Foundations of
Materials Science and Engineering

WILLIAM SMITH | JAVAD HASHEMI

SIXTH EDITION

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Foundations of Materials Science and Engineering

Sixth Edition

William F. Smith
Late Professor Emeritus of Engineering of
University of Central Florida

Javad Hashemi, Ph.D.
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PREFACE

The subject of materials science and engineering is an essential course to engineers and scientists from all disciplines. With advances in science and technology, development of new engineering fields, and changes in the engineering profession, today's engineer must have a deeper, more diverse, and up-to-date knowledge of materials-related issues. At a minimum, all engineering students must have the basic knowledge of the structure, properties, processing, and performance of various classes of engineering materials. This is a crucial first step in the materials selection decisions in everyday rudimentary engineering problems. A more in-depth understanding of the same topics is necessary for designers of complex systems, forensic (materials failure) analysts, and research and development engineers/scientists.

Accordingly, to prepare materials engineers and scientists of the future, *Foundations of Materials Science and Engineering* is designed to present diverse topics in the field with appropriate breadth and depth. The strength of the book is in its balanced presentation of concepts in science of materials (basic knowledge) and engineering of materials (applied knowledge). The basic and applied concepts are integrated through concise textual explanations, relevant and stimulating imagery, detailed sample problems, electronic supplements, and homework problems. This textbook is therefore suitable for both an introductory course in materials at the sophomore level and a more advanced (junior/senior level) second course in materials science and engineering. Finally, the sixth edition and its supporting resources are designed to address a variety of student learning styles based on the well-known belief that not all students learn in the same manner and with the same tools.

The following improvements have been made to the sixth edition:

- Chapter 1, Introduction to Materials Science and Engineering, has been updated to reflect the most recent available data on the use of various classes of materials in diverse industries. The use of materials in aerospace and automotive industries is discussed in detail. The historical competition among major classes of materials has been discussed in more detail and updated.
- All chapters have been reviewed for accuracy of content, images, and tables. New images representing more recent engineering applications have been included in all chapters. Diffusivity data in Chapter 5 has been updated. The mechanical property discussion in Chapter 6 has been expanded to include modulus of resilience and toughness. The iron-carbon phase diagram in Chapter 9 has been updated and improved. The concept of glass transition temperature has been expanded upon in the discussion of polymers in Chapter 10. The classification of composite materials in Chapter 12 has been expanded and improved. In Chapter 13, the sign convention in reporting the half-cell potentials has been made consistent with IUPAC conventions. The state of the art in microprocessor manufacturing, capability, and design has been updated.

- The end-of-chapter problems have been classified according to the learning/understanding level expected from the student by the instructor. The classification is based on Bloom's Taxonomy and is intended to help students as well as instructors to set goals and standards for learning objectives. The first group in the classification is the Knowledge and Comprehension Problems. These problems will require students to show learning at the most basic level of recall of information and recognition of facts. Most problems ask the students to perform tasks such as define, describe, list, and name. The second group is the Application and Analysis Problems. In this group, students are required to apply the learned knowledge to the solution of a problem, demonstrate a concept, calculate, and analyze. Finally, the third class of problems is called Synthesis and Evaluation Problems. In this class of problems, the students are required to judge, evaluate, design, develop, estimate, assess, and in general synthesize new understanding based on what they have learned from the chapter. It is worth noting that this classification is not indicative of the level of difficulty, but simply different cognitive levels.
- For most chapters, new problems—mostly in the synthesis and evaluation category—have been developed. These problems are intended to make the students think in a more in-depth and reflective manner. This is an important objective of the authors to help instructors to train engineers and scientists who operate at a higher cognitive domain.
- The instructors' PowerPoint® lectures have been updated according to the changes made to various chapters. These detailed, yet succinct, PowerPoint lectures are highly interactive and contain technical video clips, tutorials for problem solving, and virtual laboratory experiments. The PowerPoint lectures are designed to address a variety of learning styles including innovative, analytic, common sense, and dynamic learners. Not only is this a great presentation tool for the instructor, it creates interest in the student to learn the subject more effectively. We strongly recommend that the instructors for this course view and test these PowerPoint lecture presentations. This could be especially helpful for new instructors.

Additional resources available through the Instructor Resources are interactive quizzing, and step-by-step, real-life processes; animations; and a searchable materials properties database.

