
Melting, Preparation, and Casting	Transferring the melt metal from dedicated melters to on-line melting furnaces for can stock manufacturing.
Automotive Scrap Recycling Technology	
Physical Separation Methods	Using electromagnetic or eddy current methods to separate nonferrous metal from nonmetallic particles.

Innovation and Approaches

The need for effective and efficient recycling technology is rapidly becoming more important as aluminum recycling is becoming crucial to sustain the aluminum industry in the United States. The corresponding growth and diversification of the scrap-recycling industry are driven by several factors, including increased production requirements, alloy development, scarcity of energy and resources, and increased availability of mixed scrap. To address issues, efforts have been initiated to improve the efficiency of metal recovery and the effectiveness of shredding and sorting technology; identify useful by-products available through use of secondary scrap; broaden the range of alloys readily produced from recycled metal; and retain domestic aluminum scrap in the United States and reduce exports to China and India.

One of the major tasks in building a sustainable aluminum fabrication industry is to develop recycle-friendly alloys. So far, the identification of new alloys that will more readily use recycled aluminum has received little attention and, in fact, is considered impractical by some because of the generally negative effects of impurity elements. However, the potential economic and environmental benefits are sufficiently great that it is indeed useful to consider this approach.

MARKETS AND APPLICATIONS

Top markets for the industry are: transportation, including aerospace and automotive; beverage cans, packaging foil, and other packaging products; and building and construction, including infrastructure and highway structures.

In fact, transportation first emerged in 1994 as the largest market for aluminum at ~25% of the market, with passenger cars accounting for the large majority of the growth. That trend has continued each subsequent year.

Transportation

The performance of the aluminum industry is noteworthy, particularly in light of the proliferation of alternative materials and global competition. Transportation represents the largest market for aluminum in the United States. Automotive and light truck applications accounted for almost 2.35 million tonnes of aluminum in 2000,[1,2,5] or about one fifth of industry shipments. Aluminum-intensive automobiles include the Audi *A8*, with its aluminum body, aluminum front and rear axle, and numerous other aluminum components; the Honda *Insight* with its aluminum monocoque body and an aluminum alloy in-line three-cylinder engine; and the Lincoln *LS*, featuring a sheet aluminum hood, deck lid, and front fender and forged aluminum wheels.

In 2000, transportation accounted for 32.5% of all U.S. shipments. That same year aluminum passed plastic—with an average content of 116.57 kg per vehicle—to become the third most used material in automobiles.[1,2,5] Automakers are increasingly choosing aluminum to improve fuel economy, reduce emissions, enhance vehicle performance, and improve safety.

Aerospace Applications

Aluminum comprises ~80% of the unladen weight of most aircraft; the standard Boeing 747 jumbo jet contains ~75,000 kg of aluminum.[1,2,5] Because aluminum is corrosion resistant, the metal does not need painting, which can save several hundred kilograms of weight if airlines choose not to paint their planes.

Currently there are approximately 5,300 commercial passenger aircraft and many thousands of light aircraft and helicopters worldwide, and the demand for commercial aircraft is expected to increase by ~60% in the next decade. North America is the leading player in the global aerospace industry, with a 39% share in 2005 shipments. As the market in North America matures, Asia will become the major driving force behind growth in the industry, led by the rapid growth in civil aviation in China and India. Increasing pressure is being felt from carbon-fiber-reinforced plastics, which replaced a considerable amount of the aluminum in Boeing's latest 787 Dreamliner. High production costs and concerns about uncertain long-term performance will keep aluminum dominant in all but the most sophisticated aircraft.

Aluminum must develop novel products, fabrication, and assembly techniques at competitive costs to stay competitive with materials such as titanium and carbon-fiber composites.

Automotive Industries

Aluminum has made great strides in taking a portion of the automotive spotlight from steel, especially considering its relatively recent entry into the automotive industry.[5,7–9] According to the Aluminum Association, the use of automotive aluminum quadrupled between 1991 and 2005. Annual global vehicle production is expected to increase by 11 million to reach 67.8 million in 2009; with a 3% annual growth rate, aluminum consumption could be even greater in this industry. A recent global study by Ducker Research Company on aluminum content in light vehicles showed that the aluminum content has maintained consistent, uninterrupted, annual growth for the last 30 years and is expected to continue to climb at a rate of approximately 3.6–4.5 kg/vehicle, or about 3%, for the near future.[7] These percentages will fluctuate before stabilizing if the use of aluminum grows as predicted.

The rise in energy costs and the need for emissions reduction worldwide make aluminum more attractive for automotive use. Aluminum has been used increasingly by the automotive industry to reduce vehicle weight without sacrificing performance and safety. The oil crisis in the 1970s made people aware of the need for fuel-efficient cars, and recent energy price hikes demand speedy action for weight reduction. This further drives the increased use of aluminum, which already has been applied in a variety of parts, including the engine, body, hood, and front end.

