ASM HANDBOOK

VOLUME 2

Properties and Selection: Nonferrous Alloys and Special-Purpose Materials

ASM INTERNATIONAL ®

The Materials Information Company

Properties and Selection: Nonferrous Alloys and Special-Purpose Materials was published in 1990 as Volume 2 of the 10 Edition Metals Handbook. With the second printing (1992), the series title was changed to ASM Handbook. The Volume was prepared under the direction of the ASM International Handbook Committee.

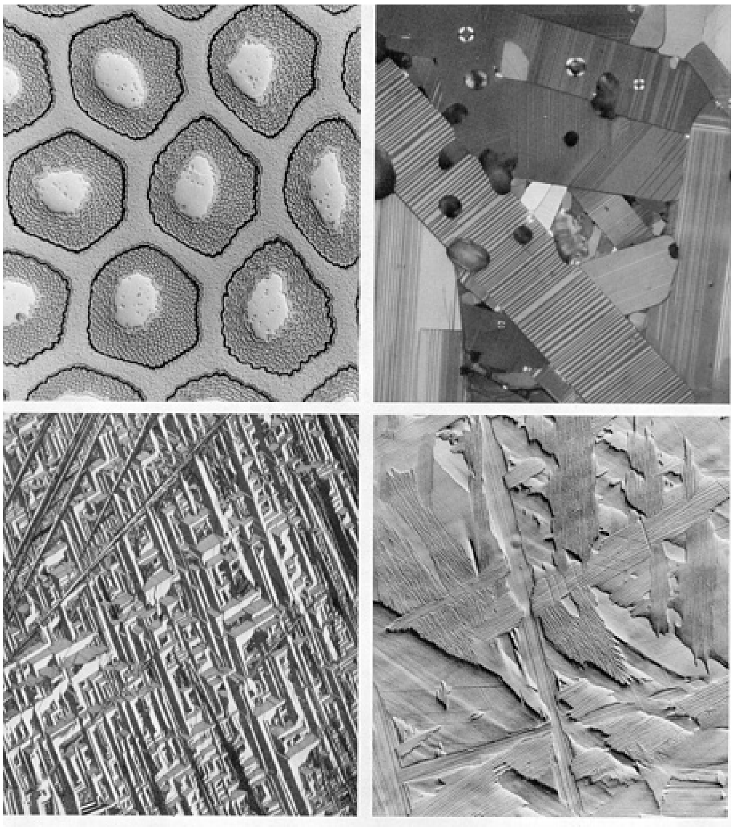

Fig. 1 ***Examples of some of the many nonferrous alloys and special-purpose materials described in this Volume. Shown clockwise from the upper left-hand corner are: (1) a cross-section of a multifilament Nb_3Sn superconducting wire, 1000×; (2) a high-temperature ceramic $YBa_2Cu_3O_{7-x}$ superconductor, 600×; (3) beta martensite in a cast Cu-12Al alloy, 100× and (4) alpha platelet colonies in a Zr-Hf plate, 400×. Courtesy of Paul E. Danielson, Teledyne Wah Chang Albany (micrographs 1 and 4) and George F. Vander Voort, Carpenter Technology Corporation (micrographs 2 and 3).***

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Foreword

Throughout the history of *Metals Handbook,* the amount of coverage accorded nonferrous alloys, special-purpose materials, and pure metals has steadily, if not dramatically, increased. That this trend has continued into the current 10th Edition is easily justified when one considers the significant developments that have occurred in the past decade. For example, metal-matrix composites, superconducting materials, and intermetallic alloys--materials described in detail in the present volume--were either laboratory curiosities or, in the case of high-temperature superconductors, not yet discovered when the 9th Edition Volume on this topic was published 10 years ago. Today, such materials are the focus of intensive research efforts and are considered commercially viable for a wide range of applications. In fact, the development of these new materials, combined with refinements and improvements in existing alloy systems, will ensure the competitive status of the metals industry for many years to come.

Publication of this Volume is also significant in that it marks the completion of a two-volume set on properties and selection of metals that serves as the foundation for the remainder of the 10th Edition. Exhaustive in scope, yet practical in approach, these companion volumes provide engineers with a reliable and authoritative reference that should prove a useful resource during critical materials selection decision-making.

On behalf of ASM International, we would like to extend our sincere thanks and appreciation to the authors, reviewers, and other contributors who so generously donated their time and efforts to this Handbook project. Thanks are also due to the ASM Handbook Committee for their guidance and unfailing support and to the Handbook editorial staff for their dedication and professionalism. This unique pool of talent is to be credited with continuing the tradition of quality long associated with *Metals Handbook.*

Klaus M. Zwilsky
President
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Edward L. Langer
Managing Director
ASM International

Preface

This is the second of two volumes in the *ASM Handbook* that present information on compositions, properties, selection, and applications of metals and alloys. In the first volume, irons, steels, and superalloys were described. In the present volume, nonferrous alloys, superconducting materials, pure metals, and materials developed for use in special applications are reviewed. In addition to being vastly expanded from the coverage offered in the 9th Edition, these companion volumes document some of the more important changes and developments that have taken place in materials science during the past decade--changes that undoubtedly will continue to impact materials engineering into the 21st century.

