THE SCIENCE AND ENGINEERING OF MATERIALS

SI Edition

DONALD R. ASKELAND

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PREFACE

Our understanding of the relationship between structure and properties provides the basis for our development of new materials. For instance, the electronic and atomic structure of materials has been our model for a myriad miniaturized electronic components. By manipulating molecular structure, we have produced a vast spectrum of polymers; by controlling microstructure, we have developed many new metal alloys and ceramics. And we've played wizard, juggling composite materials that have unique properties.

In engineering materials, we use such scientific understanding to shape materials into useful products. Our materials processing both depends on and influences the structure and properties we are using. For instance, we can obtain directional properties while casting or deformation-processing metals; the directional properties thus obtained in turn influence the subsequent processing and behavior of the metal. So we must link science and processing in order to understand and select materials for engineering applications.

The environments present during processing and use also affect the characteristics of a material. By melting and pouring aluminum alloys in air, for example, we can produce gas pores in the finished casting. High-strength alloys may (catastrophically) lose their properties when exposed to high temperatures. And the properties of polymers may change dramatically when the material is exposed to radiation.

This book presents the three-way relationship between structure, properties, and processing. The text can serve, first, those engineering students who are formally introduced to materials in only one course, who do not continue in this field. Such students need a basic understanding of material behavior, available materials, and the processing of materials so that they can help select materials. Second, this text can introduce the science of materials, the types of materials available, and the application and processing of materials to the materials-oriented engineering student. Such students will later go on to study the details in more advanced courses.

Part I of the text introduces atomic and crystal structure, the foundation for understanding the mechanical and physical behavior of materials. Part II explains how we control the structure and mechanical properties of metals, with an emphasis on strengthening mechanisms. This part also explores structure-property relationship by considering processing techniques—solidification, deformation, and heat treatment—as well as alloying. Part III describes the common alloys, ceramics, polymers, and composite materials, showing how to control their mechanical properties. For each, the structure-property relationship is developed, then individual materials are discussed, including processing and applications. Part IV presents physical properties via a reexamination of electronic and atomic structure. Changes in structure and processing affect engineering applications of materials. Finally, Part V describes the way materials perform during service, with an emphasis on preventing and analyzing corrosion and mechanical failure.

To use this book, students need some background in chemistry, physics, and higher mathematics; sophomore standing is recommended. By selecting topics, an instructor can emphasize metals, mechanical behavior, physical properties, or introductory materials science. The book offers many examples and practice problems to help students understand the principles of materials science and engineering.

Thanks are due to many people who have helped me prepare this text, especially Robert Wolf, Fred Kisslinger, Mike Norberg, Greg Lynch, and Darren Washaüsen. I am particularly indebted to my wife Mary and son Per.

NOTE TO SI EDITION

The adoption in Europe of the International System of units (SI) has prompted the editing of this textbook. An opportunity has been taken to change to SI units throughout the text with the exception of certain units which have been deliberately left in metric form because of the frequency of their use.

With the exception of very few minor alterations the text remains unchanged.

Certain British Standard Specifications have been included in Chapter 13—Ferrous Alloys.

Appendix C has been introduced to include certain SI nomenclature and a limited number of conversion factors.

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CHAPTER 1

Introduction to Materials

1-1 Introduction

All engineers are involved with materials on a daily basis. We manufacture and process materials, design and construct components or structures using materials, select materials, analyze failures of materials, or simply hope the materials we are using perform adequately.

As responsible engineers, we are interested in improving the performance of the product we are designing or manufacturing. Electrical engineers want integrated circuits to perform properly, switches in computers to react instantly, and insulators to withstand high voltages even under the most adverse conditions. Civil, structural, and architectural engineers wish to construct strong, reliable structures that are aesthetic and resistant to corrosion. Petroleum and chemical engineers require drill bits or piping that survive in abrasive or corrosive conditions. Automotive engineers desire lightweight yet strong and durable materials. Aerospace engineers demand lightweight materials that perform well both at high temperatures and in the cold vacuum of outer space. Metallurgical, ceramic, and polymer engineers wish to produce and shape materials that are more economical and possess improved properties.

The intent of this text is to permit the student to become aware of the types of materials available, to understand their general behavior and capabilities, and to recognize the effects of the environment and service conditions on the material's performance.

1-2 Types of Materials

We will classify materials into four groups—metals, ceramics, polymers, and composite materials (Table 1-1).

Metals. Metals and alloys, which include steel, aluminum, magnesium, zinc, cast iron, titanium, copper, nickel, and many others, have the general characteristics of good electrical and thermal conductivity, relatively high strength, high stiffness, ductility or formability, and shock resistance (Figure 1-1). They are particularly useful for structural or load-bearing applications. Although pure metals are occasionally used, combinations of metals called *alloys* are normally designed to provide improvement in a particular desirable property or permit better combinations of properties.