ACKNOWLEDGMENTS

The co-author, Javad Hashemi, would like to dedicate his efforts on this textbook to the eternal-loving memory of his parents Seyed-Hashem and Sedigheh; to his wife, mentor, and friend, Eva; to his sons Evan Darius and Jonathon Cyrus; and last but not least to his siblings (thank you for your ceaseless love and support).

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ABOUT THE COVER

A race car is an example of a complex mechanical system that utilizes a variety of materials from all five classes in its structure. For instance, for the race car in the image, the body is made of lightweight carbon fiber composites to save weight, the chassis is made of strong and tough steel alloys, the tires are made of durable vulcanized rubber, key components in the engine and brake system are either made of or coated with ceramic materials to withstand high temperature, and a variety of sensors as well as the on-board computer system uses electronic materials. The design and selection of materials for the race car is based on many factors including safety, performance, durability, and cost.

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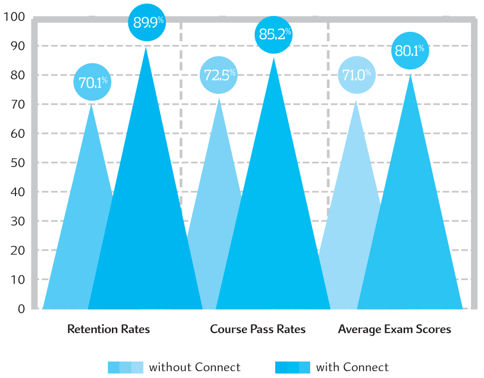

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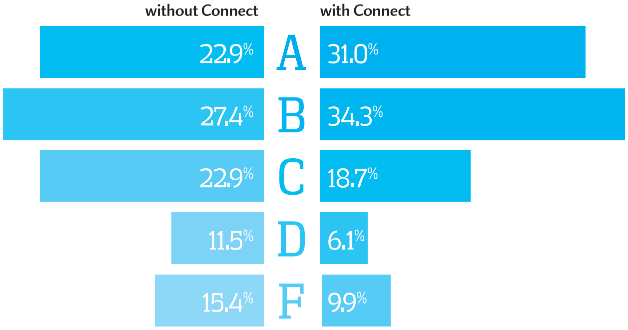

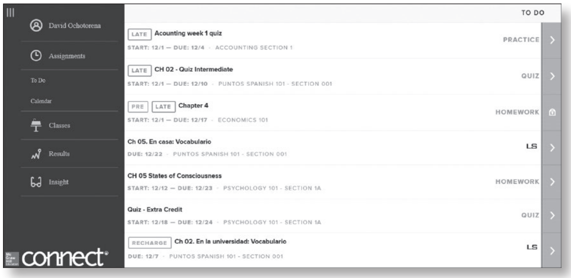

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PRACTICE

LATE CH 02 - Quiz Intermediate
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QUIZ

PRE LATE Chapter 4
START: 12/1 — DUE: 12/17 · ECONOMICS 101
HOMEWORK

Ch 05. En casa: Vocabulario
DUE: 12/22 · PUNTOS SPANISH 101 - SECTION 001
LS

CH 05 States of Consciousness
START: 12/12 — DUE: 12/23 · PSYCHOLOGY 101 - SECTION 1A
HOMEWORK

Quiz - Extra Credit
START: 12/18 — DUE: 12/24 · PSYCHOLOGY 101 - SECTION 1A
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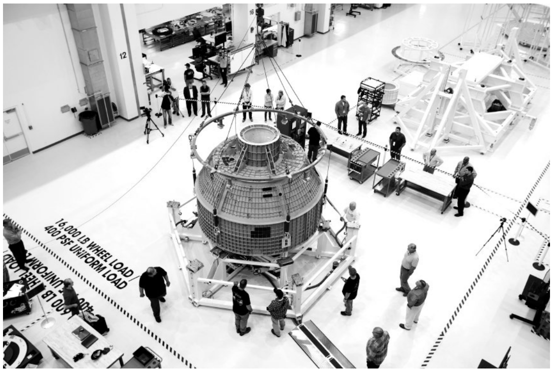
Foundations of Materials Science and Engineering

CHAPTER

1

Introduction to Materials Science and Engineering

(Source: NASA)



(Source: Daniel Casper/NASA)