During the 1970s and '80s, the metals industry was forced to respond to the challenges brought about by rapid advancements in composite, plastic, and ceramic technology. During this time, the use of metals in a number of key industries declined. For example, Fig. 1 shows materials selection trends in the aircraft industries. As can be seen, the use of aluminum, titanium, and other structural materials is expected to level off during the 1990s, while polymer-matrix composites, carbon-carbon composites, and ceramic-matrix composites probably will continue to see increased application. However, this increasing competition has also spurred new alloy development that will ensure that metals will remain competitive in the aerospace industry. Some of these new or improved materials and methods include:

- Ingot metallurgy aluminum-lithium alloys for airframe components that have densities 7 to 12% lower and stiffnesses 15 to 20% higher than existing high-strength aluminum alloys
- High-strength aluminum P/M alloys made by rapid solidification or mechanical alloying
- Advances in processing of titanium alloys that have resulted in improved elevated-temperature performance
- The continuing development and research of metal-matrix composites and intermetallic alloys such as Ni_3Al, Fe_3Al, and Ti_3Al

These are but four of the many new developments in nonferrous metallurgy that are documented in Volume 2's 1300 pages.

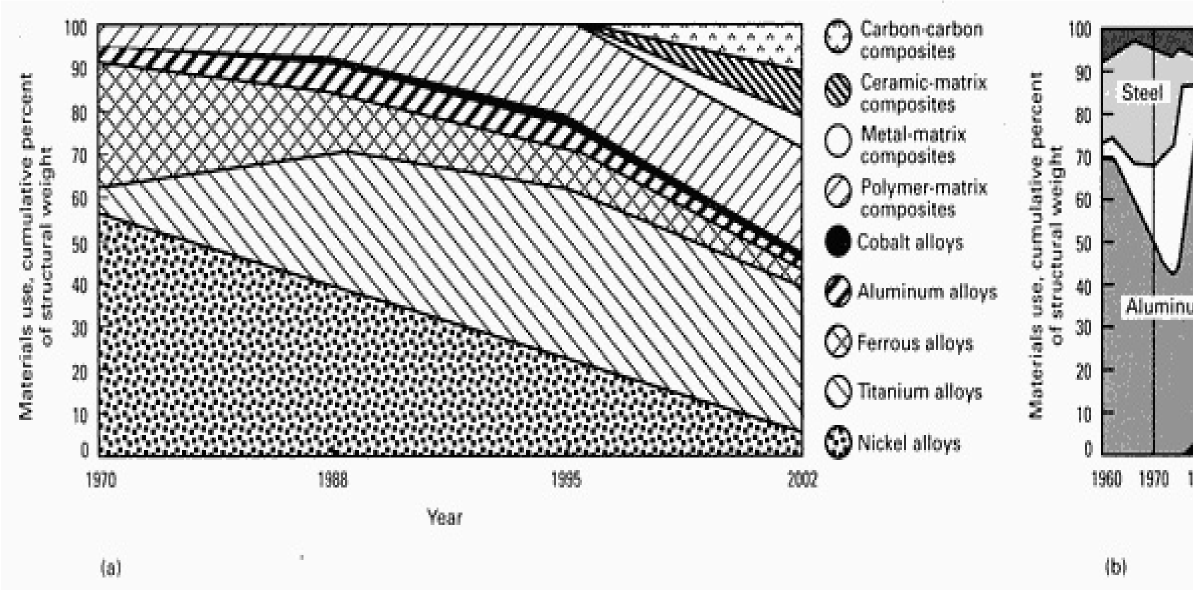

Fig. 1 Trends in materials usage for the aircraft industry. (a) Jet engine material usage. Source: Titanium Develop Company. (b) Airframe materials usage for naval aircraft. Source: Naval Air Development Center and Naval Air Sys

Principal Sections

Volume 2 has been organized into five major sections:

- Specific Metals and Alloys
- Special-Purpose Materials
- Superconducting Materials
- Pure Metals
- Special Engineering Topics

A total of 62 articles are contained in these sections. Of these, 31 are completely new to the *ASM Handbook* series, 8 were completely rewritten, with the remaining revised and/or expanded. A summary of the content of the major sections is given in Table 1 and discussed below. Differences between the present volume and its *Metals Handbook,* 9th Edition predecessor are highlighted.

