PRINCIPLES OF

MATERIALS SCIENCE AND ENGINEERING

William F. Smith

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PREFACE

The primary purpose of this book is to provide a modern textbook for a basic course in engineering materials for undergraduate engineering students which can be used early in their program of studies. This book attempts to provide basic knowledge about the structure, properties, and processing of engineering materials and their applications. By studying the material presented in this book, the student engineer should be able to achieve the following:

1. Be aware of the main types of engineering materials used in industry and have some elementary knowledge of their processing.

2. Have basic knowledge of the structure of engineering materials and how their structure is related to some of their properties.

3. Be better able to select a material for a specific engineering application.

4. To have some direction of where to obtain further information about engineering materials.

To achieve the above purposes a great deal of effort has been made to provide as up-to-date information and photographs as possible. As we all know, new materials and processes are constantly being developed, and materials usage is constantly changing.

The material in this book has been divided into 13 chapters. At the ends of each chapter are a summary, definitions of important terms, an extensive list of problems relating to the material of the chapter, and a list of references for further study.

The first chapter gives an introduction to materials science and engineering and briefly describes the main types of engineering materials. Chapters 2 to 4 cover basic materials science subjects dealing primarily with structure. Chapters 5 and 6 relate structure to some basic electrical and mechanical properties. Chapter 5 provides extra material on microelectronics which may be optional. Attention is then turned to polymeric, metallic, and ceramic materials. Polymeric materials are treated first in Chapter 7 since they do not require a background in phase-diagram analysis. Chapter 8 then discusses phase diagrams as preparation for the study of metallic and ceramic materials that are covered in Chapters 9 and 10, respectively.

Chapter 11 deals with magnetic materials, which is of special interest to electrical engineering students, while Chapter 12 discusses some aspects of corrosion, which is of special interest to chemical and mechanical engineering students. Finally, Chapter 13 presents some information on composite materials including some discussion of advanced composites, our latest-type materials used in engineering designs. The last part of Chapter 13 deals with the structure and properties of concrete and wood, materials of particular interest to civil engineering students.

It is understood that not all the material in this book can be covered formally in a one-semester course in materials science and engineering, but the extra material provides the professor some flexibility with the subject matter covered in class and provides students an opportunity to expand their horizons in materials knowledge. Extra material on electronic, polymeric, ceramic, and composite materials has been included in the book as encouraged by many of the universities who participated in the "Survey of the Initial Engineering Materials Course" (*Journal of Materials Education*, vol. 5, no. 3, 1983). Also, many qualitative questions have been included at the end of each chapter to aid the student in the review of the material.

In writing a book it is always a pleasure to acknowledge the help of others. For this book in particular, the author acknowledges the use of excellent figures and photographs from other professors, scientists, and engineers which have greatly enriched this book. It has been my intent to properly acknowledge each of these. The author also wishes to thank each professor, engineer, and scientist who has personally sent copies of his research papers and photographs. My personal thanks also go to the following professors who have reviewed chapters of the book: George Cahen and Glen E. Stoner of the University of Virginia, Donald Saylak of Texas A & M University, C. Wert of the University of Illinois, Richard W. Vook of Syracuse University, C. M. Balik of North Carolina State University, Thomas H. Sanders of Purdue University, J. E. Spruiell of the University of Tennessee, and George R. St. Pierre of Ohio State University. Finally, I would like to acknowledge the help and encouragement received from Engineering Editor Sanjeev A. Rao of the McGraw-Hill Book Company and Professor Stephen L. Rice, Assistant Dean J. Paul Hartman, and Dean Robert D. Kersten of the University of Central Florida.

W. F. Smith

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1

INTRODUCTION TO MATERIALS SCIENCE AND ENGINEERING

1.1 MATERIALS AND ENGINEERING

Materials are substances of which something is composed or made. Since civilization began, materials along with energy have been used by people to improve their standard of living. Materials are everywhere about us since products are made of materials. Some of the commonly encountered materials are wood (timber), concrete, brick, steel, plastic, glass, rubber, aluminum, copper, and paper. There are many more kinds of materials, and one only has to look around oneself to realize that. Because of constant research and development, new materials are frequently being created.

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 so that they will be able to select the most suitable ones for each application and be able to develop the best processing methods.