One of the most exciting proposed NASA missions is the human journey to Mars by the 2030s. The scientific questions that can be answered by actual human presence on Mars are too numerous and very exciting. A convoy of three NASA orbiters and two active rovers are already functioning on and around Mars to gather more information about the Red Planet in order to pave the way for future manned explorations. NASA engineers, together with U.S. aerospace companies such as Lockheed Martin, are putting together the Space Launch System (SLS) rocket that will take the Orion spacecraft on its manned Mars mission. Consider the technologies and the engineering knowledge needed to build the Orion spacecraft and complete such a mission. Following are some of the engineering and materials-related issues considered by NASA and Lockheed Martin in manufacturing the spacecraft.

Pressure testing: The Orion capsule, called the "birdcage," has an underlying welded metallic structure that must contain the atmosphere for the crew during launch, space travel, reentry, and landing. The capsule will provide living space for the astronauts and must withstand the loads sustained during launch and landing. It is crucial that the structure be able to withstand the maximum internal pressurization needed for the journey. What metal would be suitable for the underlying structure? What properties should it have?

Tile bonding: During reentry, the Orion spacecraft will enter Earth's atmosphere at speeds of 25,000 miles per hour and will be exposed to very high temperatures exceeding 5000°F. The "birdcage" of Orion, discussed above, cannot function at such high temperatures and requires a thermal protection system. NASA will use about 1300 ceramic tiles to protect the capsule in addition to a heat shield. Why use ceramic

LEARNING OBJECTIVES

By the end of this chapter, students will be able to

1. Describe the subject of materials science and engineering as a scientific discipline.
2. Cite the primary classification of materials.
3. Give distinctive features and charactersitics of each group of materials.
4. Name various material from each group. Give some applications of different types of materials.
5. Evaluate how much you know and how much you do not know about materials.
6. Establish the importance of materials science and engineering in the selection of materials for various applications.

tiles? What properties do they possess that makes them attractive as a thermal protection system? What is the heat shield made of? What characteristics should it have?

Flight systems and subsystems: For Orion to function and communicate, it needs its avionics. This includes electrical power storage and distribution, thermal control systems, cabin pressure monitoring, communication command, data handling, guidance, navigation and controls, propulsion, and computers. The slew of sensors and actuators needed for the these operations require the use of advanced electronics materials. What are the applications of electronics materials in space travel? Why are such materials crucial to the success of the mission?

Vibration tests: The Orion spacecraft will encounter vibrations due to interaction with Earth's atmosphere. It is crucial that the spacecraft be able to withstand such vibrations, and all systems, structural or electronic, must function under extreme conditions. NASA tested the Orion capsule using two electromagnetic shakers and exposed it to vibration frequencies ranging from 5 Mhz to 500 Mhz. What strategies for vibration dampening could be used? What materials would be beneficial for dampening vibration?

These are only some of the questions, tests, and considerations that NASA and Lockheed Martin engineers make in manufacturing of this complex system. Can you think of other issues that need be considered? What is the role of materials science and engineering in answering those questions? ■

1.1 MATERIALS AND ENGINEERING

Humankind, **materials,** and engineering have evolved over the passage of time and are continuing to do so. All of us live in a world of dynamic change, and materials are no exception. The advancement of civilization has historically depended on the improvement of materials to work with. Prehistoric humans were restricted to naturally accessible materials such as stone, wood, bones, and fur. Over time, they moved from the materials Stone Age into the newer Copper (Bronze) and Iron ages. Note that this advance did not take place uniformly everywhere—we shall see that this is true in nature even down to the microscopic scale. Even today we are restricted to the materials we can obtain from Earth's crust and atmosphere (Table 1.1). According to Webster's dictionary, materials may be defined as substances of which something is composed or made. Although this definition is broad, from an engineering application point of view, it covers almost all relevant situations.

The production and processing of materials into finished goods constitutes a large part of our present economy. Engineers design most manufactured products and the processing systems required for their production. Since products require materials, engineers should be knowledgeable about the internal structure and properties of materials, as well as methods to manufacture components form those materials, so that they can choose the most suitable material for each application and develop the best processing methods.

Research and development engineers create new materials or modify the properties of existing ones. Design engineers use existing, modified, or new materials to design and create new products and systems. Sometimes design engineers have a problem in their design that requires a new material to be created by research scientists and engineers.