TABLE 1-1 Representative examples, applications, and properties for each category of materials

	Applications	Properties
Metals		
Copper	Electrical conductor wire	High electrical conductivity, good formability
Gray cast iron	Automobile engine blocks	Castability, machinability, vibration damping
Fe—3% Si	Motors and generators	Excellent ferromagnetic properties
Alloy steels	Wrenches	Good strengthening by heat treatment
Ceramics		
SiO_2–Na_2O–CaO	Window glass	Good optical properties and thermal insulation
Al_2O_3, MgO, SiO_2	Refractories for containing molten metal	Thermal insulation, high melting temperature, relatively inert to molten metal
Barium titanate	Transducers for stereo record players	Piezoelectric behavior converting sound to electricity
Polymers		
Polyethylene	Food packaging	Easily formed into thin flexible airtight film
Epoxy	Encapsulation of integrated circuits	Good electrical insulation and moisture resistance
Phenolics	Adhesives to join plies in plywood for marine use	Strength and moisture resistance
Composites		
Graphite-epoxy	Aircraft components	High strength-to-weight ratio
Tungsten carbide-cobalt	Carbide cutting tools for machining	High hardness yet good shock resistance
Titanium-clad steel	Reactor vessels	Low cost and high strength of steel with good corrosion resistance of titanium

Ceramics. Ceramics, such as brick, glass, tableware, insulators, and abrasives, have poor electrical and thermal conductivity. Although ceramics may have good strength and hardness, their ductility, formability, and shock resistance are poor. Consequently, ceramics are less often used for structural or load-bearing applications than are metals. However, many ceramics have excellent resistance to high temperatures and certain corrosive media and have a number of unusual and desirable optical, electrical, and thermal properties.

Polymers. Polymers include rubber, plastics, and many types of adhesives. They are produced by creating large molecular structures from organic molecules, obtained from petroleum or agricultural products, in a process known as *polymerization* (Figure 1-2). Polymers have low electrical and thermal conductiv-

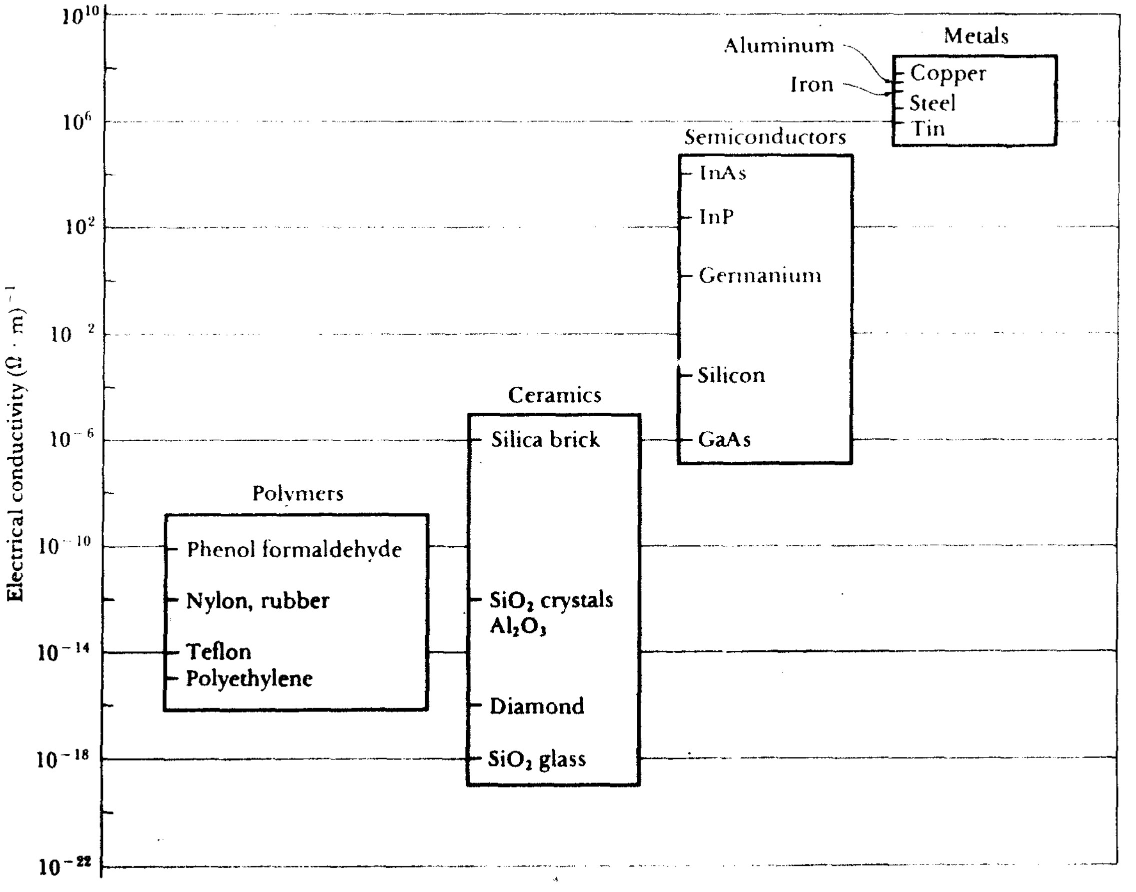


FIG. 1-1 Extremely large differences in electrical conductivity are observed between the different categories of materials.