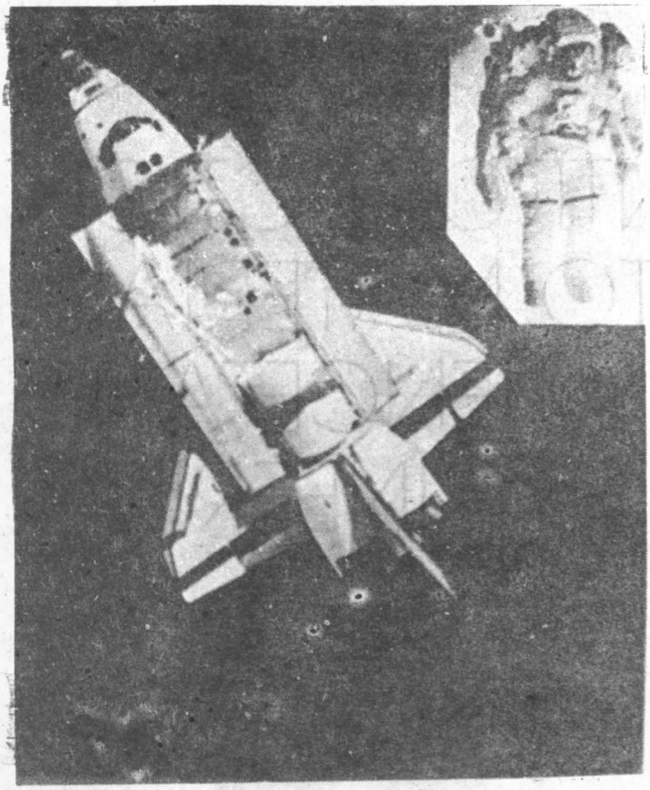

FIGURE 1.1 Materials play an important role in modern high technology. For example, the flight of the space shuttle shown was made possible in part by the development of a new ceramic material to provide a thermal protection system for the spacecraft. Another example of the application of modern materials in technology is the space-shuttle cargo bay doors that are fabricated from a carbon-fiber-epoxy composite material which has a very high strength-to-weight ratio. (*Photos courtesy of NASA.*)

Research and development engineers work to create new materials or to modify the properties of existing ones. Design engineers use existing, modified, or new materials to design and create new products and systems. Sometimes the reverse is the case, and design engineers have a problem in their design which requires a new material to be created by research scientists and engineers. For example, the engineers designing the reusable space shuttle required a thermal protection system which would protect it during a glowing 1315°C (2400°F) plunge through the earth's atmosphere. In this application a new material had to be researched and developed by scientists and engineers, and the result was the development of a new ceramic tile material. The space shuttle has been a great success partly because of the newly developed ceramic tile thermal protection system (Figs. 1.1, 1.2, and 1.7).

The search for new materials goes on continuously. For example, mechanical engineers search for higher-temperature materials so that jet engines can operate more efficiently. Electrical engineers search for new materials so that electronic devices can operate faster and at higher temperatures. Aerospace engineers search for materials with higher strength-to-weight ratios for aircraft and space vehicles. Chemical engineers look for more highly corrosion-

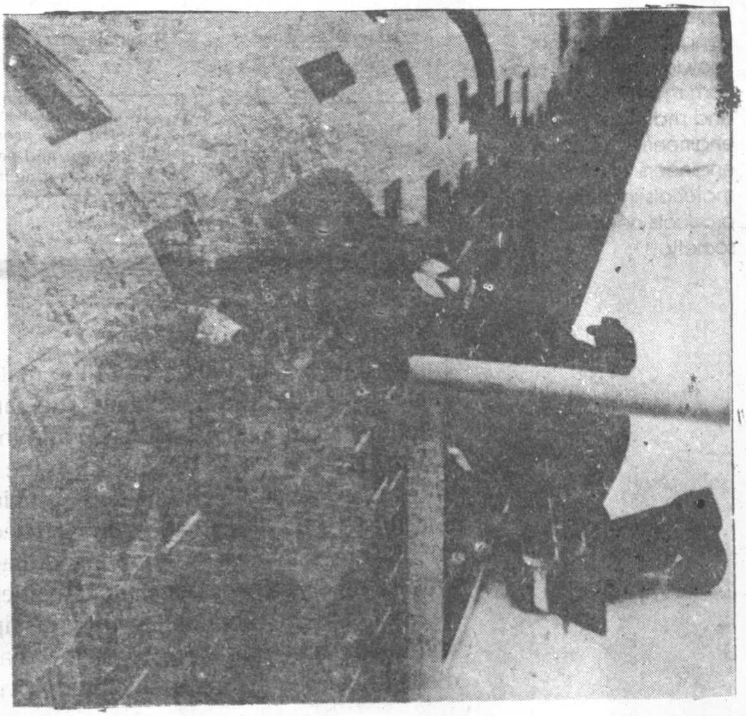

FIGURE 1.2 A Rockwell International technician is applying ceramic tiles to the outside of the space shuttle orbiter *Columbia* at the Kennedy Space Center. About 31,000 individual ceramic tiles make up the thermal protection system for the space shuttle orbiter so that the intense heat generated during its reentry into the earth's atmosphere can be absorbed. (*Photo courtesy of NASA.*)