With increasing magnesium production and the lower unit weight of magnesium as compared to aluminum, there will be increased competition from that metal for future automotive applications. The other major competing materials include microalloyed high-strength thin gauge steel, fiber glass, and carbon-fiber composites. The initial material cost and performance will always dominate the debate on material choice.

Packaging

In aluminum packaging, 100 billion aluminum beverage cans are consumed each year in North America, but the market has been flat since peaking in 1999. Plastic is beginning to take an increasing market share, and steel is also trying to reclaim the market by innovation and downgauging. Aluminum is trying to offset the competition by updating the design, shape, and size of beverage containers.

During the same period, the world aluminum packaging market grew rapidly, mostly from emerging markets in Asia and Eastern Europe. With continuing massive international investment, China has the world's fastest growing economy, and its aluminum beverage can market reflects this growth. In the next year, China's two-piece beverage can market will far exceed 10 billion cans.[10] Considering the potential for greater market share in developing countries, the growth of the aluminum packaging market could be tremendous.

In the past decade, the aluminum industry has worked hard to keep its share of the packaging market.[11] To reduce the cost of the two-piece aluminum can (can body and can end), the metal gauge for the most popular 12-oz aluminum can body was reduced from 0.045 mm to just 0.25 mm. In addition, the can design was modified to strengthen the can body and minimize the size of the more-expensive can end. New coatings and graphic designs were developed and applied widely in the industry; however, the efforts are not sufficient to increase the market share. Diverse groups on technology, research, and development must be created to devise new strategies to provide innovative and enhanced cost-effective packaging solutions.

Innovative products are needed to meet a variety of market needs besides traditional aluminum packaging. Aluminum packaging does more than provide basic packaging; it also offers functionality and security to the customers. Great progress has been achieved, such as the shaped bottle and the specialty can, which provide a new appearance and more convenience. The intrinsic value of aluminum, which generates more revenue for recyclers than other materials, will also continue to provide a competitive advantage.

Building and Construction

Largely because of products in the residential, industrial, commercial, farm, and highway sectors, the 2005 building and construction market accounted for 1.68 million tonnes of net shipments, good for 14% of total shipments and the third largest domestic market for aluminum. This market penetration has increased in the past 5 years, but high initial cost prevents aluminum from widely replacing other competing materials such as wood, plastic, brick, and steel in building and construction applications.

Increased emphasis on "green" building applications will keep aluminum in the forefront of this important market. Among the important components of this market are: storefront fascia and trim, high-rise commercial and residential building exteriors, solar panels and renewable energy products, and highway signage and bridges.

A largely untapped market for aluminum remains the replacement highway bridge deck. Thousands of steel and concrete bridge decks across the country are load-limited or deteriorating badly. Aluminum bridge decks may be fabricated off-site and dropped in place by cranes, greatly reducing the disruption time and inconvenience for motorists. Because aluminum bridge decks are lighter than steel or concrete decks, the replacement can be designed to carry higher loads, eliminating existing restrictions. Also, aluminum bridge decks have such inherent corrosion resistance that they do not require painting, greatly reducing the maintenance costs. Regrettably, a lack of familiarity with aluminum characteristics and conservatism in the highway industry have thus far limited the advantage taken of this opportunity. Adoption of aluminum bridge decks is also hampered by the fact that the initial costs are significantly higher than those for a concrete or steel deck, but after 20 years, the life-cycle costs are lower for the aluminum deck.

CHALLENGES AND OPPORTUNITIES FACING THE INDUSTRY

Primary aluminum production is decreasing in the United States at an accelerating pace. Its share of world production dropped from 41% in 1960 to 15% in 2000 and now accounts for less than 8%. The factors behind this decline include high energy and labor costs as compared to other regions, such as Iceland, South America, China, India, and Russia. However, the U.S. aluminum fabrication industry remains strong, although the other regions mentioned above are threatening U.S. dominance.

Competing materials are also challenging aluminum markets, including packaging (plastics), automotive (magnesium, high-strength low-alloy steel, and plastic composites), aerospace (carbon composite and titanium), and building products (plastics and composites).

In order to enhance the sustainability of the aluminum industry and its products, the recycling component must become increasingly effective in ensuring its recycling and reuse to minimize its carbon footprint affecting climate changes. Achievement of this goal requires development and implementation of recycle-friendly aluminum alloys that are competitive in the marketplace.

The U.S. Department of Energy (DOE) identified the aluminum industry as one of nine industry sectors critical to the national economy and has funded research during the past decade to improve energy efficiency and cut costs, thereby sustaining the North American industry's global competitiveness.

Changing Geography of Metal Supply

For any country, including the United States, aluminum supply comprises three basic sources: primary (domestic production from ore material), secondary (recycled metal recovered from scrap), and imports (of primary and secondary ingot and mill products).