For example, NASA engineers designing the supersonic passenger planes (X-planes) (Fig. 1.1) will have to use high-temperature materials that withstand temperatures in excess of 1800°C in the engine environment in order to achieve supersonic airspeeds as high as Mach 12 to 25 (12 to 25 times the speed of sound in air). In addition, these planes must meet the demands of today's society by flying greener (less damaging to the environment and more renewable), safer, and quieter.

Another area that demands the most from materials scientists and engineers is space exploration. The design and construction of the *International Space Station*

Table 1.1 The most common elements in planet Earth's crust and atmosphere by weight percentage and volume

Element	Weight Percentage of the Earth's Crust
Oxygen (O)	46.60
Silicon (Si)	27.72
Aluminum (Al)	8.13
Iron (Fe)	5.00
Calcium (Ca)	3.63
Sodium (Na)	2.83
Potassium (K)	2.70
Magnesium (Mg)	2.09
Total	98.70
Gas	**Percent of Dry Air by Volume**
Nitrogen (N_2)	78.08
Oxygen (O_2)	20.95
Argon (Ar)	0.93
Carbon dioxide (CO_2)	0.03

Figure 1.1
Nasa's X-plane is in the preliminary design stage and is expected to be built based on Quiet Supersonic Technology (QueSST). The major goals for the new designs are to burn half the fuel, generate 75% less pollution, and be quieter than conventional jets even during supersonic flight.
(Source: NASA)

(ISS) and the *Mars Exploration Rover* (MER) missions are examples of space research and exploration activities that require the absolute best from our materials scientists and engineers. The construction of ISS, a large research laboratory moving at a speed of 27,000 km/h through space, required the selection of materials that would function in an environment far different than ours on Earth (Fig. 1.2). The materials had to be lightweight to minimize payload weight during liftoff. The outer shell had to protect against the impact of tiny meteoroids and human-made debris. The internal air pressure of roughly 15 psi is constantly stressing the modules. Additionally, the modules must withstand the massive stresses at launch. Materials selection for MERs is also a challenge, especially considering that they must survive an environment in which night temperatures could be as low as −96°C. These and other constraints push the limits of material selection in the design of complex systems.

We must remember that materials usage and engineering designs are constantly changing. This change continues to accelerate. No one can accurately predict the long-term advances in material design and usage. In 1943 the prediction was made that successful people in the United States would own their own autogyros (auto-airplanes). How wrong that prediction was! At the same time, the transistor, the integrated circuit, and television (color and high-definition included) were neglected. Thirty years ago, many

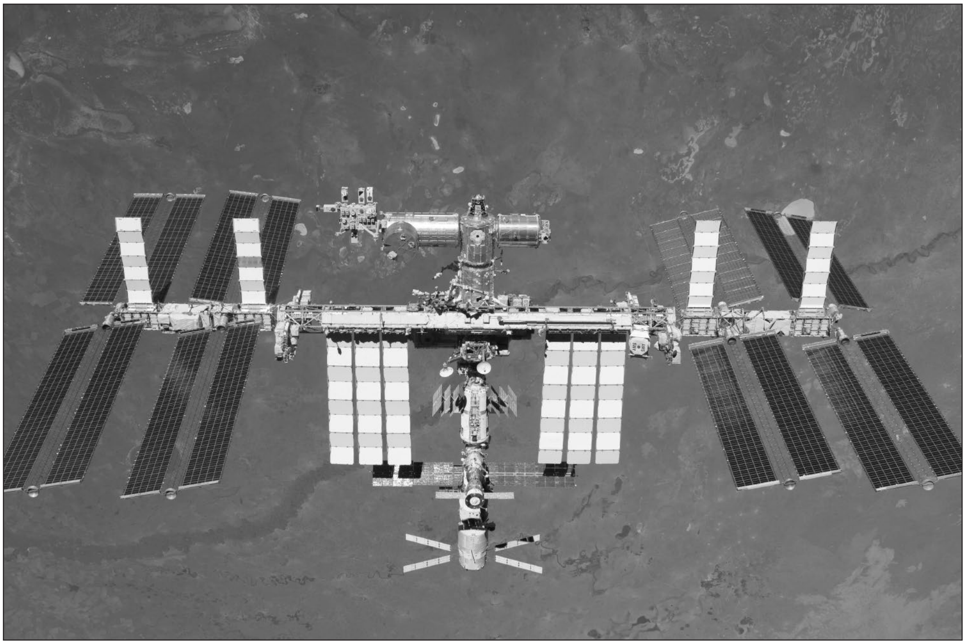


Figure 1.2
The International Space Station.
(Source: NASA)