Table 1 Summary of contents for Volume 2, *ASM Handbook*

Section title	Number of articles	Pages	Figures[a]	Tables[b]	References
Specific Metals and Alloys	36	757	586	703	646
Special-Purpose Materials	15	265	292	142	694
Superconducting Materials	7	64	101	6	325
Pure Metals	2	111	156	230	622
Special Engineering Topics	2	67	26	21	384
Totals	**62**	**1,264**	**1,161**	**1,102**	**2,671**

(a) Total number of figure captions; some figures may include more than one illustration.

(b) Does not include in-text tables or tables that are part of figures

Specific Metals and Alloys are described in 36 articles. Extensive new data have been added to all major alloys groups. For example, more than 400 pages detail processing, properties, and applications of aluminum-base and copper-base alloys. Included are new articles on "Aluminum-Lithium Alloys," "High-Strength Aluminum P/M Alloys," "Copper P/M Products," and "Beryllium-Copper and Other Beryllium-Containing Alloys." When appropriate, separate articles describing wrought, cast, and P/M product forms for the same alloys system have been provided to assist in materials selection and comparison. Articles have also been added on technologically important, but less commonly used, metals and alloys such as beryllium, gallium and gallium arsenide (used in semiconductor devices), and rare earth metals.

Special-Purpose Materials. The 15 articles in this section, 7 of which are completely new, examine materials used for more demanding or specialized application. Alloys with outstanding magnetic and electrical properties (including rare earth magnets and metallic glasses), heat-resistant alloys, wear-resistant materials (cemented carbides, ceramics, cermets, synthetic diamond, and cubic boron nitride), alloys exhibiting unique physical characteristics (low-expansion alloys and shape memory alloys), and metal-matrix composites and advanced ordered intermetallics currently in use or under development for critical aerospace components are described.

Superconducting Materials. This is the first time that a significant body of information has been presented on superconducting materials in the *ASM Handbook.* This new section was carefully planned and structured to keep theory to a minimum and emphasize manufacture and applications of the materials used for superconductors. Following brief articles on the historical background and principles associated with superconductivity, the most widely used superconductors--niobium-titanium and A15 compounds (including Nb_3Sn)--are examined in detail. The remaining articles in the section discuss Chevrel-phase superconductors ($PbMo_6S_8$ and $SnMo_6S_8$), thin-film superconductors, and high-temperature oxide superconductors ($YBa_2Cu_3O_7$, $Bi_2Sr_2Ca_2Cu_3O_x$, and $Tl_2Ba_2Ca_2Cu_3O_x$.

Pure Metals are described in an extensive collection of data compilations that describe crystal structures, mass characteristics, as well as thermal, electrical/magnetic optical, nuclear, chemical, and mechanical properties for more than 80 elements. Also included is a review of methods used to prepare and characterize pure metals.

Special Engineering Topics. With environmental issues more important than ever, recycling behavior is becoming a key consideration for materials selection. The articles on recycling in Volume 2 over a wide range of materials and topics--from the recycling of aluminum beverage cans to the reclaiming of precious metals from electronic scrap. Statistical information on scrap consumption and secondary recovery of metals supplements each contribution. A detailed review of the toxic effects of metals is also included in this section.

Acknowledgements

Volume 2 has proved to be one of the largest and most comprehensive volumes ever published in the 67-year history of the *ASM Handbook* (formerly *Metals Handbook*). The extensive data and breadth of information presented in this book were the result of the collective efforts of more than 400 authors, reviewers, and miscellaneous contributors. Their generous gifts of time, effort, and knowledge are greatly appreciated by ASM.

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Thanks to the spirit of cooperation and work ethic demonstrated by all of these individuals, a book of lasting value to the metals industry has been produced.

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Introduction to Aluminum and Aluminum Alloys

Elwin L. Rooy, Aluminum Company of America

Introduction

ALUMINUM, the second most plentiful metallic element on earth, became an economic competitor in engineering applications as recently as the end of the 19th century. It was to become a metal for its time. The emergence of three important industrial developments would, by demanding material characteristics consistent with the unique qualities of aluminum and its alloys, greatly benefit growth in the production and use of the new metal.

When the electrolytic reduction of alumina (Al_2O_3) dissolved in molten cryolite was independently developed by Charles Hall in Ohio and Paul Heroult in France in 1886, the first internal-combustion-engine-powered vehicles were appearing, and aluminum would play a role as an automotive material of increasing engineering value. Electrification would require immense quantities of light-weight conductive metal for long-distance transmission and for construction of the towers needed to support the overhead network of cables which deliver electrical energy from sites of power generation. Within a few decades the Wright brothers gave birth to an entirely new industry which grew in partnership with the aluminum industry development of structurally reliable, strong, and fracture-resistant parts for airframes, engines, and ultimately, for missile bodies, fuel cells, and satellite components.