The aluminum supply chain is experiencing a major change within the existing markets as well as in the emerging markets. The increase in energy costs and raw materials prices requires more efficiency in operation and management. As a result, the aluminum industry in the western countries was consolidated and reorganized during the past few years; the market share is split between more competitive but fewer suppliers as some players went out of business. International corporations not only build new manufacturing facilities and acquire local manufacturers in the emerging market, but also redistribute their existing facilities worldwide.

Similarly, suppliers in Brazil, Russia, India, and China are also growing at unparalleled rates because of effective cost, soaring worldwide demand, and strong government support. The Russian aluminum giant Rusal became one of the largest aluminum suppliers in the world after merging with two partners. Chalco (Aluminum Corporation of China) also is ranked among the leading global aluminum companies.

Industry Consolidation

Recently, the global aluminum industry has become extremely active in the area of mergers, acquisitions, consolidations, and rationalization. The following trends have been observed:

- Decoupling of primary production from semi-finished product fabrication (Alcan spins off Novelis to focus on primary production)
- Coupling of recycling operations with semi-finished product fabrication (Commonwealth Aluminum merging with Imco Recycling forming Aleris International)
- A large international mining company acquiring a primary alumi-

num producer (Rio Tinto acquired Alcan)
- BRIC countries (Brazil, Russia, India, and China) acquiring major North American and European operations (Hindalco acquiring Novelis)
- Private equity group purchasing aluminum operations (Texas Pacific Group purchasing Aleris International)

Technology Improvement and New Applications

The aluminum industry employs the latest technology to make the process of refining bauxite ore and reducing alumina to aluminum more efficient and energy saving. The industry, through its partnership with the U.S. DOE and the Aluminum Association, is vigorously working to help make greater gains in reducing energy consumption. Increased aluminum use in transportation applications and elsewhere also has significantly reduced energy and fuel consumption and reduced carbon dioxide emissions.

Although aluminum is lightweight, highly recyclable, and corrosion resistant, the cost per kilogram of aluminum sheet is currently four to five times more than steel for automotive applications. Aluminum is considered to be more difficult to weld and stamp than steel and behaves differently when stressed, which means engineering a body structure to meet crash safety and stiffness requirements demands a different approach. Typically, components such as door panels and hoods are formed using conventional mechanical presses that stamp steel or aluminum sheet into their final shape.

Because of these issues, a single aluminum part might require more stamping stages than a comparable steel part or the part may need divided into two or more pieces that are then joined together, adding time and cost to the manufacturing process. A less desirable alternative is to make compromises on either the material choice or the part shape.[12] Thus, engineers have tried to develop other methods to replace or complement the conventional mechanical stamping process to fully realize the potential mass savings of using aluminum components.

Several new energy saving technologies are now in the early stages of commercialization, including electromagnetic forming and aluminum body technology for automobiles. The semisolid forming process combining casting and forming[13] rheocasting makes near net-shaped parts, or parts that need little if any additional shaping after they are formed, thus saving time and expense. Researchers have experimented with a technique known as electromagnetic forming to reduce or even eliminate the wrinkling and springback associated with conventional forming processes as well as to increase the formability of aluminum sheet.

The aluminum body technology crafted around the Audi Space Frame (ASF) was created in the Audi *A8*. The ASF is a high-strength aluminum structure in which the large integral aluminum-sheet components also perform a load-bearing function. The actual frame consists of extruded sections joined by vacuum-formed die cast nodes. Acting as a safety cell, the aluminum-alloy structural members of the ASF absorb energy better in relation to their weight than steel.

Industry Collaboration and Partnership

By the mid-1990s, competitive pressures on North American industry forced a collective response to its most pressing needs, which included reducing energy and production costs; meeting regulatory requirements; and developing new markets, processes, and products. Successfully addressing these needs requires collaborative partnerships that extend beyond the technical sphere, ones that recognize and take advantage of the intellectual capital resident in institutions of higher learning, especially business schools and economics departments.

The industry has amassed a proven track record in sponsoring and implementing collaborative R&D designed to benefit the industry as a whole. Most of this effort has been in the area of technology-related R&D, but the most recent strategic vision document enumerates several goals that require significant investments in business and economic R&D to achieve their maximum potential. A major challenge is to transfer the highly successful collaborative technology R&D model to the business setting and in so doing create an independent source of cutting-edge business and economics R&D for the aluminum industry.

CONCLUSIONS

Aluminum production applications are increasing globally, and industry is undergoing significant changes in production demographics. The United States, which classically was the top aluminum producer, has become the fourth-largest producer in a matter of years. However, the demand for aluminum products in the United States will increase. To meet this demand, the United States must improve scrap recycling rates and increase the importation of foreign sources of material.

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