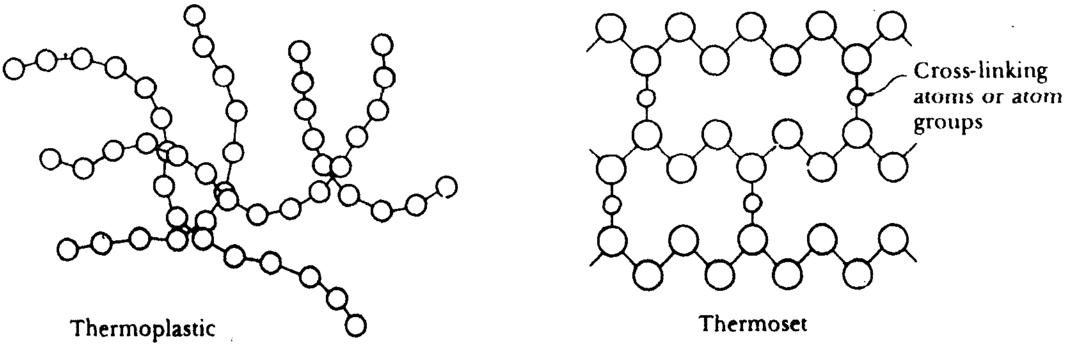
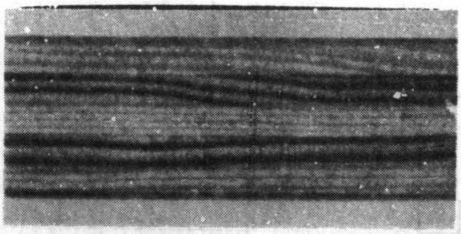


FIG. 1-2 Polymerization occurs when small molecules combine to produce larger molecules, or polymers. The polymer molecules can have a chainlike structure (thermoplastics) or can form three-dimensional networks (thermosets).

ity, have low strengths, and are not suitable for use at high temperatures. Some polymers (*thermoplastics*) have excellent ductility, formability, and shock resistance while others (*thermosets*) have the opposite properties. Polymers are lightweight and frequently have excellent resistance to corrosion.

Composite materials. Composites are formed from two or more materials, producing properties that cannot be obtained by any single material. Concrete, plywood, and fiberglass are typical, although crude, examples of composite materials (Figure 1-3). With composites we can produce lightweight, strong, ductile, high temperature-resistant materials that are otherwise unobtainable, or produce hard yet shock-resistant cutting tools that would otherwise shatter.



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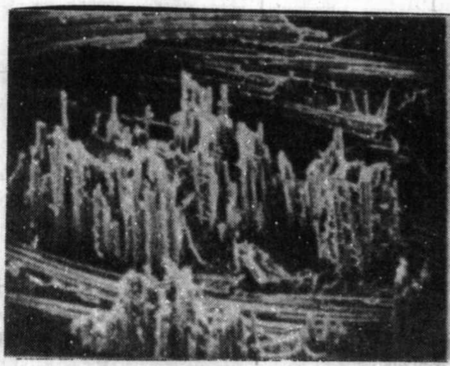

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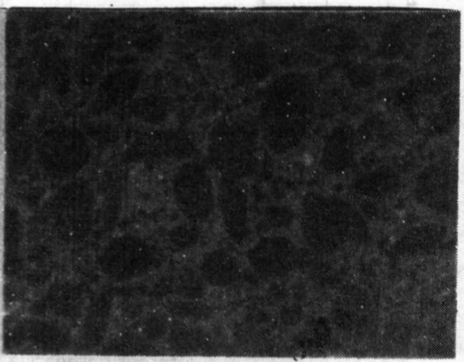

(c)

FIG. 1-3 Some examples of composite materials. (a) Plywood is a laminar composite composed of layers of wood veneer. (b) Fiberglass is a fiber-reinforced composite containing stiff, strong glass fibers in a softer polymer matrix. (c) Concrete is a particulate composite containing coarse sand or gravel in a cement matrix.

EXAMPLE 1-1

You wish to select the materials needed to carry a current between the components inside an electrical "black box." What materials would you select?

Answer:

The material that actually carries the current must have a high electrical conductivity. Thus, we need to select a *metal* wire. Copper, aluminum, gold, or silver might all serve. However, the metal wire must be insulated from the rest of the "black box" to prevent short circuits or arcing. Although a ceramic coating would be an excellent insulator,