people would not have believed that someday computers would become a common household item similar to a telephone or a refrigerator. And today, we still find it hard to believe that someday space travel will be commercialized, and we may even colonize Mars. Nevertheless, science and engineering push and transform our most unachievable dreams to reality.

The search for new advanced materials goes on continuously. The industries that benefit heavily from new advances in materials science and engineering and require a tremendous number of materials experts in their daily operations are aerospace, automotive, biomaterials, chemical, electronics, energy, metals, and telecommunications. The focus on certain materials differs significantly between industries. For instance, in aerospace and automobile industries, the focus is mainly structural and is on airframe and engine materials. In biomaterials industries, the focus is on materials that are biocompatible (can survive in the human body) and also on synthesizing biological materials and components. In the chemical industries, the focus is on traditional chemicals, polymers, and advanced ceramics. In the electronics industries, material used in computers and commercial electronics takes center stage. In the energy industry, materials used in extraction of both fossil-based and renewable energy are the focus. Each industry also seeks different characteristics in their materials. These characteristics and the needs in the respective industries are presented in Table 1.2.

Table 1.2 Use of advanced materials in selected industries and their desired characteristics.

	Industry							
Desired Characteristics	**Aerospace**	**Automotive**	**Biomaterials**	**Chemical**	**Electrical**	**Energy**	**Metals**	**Telecommunication**
Light and strong	✓	✓	✓					
High temperature resistance	✓			✓		✓	✓	
Corrosion resistance	✓	✓	✓	✓		✓	✓	
Rapid switching					✓	✓		✓
Efficient processing	✓	✓	✓	✓	✓	✓	✓	✓
Near net shape forming	✓	✓	✓	✓	✓	✓	✓	✓
Recycling		✓		✓			✓	
Prediction of service life	✓	✓	✓	✓	✓	✓		✓
Prediction of physical properties	✓	✓	✓	✓	✓	✓	✓	✓
Materials data base	✓	✓	✓	✓	✓	✓	✓	✓

Source: National Academy of Sciences.

More recently, the field of nanomaterials has attracted a great deal of attention from scientists and engineers all over the world. Novel structural, chemical, and mechanical properties of nanomaterials have opened new and exciting possibilities in the application of these materials to a variety of engineering and medical problems. These are only a few examples of the search by engineers and scientists for new and improved materials and processes for a multitude of applications. In many cases, what was impossible yesterday is a reality today!

Engineers in all disciplines should have some basic and applied knowledge of engineering materials so that they will be able to do their work more effectively when using them. The purpose of this book is to serve as an introduction to the internal structure, properties, processing, and applications of engineering materials. Because of the enormous amount of information available about engineering materials and due to the limitations of this book, the presentation has had to be selective.

1.2 MATERIALS SCIENCE AND ENGINEERING

Materials science is primarily concerned with the search for basic knowledge about the internal structure, properties, and processing of materials. **Materials engineering** is mainly concerned with the use of fundamental and applied knowledge of materials so that the materials can be converted into products needed or desired by society. The term *materials science and engineering* combines both materials science and materials engineering and is the subject of this book. Materials science is at the basic knowledge end of the materials knowledge spectrum, and materials engineering is at the applied knowledge end, and there is no demarcation line between the two (Fig. 1.3).

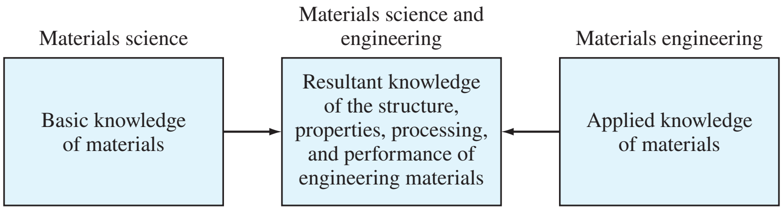


Figure 1.3
Materials knowledge spectrum. Using the combined knowledge of materials from materials science and materials engineering enables engineers to convert materials into the products needed by society.

