THE NEED FOR THIS BOOK stems directly from the increasing use of aluminum and aluminum alloys in automobiles and a great variety of other products that we encounter in everyday living. The excellent combination of light weight, high strength, great corrosion resistance, and reasonable cost has made aluminum and its alloys one of the most commonly used metal groups. Whereas weight saving by substituting light metals for heavy metals has been standard practice for generations in critical aerospace structures, it has now reached top priority status in a variety of other industries, including those manufacturing cars, trucks, military vehicles, aviation ground support vehicles, munitions, building and highway structures, and construction equipment.

The transition from heretofore more widely used iron and steel can be especially difficult for those with little or no experience with aluminum and aluminum alloys. Of necessity, they must become conversant with a new alloy designation system and, perhaps even more importantly, with a great number and variety of tempers, the designations for which provide background on how the alloys have been produced to obtain the desired properties and characteristics.

The positive news is twofold. First, contrary to the case for other metals, there are widely accepted alloy and temper designation systems for aluminum, created and maintained by the Aluminum Association, that are used throughout the aluminum industry. Those systems are published in the Aluminum Association publication *Aluminum Standards and Data* (see Chapter 8, “Selected References”) and are recognized by the American National Standards Institute (ANSI) as the *American National Standard Alloy and Temper Designation Systems for Aluminum* (see Chapter 8). The second item of positive news is that, with a little concentration, the aluminum alloy and temper designation systems are consistent, logical, and easily understood.
The Aluminum Association maintains the alloy and temper designations systems and, in fact, is accredited by ANSI to carry out this role for the United States. The procedures for registering alloys and tempers, and a record of the alloys and tempers registered, are published in Alloy and Temper Registration Records (see Chapter 8) and are available at minimal cost for any producer or user to track. Further, standard aluminum tempers that have been registered with the Aluminum Association and are in widest use are described in Aluminum Standards and Data.

An additional complication to be dealt with is the fact that, typically, each country around the world has its own designations system for aluminum alloys and tempers. Fortunately, great progress is being made in improving that situation, and the Aluminum Association’s alloy designation system is now recognized by about 90% of the world’s aluminum industry. The publication Recommendation: International Designation System for Wrought Aluminum and Wrought Aluminum Alloys (see Chapter 8) has been accepted almost universally, and progress is slowly being made in broadening the agreement to cast alloys and certain basic temper designations as well. Regrettably, however, experience indicates that full acceptance of universal equivalents has not yet been completed, and situations requiring producers and buyers to discuss clarifications can still occur.

The Keys to Understanding

Thus, the principal keys to gaining a good introduction to aluminum alloys and tempers are knowledge and understanding of the alloy and temper designations systems themselves. The main mission of this book is to build upon the information available in sources such as The Aluminum Association Alloy and Temper Registration Records and Aluminum Standards and Data to shed more light and understanding on the characteristics, production technology, and applications for the most commonly used aluminum alloys and tempers.

To accomplish this, the basic aluminum alloy and temper designation systems, as developed by the Aluminum Association and documented in Aluminum Standards and Data and ANSI H35.1, are presented in Chapter 2. Chapter 3 explains the alloy designation system in greater detail with examples, and Chapter 4 covers the temper designation system in a similar manner. The processes used to produce aluminum alloy products are described briefly in Chapter 5, and representative applications are described in Chapter 6.

We want to emphasize that the real authority on aluminum alloys and tempers is the Aluminum Association Technical Committee on Product Standards (TCPS), the group that, on behalf of the Aluminum Associa-
tion, maintains the alloy and temper designation systems and registers new alloys and tempers as they come along. At times, there is an unfortunate tendency on the part of some producers and fabricators to intentionally or unintentionally create their own designations for aluminum alloys and tempers and to do so in a style that misleadingly suggests that the newly created designations have been recognized by the industry as a whole through the registration process. This is unethical and improper because it misleads producers and users alike as to the heritage of the designation and dilutes the value of systems based on uniformity and industry standards. The independent creation of either alloy or temper designations without the complete registration process defined by the Aluminum Association and ANSI H35.1 is to be avoided.

Any questions or decisions needed on existing or new registrations should be directed to that group at the following address:

Aluminum Association Technical Committee on Product Standards
The Aluminum Association, Inc.
900 Nineteenth Street, NW, Suite 300
Washington, DC 20006

We want to emphasize that the mission of this publication is to provide a brief introduction to aluminum alloys, including their applications. For more detail on the various aspects of this subject, readers are encouraged to consult the selected references in Chapter 8, particularly the complete treatise on the aluminum industry by D.G. Altenpohl, *Aluminum: Technology, Applications, and Environment.*

**Characteristics of Wrought Aluminum Alloys**

It is appropriate to briefly note at this stage some of the basic characteristics of wrought aluminum alloys that make them desirable candidates for a wide range of applications. Wrought alloys are addressed first, then cast alloys.

**Corrosion Resistance.** As a result of a naturally occurring tenacious surface oxide film, many aluminum alloys provide exceptional resistance to corrosion in many atmospheric and chemical environments. Alloys of the 1xxx, 3xxx, 5xxx, and 6xxx systems are especially favorable in this respect and are even used in applications where they are in direct contact with seawater and antiskid salts.