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

Properties. Among the most striking characteristics of aluminum is its versatility. The range of physical and mechanical properties that can be developed--from refined high-purity aluminum (see the article "Properties of Pure Metals" in this Volume) to the most complex alloys--is remarkable. More than three hundred alloy compositions are commonly recognized, and many additional variations have been developed internationally and in supplier/consumer relationships. Compositions for both wrought and cast aluminum alloys are provided in the article "Alloy and Temper Designation Systems for Aluminum and Aluminum Alloys" that immediately follows.

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

Aluminum has a density of only 2.7 g/cm^3, approximately one-third as much as steel (7.83 g/cm^3), copper (8.93 g/cm^3), or brass (8.53 g/cm^3). It can display excellent corrosion resistance in most environments, including atmosphere, water (including salt water), petrochemicals, and many chemical systems. The corrosion characteristics of aluminum are examined in detail in *Corrosion,* Volume 13 of *ASM Handbook,* formerly 9th Edition *Metals Handbook.*

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

Aluminum typically displays excellent electrical and thermal conductivity, but specific alloys have been developed with high degrees of electrical resistivity. These alloys are useful, for example, in high-torque electric motors. Aluminum is often selected for its electrical conductivity, which is nearly twice that of copper on an equivalent weight basis. The requirements of high conductivity and mechanical strength can be met by use of long-line, high-voltage, aluminum steel-cored reinforced transmission cable. The thermal conductivity of aluminum alloys, about 50 to 60% that of copper, is advantageous in heat exchangers, evaporators, electrically heated appliances and utensils, and automotive cylinder heads and radiators.

Aluminum is nonferromagnetic, a property of importance in the electrical and electronics industries. It is nonpyrophoric, which is important in applications involving inflammable or explosive-materials handling or exposure. Aluminum is also nontoxic and is routinely used in containers for foods and beverages. It has an attractive appearance in its natural finish, which can be soft and lustrous or bright and shiny. It can be virtually any color or texture.

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

Aluminum Production

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

The major impurities of smelted aluminum are iron and silicon, but zinc, gallium, titanium, and vanadium are typically present as minor contaminants. Internationally, minimum aluminum purity is the primary criterion for defining composition and value. In the United States, a convention for considering the relative concentrations of iron and silicon as the more important criteria has evolved. Reference to grades of unalloyed metal may therefore be by purity alone, for example, 99.70% aluminum, or by the method sanctioned by the Aluminum Association in which standardized P*xxx* grades have been established. In the latter case, the digits following the letter P refer to the maximum decimal percentages of silicon and iron, respectively. For example, P1020 is unalloyed smelter-produced metal containing no more than 0.10% Si and no more than 0.20% Fe. P0506 is a grade which contains no more than 0.05% Si and no more than 0.06% Fe. Common P grades range from P0202 to P1535, each of which incorporates additional impurity limits for control purposes.

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

Production Statistics. World production of primary aluminum totaled 17,304 thousand metric tonnes (17.304×10^6 Mg) in 1988 (Fig. 1). From 1978 to 1988, world production increased 22.5%, an annual growth rate of 1.6%. As shown in Fig. 2, the United States accounted for 22.8% of the world's production in 1988, while Europe accounted for 21.7%. The remaining 55.5% was produced by Asia (5.6%), Canada (8.9%), Latin/South America (8.8%), Oceania (7.8%), Africa (3.1%), and others (21.3%). The total U.S. supply in 1988 was 7,533,749 Mg in 1988, with primary production representing 54% of total supply, imports accounting for 20%, and secondary recovery representing 26% (Fig. 3). The source of secondary production is scrap in all forms, as well as the product of skim and dross processing. Primary and secondary production of aluminum are integrally related and complementary. Many wrought and cast compositions are constructed to reflect the impact of controlled element contamination that may accompany scrap consumption. A recent trend has been increased use of scrap in primary and integrated secondary fabricating facilities for various wrought products, including can sheet.