resistant materials. These are only a few examples of the search by engineers for new and improved materials for 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 materials. 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 material presented has had to be selective. However, when possible, up-to-date references are listed to enable the student engineer to further study the fascinating world of engineering materials.

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

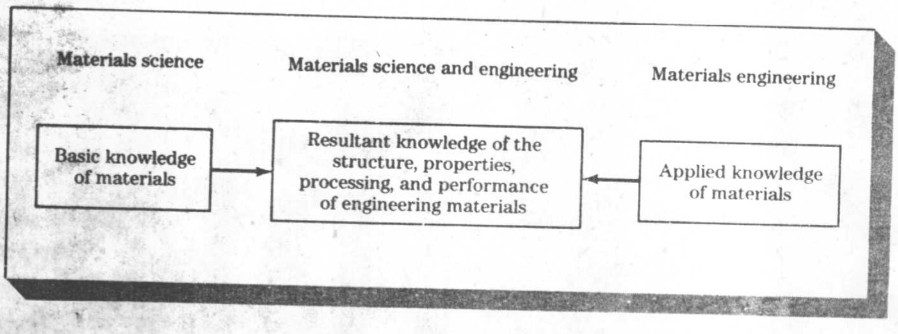

FIGURE 1.3 Materials knowledge spectrum. Using the combined knowledge of materials from materials science and materials engineering enables engineers to convert materials into the products needed by society.

knowledge of materials so that the materials can be converted into products necessary or desired by society. The name *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 at the applied knowledge end, and there is no demarcation line between the two (Fig. 1.3).

Figure 1.4 shows a three-ringed diagram which 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 first ring or core of the diagram, while the various engineering disciplines (mechanical, electrical, civil, chemical, etc.) are located in the

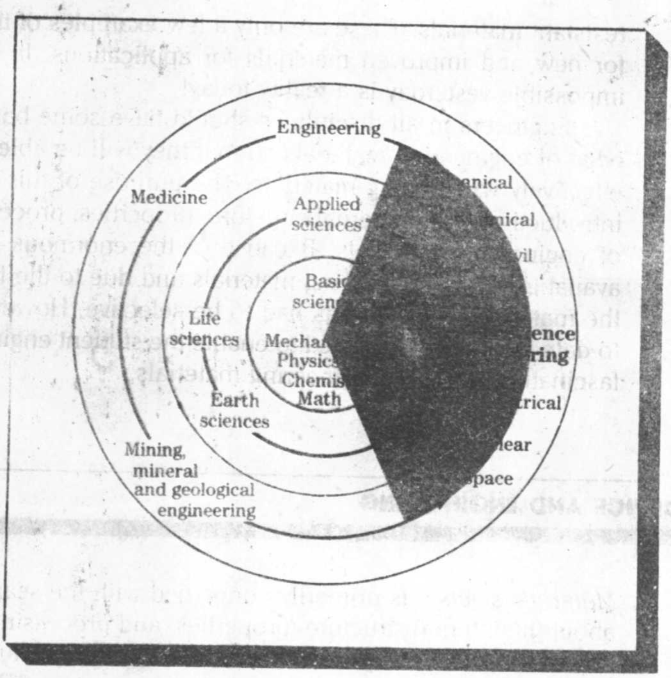

FIGURE 1.4 This diagram illustrates how materials science and engineering form a bridge of knowledge from the basic sciences to the engineering disciplines. (*Courtesy of the National Academy of Science.*)

outermost third ring. The applied sciences, metallurgy, ceramics, and polymer science are located in the middle or second 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 classes: *metallic, polymeric (plastic)*, 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 of these types of materials. In addition to the three main classes of materials, we shall consider two more types, *composite materials* and *electronic materials*, because of their great engineering importance.

Metallic Materials These materials are inorganic substances which 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 of electricity. Most metals are relatively strong and ductile at room temperature and many maintain good strength 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 only a relatively small amount of iron. Examples of nonferrous metals are aluminum, copper, zinc, titanium, and nickel.