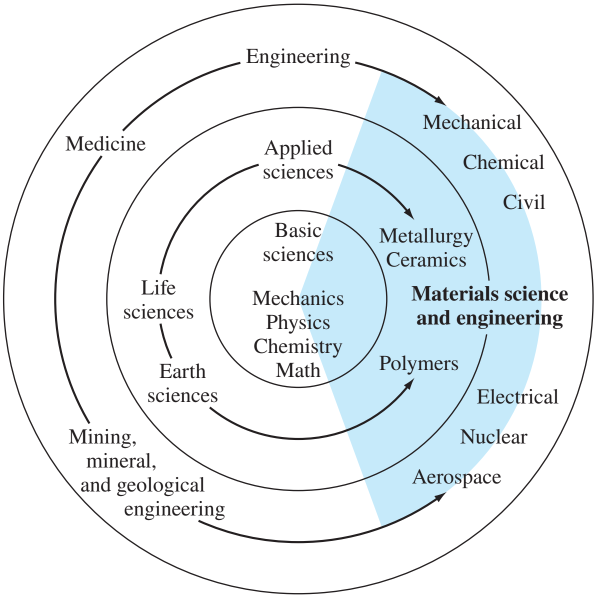


Figure 1.4
This diagram illustrates how materials science and engineering forms a bridge of knowledge from the basic sciences to the engineering disciplines.
(Source: National Academy of Sciences.)

Figure 1.4 shows a three-ringed diagram that indicates the relationship among the basic sciences (and mathematics), materials science and engineering, and the other engineering disciplines. The basic sciences are located within the inner ring or core of the diagram, while the various engineering disciplines (mechanical, electrical, civil, chemical, etc.) are located in the outermost third ring. The applied sciences, metallurgy, ceramics, and polymer science are located in the middle ring. Materials science and engineering is shown to form a bridge of materials knowledge from the basic sciences (and mathematics) to the engineering disciplines.

1.3 TYPES OF MATERIALS

For convenience most engineering materials are divided into *three* main or fundamental classes: **metallic materials, polymeric materials,** and **ceramic materials.** In this chapter we shall distinguish among them on the basis of some of their important mechanical, electrical, and physical properties. In subsequent chapters, we shall study the internal structural differences among these types of materials. In addition to the three main classes of materials, we shall consider two processing or applicational classes, **composite materials** and **electronic materials,** because of their great engineering importance.

1.3.1 Metallic Materials

These materials are inorganic substances that are composed of one or more metallic elements and may also contain some nonmetallic elements. Examples of metallic elements are iron, copper, aluminum, nickel, and titanium. Nonmetallic elements such as carbon, nitrogen, and oxygen may also be contained in metallic materials. Metals have a crystalline structure in which the atoms are arranged in an orderly manner. Metals in general are good thermal and electrical conductors. Many metals are relatively strong and ductile at room temperature, and many maintain good strength even at high temperatures.

Metals and alloys[1] are commonly divided into two classes: **ferrous metals and alloys** that contain a large percentage of iron such as the steels and cast irons and **nonferrous metals and alloys** that do not contain iron or contain only a relatively small amount of iron. Examples of nonferrous metals are aluminum, copper, zinc, titanium, and nickel. The distinction between ferrous and nonferrous alloys is made because of the significantly higher usage and production of steels and cast irons when compared to other alloys.

Metals in their alloyed and pure forms are used in many industries, including aerospace, biomedical, semiconductor, electronic, energy, civil structural, and transport. The U.S. production of basic metals such as aluminum, copper, zinc, and magnesium is expected to follow the U.S. economy fairly closely. For instance, in the United States alone, the primary metal product manufacturing industry distributed approximately $280 billion worth of products in 2014. The production of iron and steel (41% of the total primary metal distributed) has been steady considering global competition and the always-important economic reasons.

Materials scientists and engineers are constantly trying to improve the properties of existing alloys and to design and produce new alloys with improved strength, high-temperature strength, creep (see Sec. 7.4), and fatigue (see Sec. 7.2) properties. The existing alloys may be improved by better chemistry, composition control, and

---

[1] A metal alloy is a combination of two or more metals or a metal (metals) and a nonmetal (nonmetals).