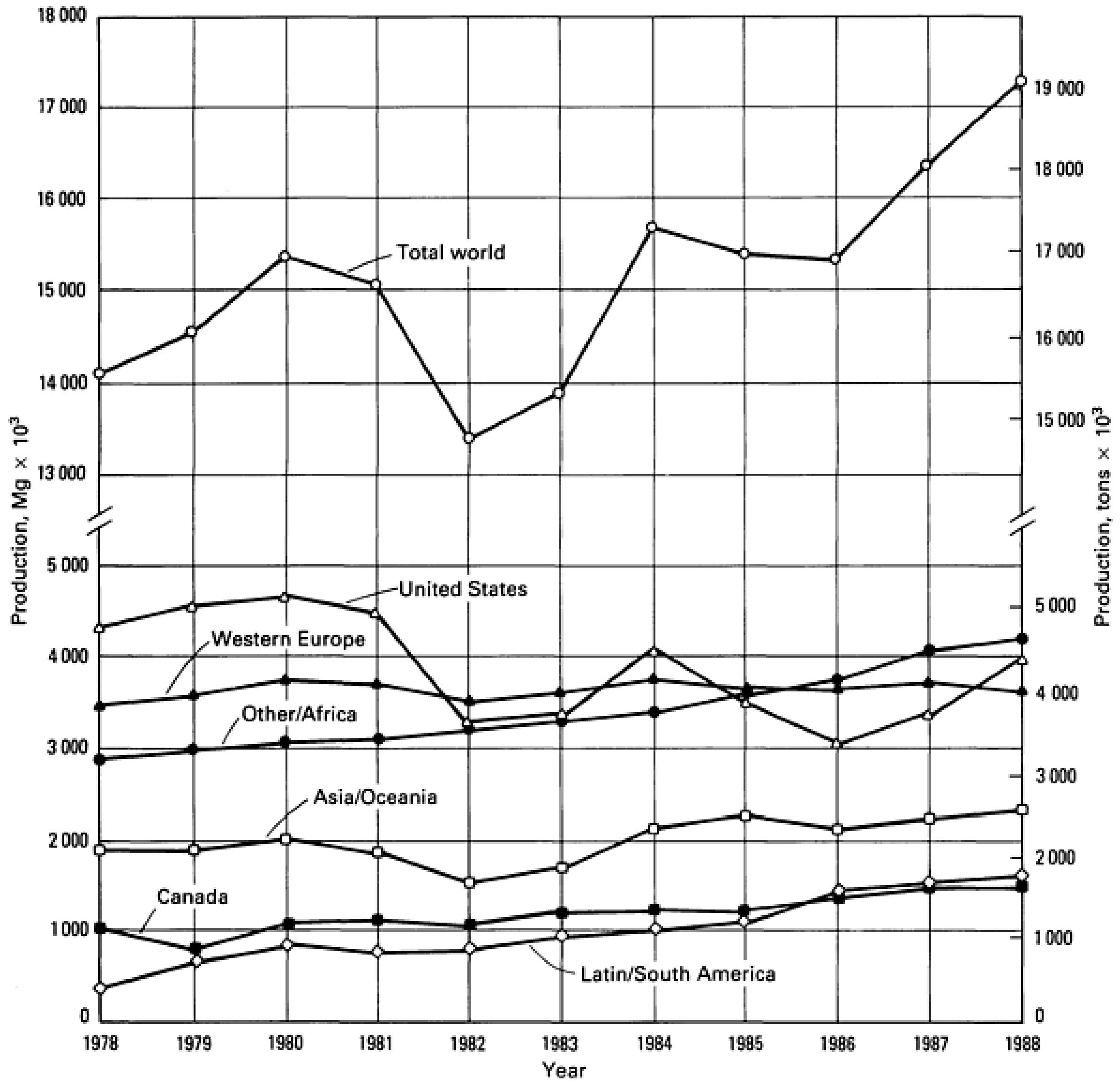

Fig. 1 Annual world production of primary aluminum. Source: Aluminum Association, Inc.