Figure 1.5 is a photograph of a commercial aircraft jet engine which is made primarily of metal alloys. The metal alloys used inside the engine must be able to withstand the high temperatures and pressures generated during its operation. Many years of research and development work by scientists and engineers were required to perfect this advanced-performance engine.

Polymeric (Plastic) Materials Most polymeric materials consist of organic (carbon-containing) long molecular chains or networks. Structurally, most polymeric materials are noncrystalline but some consist of mixtures of crystalline and noncrystalline regions. The strength and ductility of polymeric materials vary greatly. Because of the nature of their internal structure, most polymeric materials are poor conductors of electricity. Some of these materials are good insulators and are used for

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

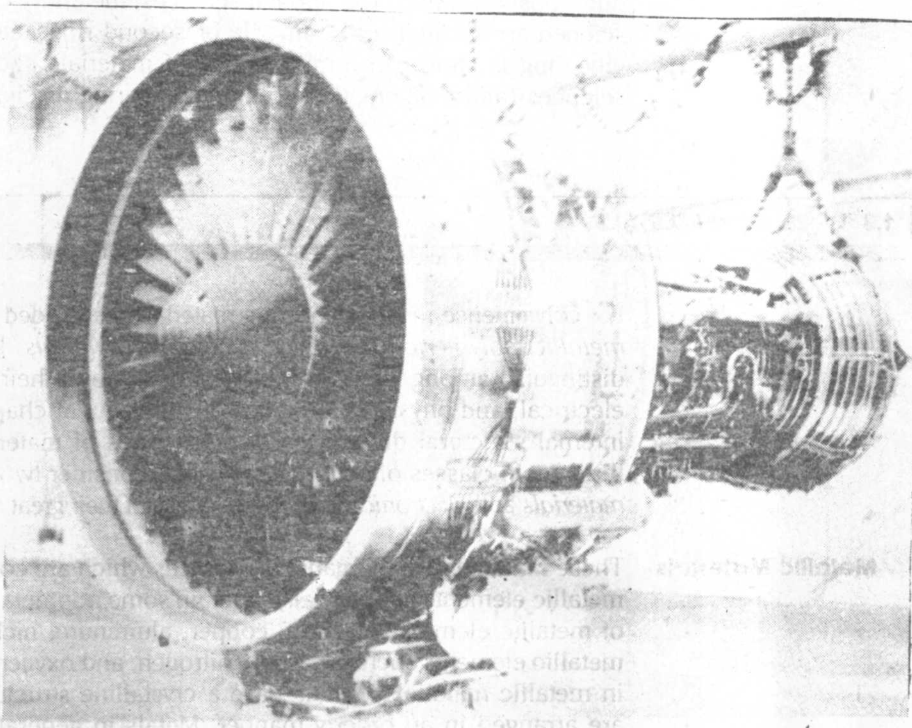

FIGURE 1.5 The aircraft turbine engine (PW2037) shown is made principally of metal alloys. The latest high-temperature-resistant, high-strength nickel-base alloys are used in this engine. The engine features a new solid-state digital electronic control system that eliminates frequent movement of the throttle by the flight crew. More efficient engine cooling also improves engine efficiency and fuel consumption. Engines of this type are constantly being improved by intensive engineering research and developmental work. (*Courtesy of the Pratt and Whitney Co.*)