**Thermal Conductivity.** Aluminum and aluminum alloys are good conductors of heat, and while they melt at lower temperatures than steels, approximately 535 °C (1000 °F). They are slower than steel to reach very high temperatures in fire exposure.
Electrical Conductivity. Pure aluminum and some of its alloys have exceptionally high electrical conductivity (i.e., very low electrical resistivity), second only to copper among common metals as conductors.

Strength/Weight Ratio. The combination of relatively high strength with low density means a high strength efficiency for aluminum alloys and many opportunities for replacement of heavier metals with no loss (and perhaps a gain) in load-carrying capacity. This characteristic, combined with excellent corrosion resistance and recyclability, has led to the broad use of aluminum in containers, aircraft, and automotive applications.

Fracture Toughness and Energy Absorption Capacity. Many aluminum alloys are exceptionally tough and make excellent choices for critical applications where resistance to brittle fracture and unstable crack growth are imperatives. Alloys of the 5xxx series, for example, are prime choices for liquefied natural gas tankage. In addition, special high-toughness versions of aircraft alloys, such as 2124, 7050, and 7475, replace the standard versions of these alloys for critical bulkhead applications.

Cryogenic Toughness. Aluminum alloys, especially of the 3xxx, 5xxx, and 6xxx series, are ideal for very low temperature applications because of the detailed documentation that their ductility and toughness, as well as strength, are higher at subzero temperatures, even down to near absolute zero, than at room temperature.

Workability. Aluminum alloys are readily workable by a great variety of metalworking technologies and are especially amenable to extrusion (the process of forcing heated metal through shaped dies to produce specific shaped sections). This characteristic enables aluminum to be produced in a remarkable variety of shapes in which the metal can be placed in locations where it can most efficiently carry the applied loads.

Ease of Joining. Aluminum alloys can be joined by a very broad variety of commercial methods, including welding, brazing, soldering, riveting, bolting, and even nailing, in addition to an unlimited variety of mechanical procedures. Welding, while considered difficult by those familiar only with joining steel and who try to apply the same techniques to aluminum, is particularly easy when performed by proven techniques such as gas metal arc welding (GMAW or MIG) or gas tungsten arc welding (GTAW or TIG).

Recyclability. Aluminum and aluminum alloys are among the easiest to recycle of any structural materials. They are recyclable in the truest sense, unlike materials that are reused but in lower-quality products; aluminum alloys may be recycled directly back into the same high-quality products, such as rigid containers, sheet, and automotive components.
Characteristics of Cast Aluminum Alloys

The desirable characteristics of wrought alloys also are generally applicable to cast alloys, but in fact, the choice of one casting alloy over another tends to be determined by the relative abilities of the alloy to meet one or more of the following characteristics:

- Ease of casting
- Strength
- Quality of finish

Unfortunately, few alloys or alloy series possess all three characteristics, but some generalizations may be made.

**Ease of Casting.** The high-silicon 3xx.x series are outstanding in this respect because their relatively high silicon contents lend a characteristic of good flow and mold-filling capability. As a result, the 3xx.x series are the most widely used and especially chosen for large and very complex castings.

**Strength.** The 2xx.x alloys typically provide the very highest strengths but are more difficult to cast and lack good surface characteristics. Therefore, their use usually is limited to situations where expert casting techniques can be applied and where strength and toughness are at a premium, such as in the aerospace industry.

**Finish.** The 5xx.x and 7xx.x series are noteworthy for the fine finish they provide, but they are more difficult to cast than the 3xx.x series and so usually are limited to those applications where that finish is paramount. A good example is the use of 7xx.x alloys for bearings.

Definitions for Aluminum and Aluminum Alloys

A few of the most useful definitions for aluminum and aluminum alloys and products applicable to the discussion in this book are listed in this section. A more complete listing of applicable terminology is included in the Appendix. The definitions included therein are taken primarily from *Aluminum Standards and Data*, with some additions from *Product Design for Die Casting in Recyclable Aluminum, Magnesium, Zinc, and ZA Alloys* and *Aluminum Casting Technology* (Chapter 8, “Selected References,” contains details).

Some widely used definitions include:

- *Commercially pure aluminum:* Commercially pure (CP) aluminum contains a minimum of 99% “pure” metal. Various specialty grades of
higher purity exist for use in special applications, up to and including
the “six nines” aluminum (i.e., 99.9999% pure aluminum).

- **Aluminum alloy:** A substance having metallic properties and composed of two or more elements of which at least one is an elemental metal. Most aluminum alloys contain 90 to 96% aluminum, with one or more other elements added to provide a specific combination of properties and characteristics. It is quite usual to have several minor alloying elements in addition to one or two major alloying elements to impart special fabrication or performance characteristics.