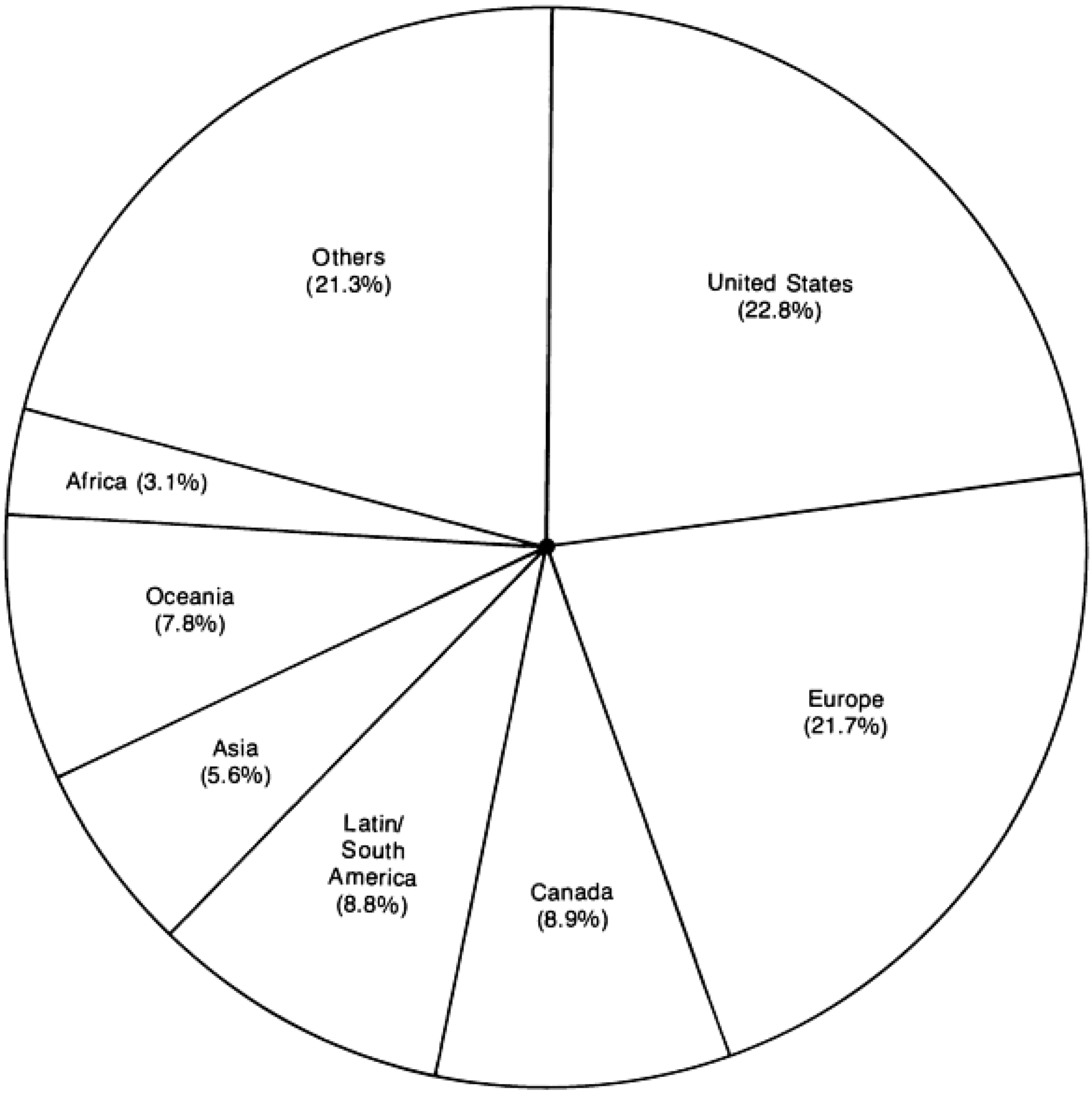

Fig. 2 Percentage distribution of world primary aluminum production in 1988. Source: Aluminum Association, Inc.