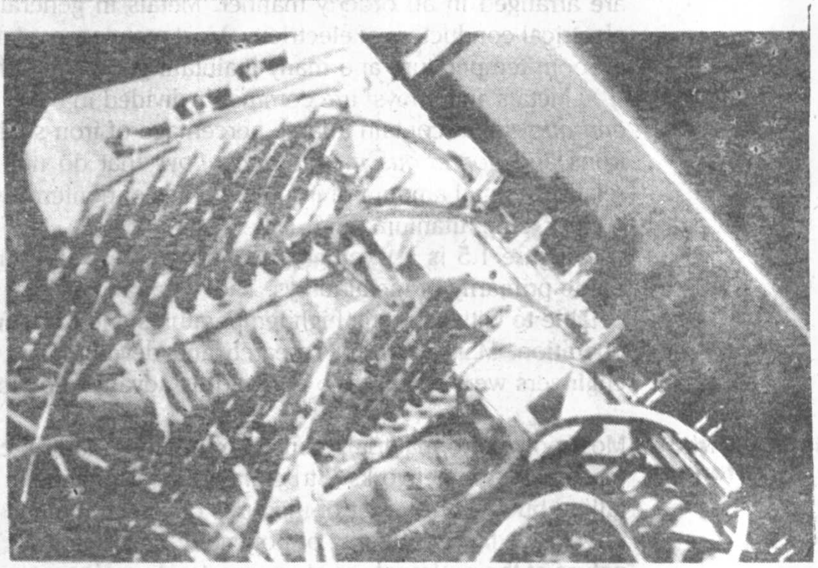

FIGURE 1.6 The excellent insulative properties of polycarbonate polymeric materials enable them to be used for electrical wire terminal boards such as the one shown, which is made of General Electric's Lexan 940. This type of material has superior dimensional stability, high-impact strength, and low-moisture absorption, which are advantageous properties for this application. (*Courtesy of General Electric Co.*)

electrical insulative applications (Fig. 1.6). In general polymeric materials have low densities and relatively low softening or decomposition temperatures.

Ceramic Materials Ceramic materials are inorganic materials which consist of metallic and nonmetallic elements chemically bonded together. Ceramic materials can be crys-

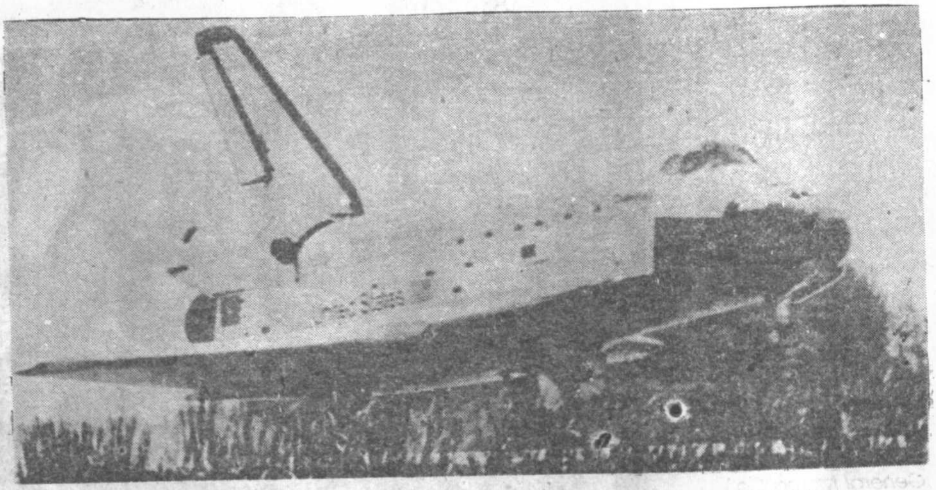

FIGURE 1.7 Landing of the thirteenth flight of the space shuttle on Oct. 13, 1984. The return of the space shuttle to the earth's surface is made possible by a thermal protection system of silica tiles which cover over about 70 percent of the shuttle's surface. The tiles are made of a rigidized, fibrous silica ceramic material. The silica-fiber tiles are able to undergo large temperature changes (e.g., from 1260°C to ambient temperature in a few minutes) without cracking from thermal shock. See Sec. 10.8 for further details. (*Photo: Orlando Sentinel.*)

talline, noncrystalline, or mixtures of both. Most ceramic materials have mechanical brittleness, high hardness, and high-temperature strength. Many ceramics have low thermal conductivity which makes them useful for insulative applications such as furnace linings for liquid metals. An important recent application of newly developed ceramic materials are the ceramic tiles for the space shuttle. These ceramic materials thermally protect the aluminum internal structure of the space shuttle during ascent out of and reentry into the earth's atmosphere (Figs. 1.2 and 1.7).

Composite Materials

Composite materials are mixtures of two or more materials. Most composite materials consist of a selected filler or reinforcing material and a compatible resin binder to obtain the specific characteristics and properties desired. Usually, the components do not dissolve in each other and can be physically identified by an interface between the components. Composites can be of many types. Some of the predominant types are fibrous (composed of fibers in a matrix) and particulate (composed of particles in a matrix). There are many different combinations of reinforcements and matrices used to produce composite materials. Two outstanding types of *modern composite materials* used for engineering applications are fiberglass-reinforcing material in a polyester or epoxy matrix and carbon fibers in an epoxy matrix. Figure 1.8 shows the single-leaf rear spring for the 1981 Corvette which was made from a combination of fiberglass reinforcement and an epoxy matrix.