- **Strain-hardenable aluminum alloy:** This is the type of alloy for which the major and minor alloying elements do not provide significant solid solution and precipitation strengthening during any type of thermal treatment and which, therefore, must be strengthened principally by strain hardening (i.e., by cold rolling or drawing). These alloys are referred to as **strain hardenable.**

- **Heat treatable aluminum alloy:** For this type of alloy, the major, and perhaps some minor, alloying elements do provide significant solid solution and precipitation strengthening during solution heat treatment and subsequent aging. These alloys are referred to as **heat treatable.**

- **Wrought aluminum alloy:** This term is applied to alloys produced in ingot or billet form and subsequently worked by any of a number of processes such as rolling, extruding, forging, drawing, or other metalworking process to produce semifinished products from which end-use products are subsequently made.

- **Cast aluminum alloy:** This term is used in the context of this reference to mean alloys that generally are used in parts cast to final or near-final shape and to the ingot from which such castings are made. Generally speaking, cast alloy compositions are not used for subsequent rolling, extrusion, forging, or other metal shaping processes. Casting as discussed herein does not generally apply to the production of ingots, billets, or other stock primarily intended for subsequent metalworking.

- **Specification Limits and Test Directions:** Most aluminum alloy specifications include tensile property limits, which individual lots are expected to equal or exceed in 99% of the instances with 95% confidence. Tensile test specimens used for such determinations have prescribed specimen directions or orientations. The standard orientations most often referred to in material specifications and in testing documents and reports in general are the following:

  a. **Longitudinal:** The axis of the specimen is parallel to the longitudinal axis of the product and to the direction of major grain flow in the product.

  b. **Long transverse:** The axis of the specimen is normal to the longitudinal axis of the product and to the direction of major grain flow in the product, and it is within the major plane of the product.
In relatively thin sections, this orientation may be referred to simply as the transverse direction.

c. **Short transverse:** The axis of the specimen is normal to the major plane of the product, and thus normal to both the longitudinal and long transverse directions. This orientation is used only when products are thick enough to permit the taking of practical specimen sizes.

All tensile tests and, in fact, all mechanical tests, are made in accordance with the appropriate ASTM standard test procedures as presented in the *Annual Book of ASTM Standards*.

### Applications of Aluminum Alloys

It is useful in gaining an improved understanding of the alloy and temper designations for aluminum alloys to look at a variety of typical applications for a variety of the alloys in various tempers. Accordingly, the applications are reviewed in Chapter 6, both by alloy type and by market area. This review provides additional insight into the advantages and disadvantages of the various alloy groups and illustrates the application of specific tempers for specific performance needs.

Many of the examples included herein are taken from D.G. Altenpohl’s book, *Aluminum: Technology, Applications and Environment*, and readers looking for additional details on the variety of applications of aluminum, as well as a greater understanding of the aluminum industry in total, are encouraged to consult that reference.

### Microscopy of Aluminum and Aluminum Alloys

To further assist the reader in understanding the principles of the alloy and temper designation systems and the consequences of applying the production technology implied by the temper designations, a catalog of micrographs is included in Chapter 7 of this book. While not exhaustively representing all alloys and tempers referenced in the text, a good cross section of the aluminum alloys and tempers discussed in this text is included.

### Units and Unit Conversion

The reader will note that the normal procedures for handling English/engineering and metric units in ASM publications are not followed in this book. Rather, in this book about aluminum alloys, tempers, products, and applications, the standard procedures of the aluminum industry as
documented by the publications of the Aluminum Association have been followed. These procedures are described briefly as follows.

For wrought aluminum alloy products, the U.S. aluminum industry elected upon establishing metric standards for aluminum and aluminum alloy products to develop property limits and product dimensions in normal rounded values the way they would be found in a metric environment, a practice known as “hard conversion.” This is in sharp contrast to the much less useful procedure known as “soft conversion” of using the odd numbers that result from direct calculation from the English/engineering values.

As a result, when tables of properties for wrought alloys are presented herein (e.g., Tables 2 and 2M in Chapter 4), two separate tables are shown, one of English/engineering units, and one in metric/International Standard units. These may not be readily converted back and forth since each represents a separate but compatible set of standards.

The practice followed in this book is completely consistent with that followed by the Aluminum Association, Inc., in publishing two complete sets of the standards for wrought alloys for the industry, one in each units system. For additional, more detailed information on industry practices, the reader is referred to Aluminum Standards and Data and Aluminum Standards and Data 1998 Metric SI.

For aluminum alloy castings, metric (SI) conversions used by the aluminum industry are rounded soft (direct) conversions with rounding to represent comparable rounding used in the English/engineering system. Metric values are calculated using the exact conversion factors and then rounded to the nearest five megapascals, (i.e., 5 MPa, which is similar to rounding to the nearest thousand psi [ksi]) for strengths and nearest gigapascals (i.e., 1 MPa $\times 10^6$, or GPa) for moduli.

For both wrought and cast aluminum alloys, elongations are about 5 to 10% lower when determined in accordance with international standard methods compatible with the metric system (i.e., using gage lengths of 5D [five times the specimen diameter] rather than 4D as with engineering methods). Accordingly, elongations are reported at about 10% lower in metric (SI) tables. Note that this is not the result of a calculated conversion as for strength or modulus, but the result of a difference in the standard tensile test procedure.