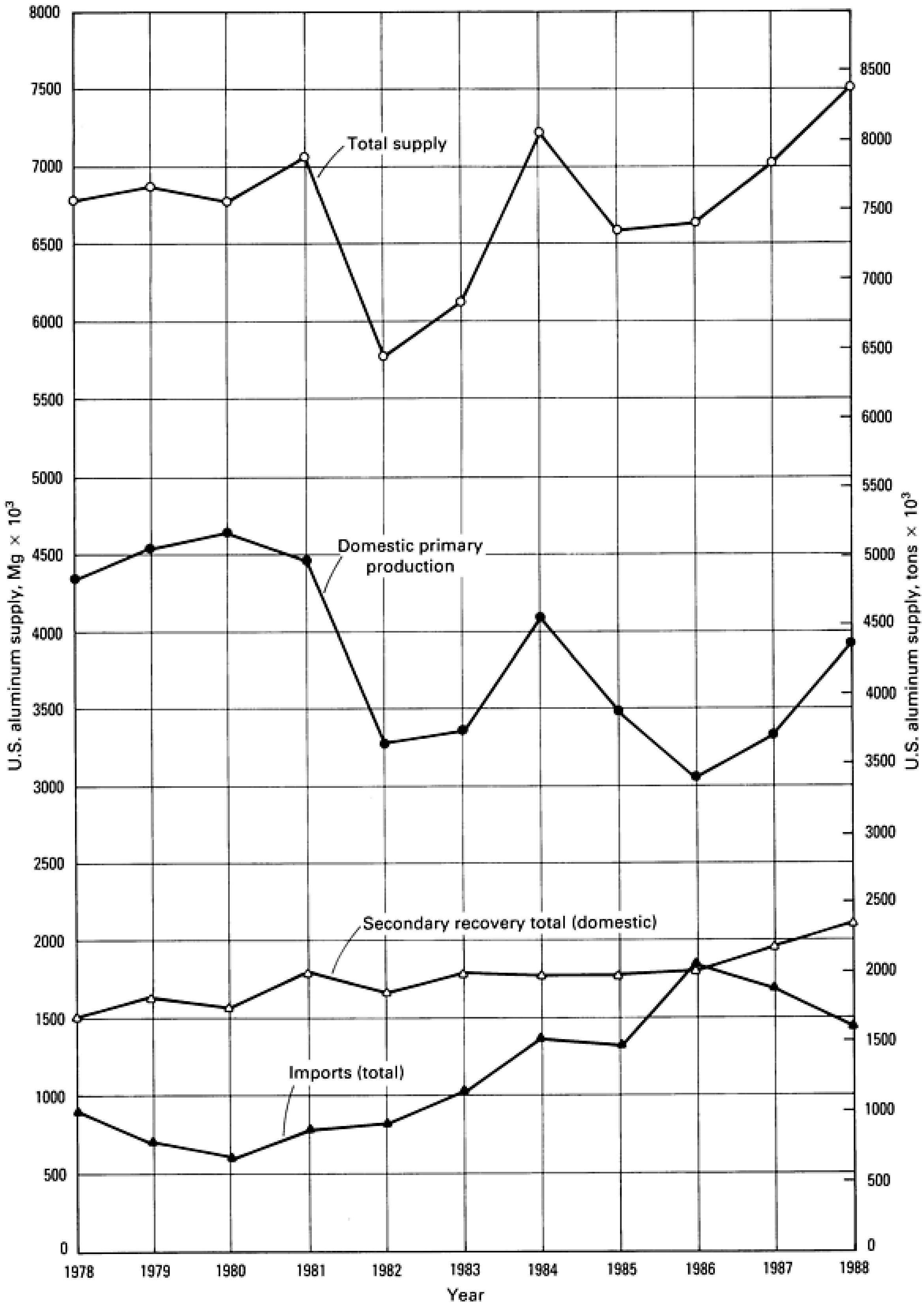

Fig. 3 U.S. aluminum production and supply statistics. Source: Aluminum Association, Inc.

Aluminum Alloys

It is convenient to divide aluminum alloys into two major categories: casting compositions and wrought compositions. A further differentiation for each category is based on the primary mechanism of property development. Many alloys respond to thermal treatment based on phase solubilities. These treatments include solution heat treatment, quenching, and precipitation, or age, hardening. For either casting or wrought alloys, such alloys are described as heat treatable. A large number of other wrought compositions rely instead on work hardening through mechanical reduction, usually in combination with various annealing procedures for property development. These alloys are referred to as work hardening. Some casting alloys are essentially not heat treatable and are used only in as-cast or in thermally modified conditions unrelated to solution or precipitation effects.

Cast and wrought alloy nomenclatures have been developed. The Aluminum Association system is most widely recognized in the United States. Their alloy identification system employs different nomenclatures for wrought and cast alloys, but divides alloys into families for simplification (see the article "Alloy and Temper Designation Systems for Aluminum and Aluminum Alloys" in this Volume for details). For wrought alloys a four-digit system is used to produce a list of wrought composition families as follows:

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

Casting compositions are described by a three-digit system followed by a decimal value. The decimal .0 in all cases pertains to casting alloy limits. Decimals .1, and .2 concern ingot compositions, which after melting and processing should result in chemistries conforming to casting specification requirements. Alloy families for casting compositions are:

- 1*xx.x* Controlled unalloyed (pure) compositions, especially for rotor manufacture
- 2*xx.x* Alloys in which copper is the principal alloying element, but other alloying elements may be specified
- 3*xx.x* Alloys in which silicon is the principal alloying element, but other alloying elements such as copper and magnesium are specified
- 4*xx.x* Alloys in which silicon is the principal alloying element
- 5*xx.x* Alloys in which magnesium is the principal alloying element
- 6*xx.x* Unused
- 7*xx.x* Alloys in which zinc is the principal alloying element, but other alloying elements such as copper and magnesium may be specified
- 8*xx.x* Alloys in which tin is the principal alloying element
- 9*xx.x* Unused

Manufactured Forms

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

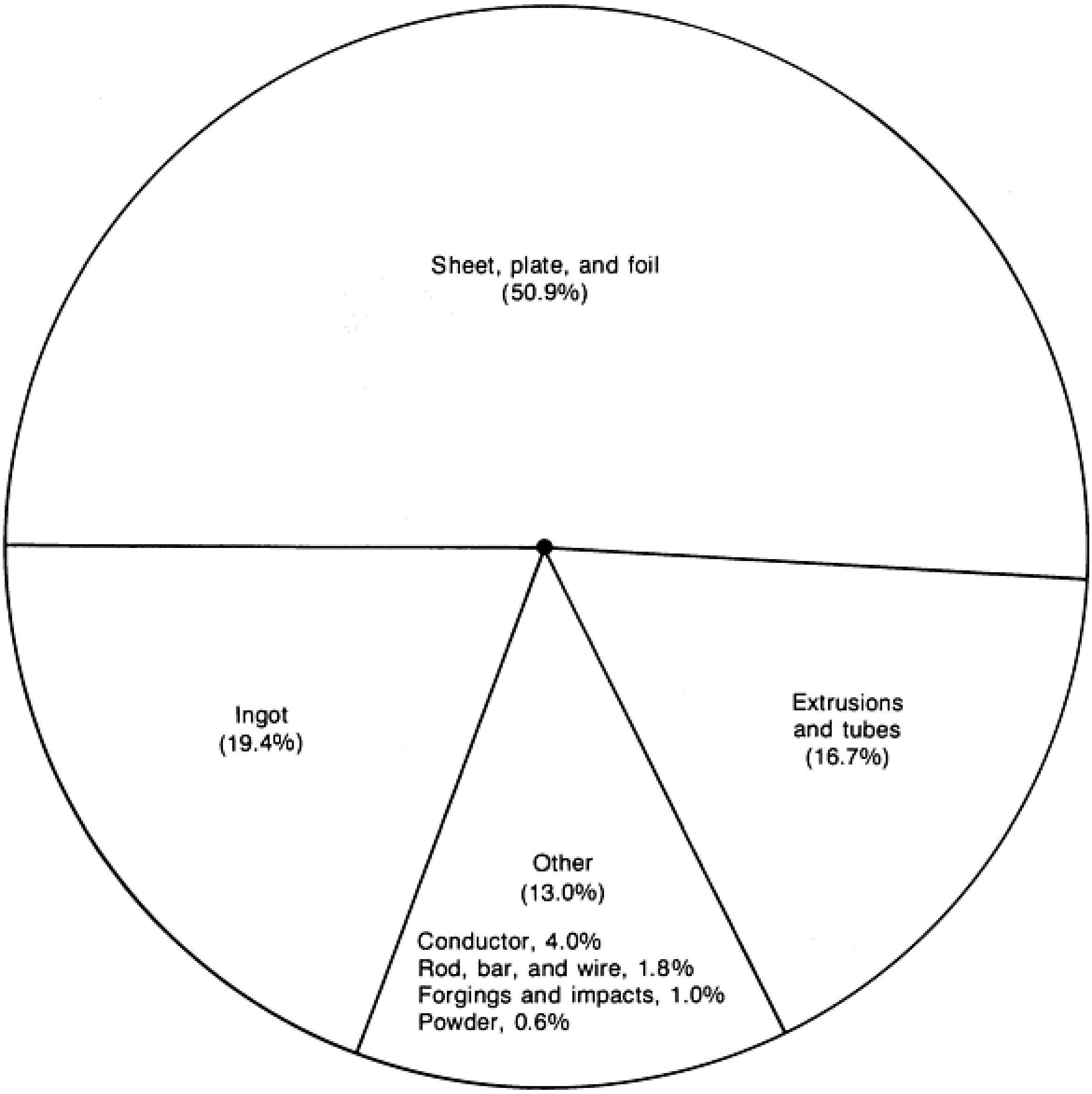

Fig. 4 Percentage distribution of major aluminum products in 1988. Source: Aluminum Association, Inc.

Standardized Products

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

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

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

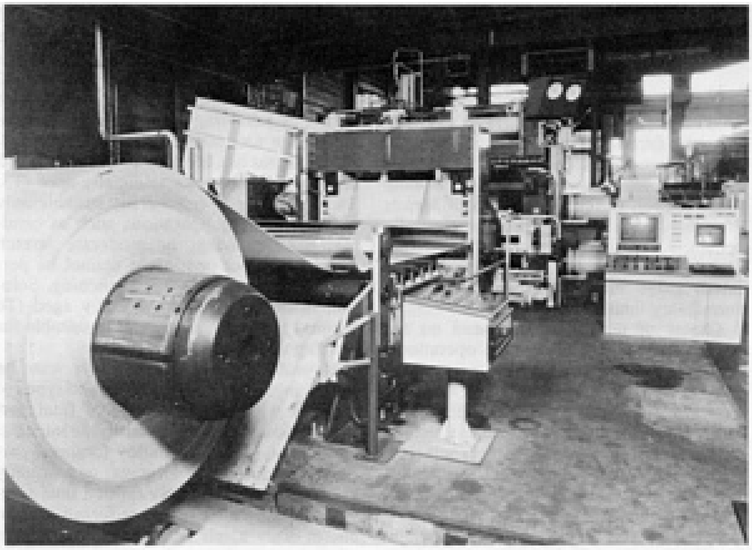

Fig. 5 Facility for producing aluminum sheet reroll directly from molten aluminum

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

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

Engineered Products

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