Seventh Edition

Engineering Materials

Properties and Selection

Kenneth G. Budinski
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ENGINEERING MATERIALS

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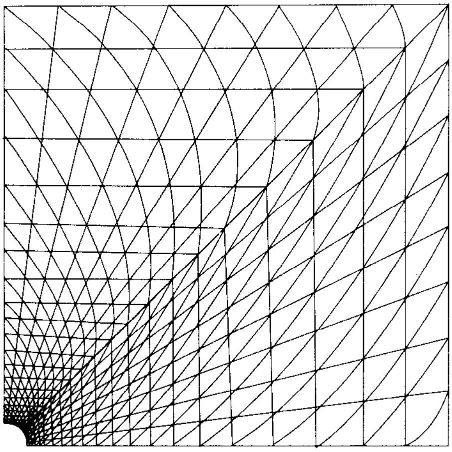


Preface

The first copyright for this book was issued in 1979. More than two decades and countless students later, the purpose of this book remains the same. It is intended for students who may only receive one materials course and also for a material selection course for advanced students or materials engineering students. We have heard that some users have described this book to their students as a "keeper" because it contains useful reference information they will need to look up from time to time. We cover all important engineering materials and we present fundamentals of every material system, with enough property information to allow reasonable material selection in most industries. There is a slight slant toward machine and product design. We are both materials engineers in a large manufacturing complex, and that is what we know best. This book reflects the need for engineering materials in industry.

The overall objective of this book is proper material selection and designs that do not fail in their anticipated lifetimes. It takes the right design, the right material, and the right treatments to make this happen. This book will assist your decision making process and will help you with successful designs.

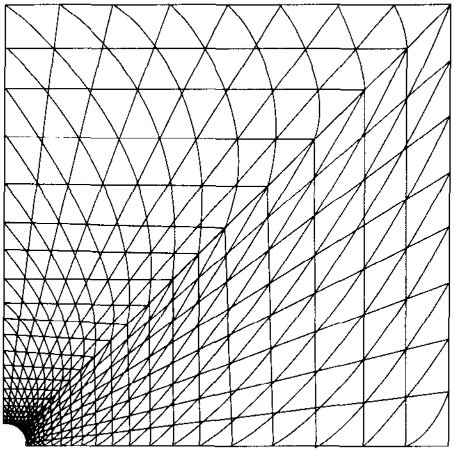
The changes in this edition include updates to each chapter to make them conform to current industrial trends, new sections to three chapters, one new chapter, and the addition of a critical concept section and a case history at the end of each chapter. We also tried to make this book more international in nature by listing ASTM standards on materials and tests wherever possible. There are other international standards, but we believe that the ASTM standards are the most current. They are available through any reference library in the world and on the Internet. We work on materials problems from company operations in China, France, England, Australia, India, Canada, Mexico, Brazil, and the United States. Designing parts or products in one country to be made in another requires diligence in material designation. You must designate your material of choice and treatments in such a way that your selection will be understood in other cultures. We have tried to pattern our designation recommendations with this in mind. The case histories we added to each chapter are real-life problems that we encountered in our company's corporate materials engineering laboratory.

The most significant change in this edition is the addition of a chapter on tribology, the study of friction, wear, bearings, and lubrication. This addition was made in response to a meeting on engineering education at a Gordon Research conference on tribology. The meeting was attended by about 30 educators from 17 countries, and the consensus of the group was that tribology is needed in engineering curricula. Most universities, though, have little room in their programs for a tribology elective and many do not have an instructor with the appropriate background to teach it. Most engineers will have to make decisions on sliding systems of some sort during their careers, having never been given the fundamentals.

All material failures are caused by fracture, corrosion, wear, or combinations thereof. We have always had a chapter on corrosion. Two chapters (2 and 20) deal with preventing mechanical failures, but wear and friction discussions were scattered throughout the book. We collected these scattered discussions into one chapter and added some new information on bearings and lubricants. We put the new tribology chapter in the front of the book because friction and wear properties of various materials are discussed in their respective chapters. We welcome comments from users on the new chapter. Do you teach it? Is it in the right place? Is it too little or too much on the subject? What is missing?

Countless people helped us with this edition. Our co-worker Mike Washo contributed the information on bearings, oils, and greases in Chapter 3. Mike has been Kodak's expert in these areas for more than 20 years. We thank him for his contribution. Professor Ken Ludema of the University of Michigan, the United States' preeminent tribologist, reviewed our tribology chapter. We thank him for his suggestions. Our company librarian, Ray Curtin, was a valuable aide in obtaining references and copies of competing texts for review. Prentice Hall had six user-professors review this edition: Norman R. Russell, Jefferson Community College; Serge Abrate, Southern Illinois University; W. Perry Seagroves, New Hampshire Technical Institute; Cynthia Barnicki, Milwaukee School of Engineering; Tom Waskom, Eastern Illinois University; and Charles L. Gibbons, II, Schoolcraft College. We thank these fellow academicians for their many suggestions. Angela Leisner is acknowledged for her typing and organizing skills and Linda Budinski for her technical writing suggestions. Finally, we acknowledge the patience and understanding of our wives, who have not seen much of us for the past year.

kgb (father)
mkb (son)



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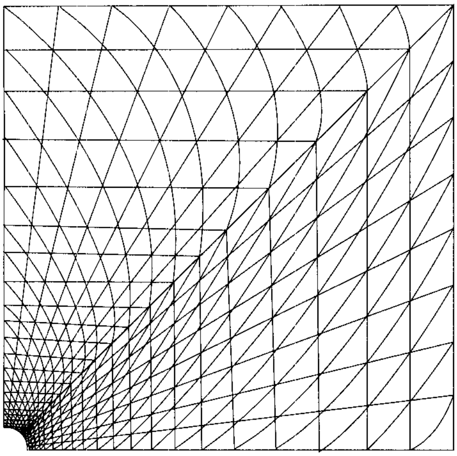

CHAPTER 1

The Structure of Materials

Chapter Goals

1. An understanding of how the elements are the building blocks for engineering materials.
2. A review of basic chemistry; the nature of the atom; how the elements combine; establishment of the language of materials.
3. An understanding of how engineering materials, metals, polymers, ceramics, and composites are related in origin and structural characteristics.

What is the importance of materials in engineering? Think about any tool, machine, device, or structure, and answer the question, How might this item fail? How might it fail to meet your expectations or lose serviceability? If you selected a tool like a screwdriver, it is likely to become useless when the blade tip deforms or wears. What is the role of materials engineering in preventing the failure of a screwdriver? If you have ever bought a set of ten screwdrivers for $3.00 (as I have) you will probably find that the blade tip will deform or twist the first time that you use it. They did not have the strength or hardness that is necessary. The maker of these low-cost screwdrivers probably used the wrong material and/or the wrong heat treatment (probably both).

If you envisioned a more complicated device, such as a sports radio (the type used by joggers and cyclists), it can fail because of an electrical problem or from a drop. A drop is more likely (I have broken at least three). The plastic case will break when dropped on a roadway or sidewalk. How does materials engineering pertain to breaking a radio by dropping it? If proper materials engineering (and design) had been applied to the radio, it would have been made from a plastic that can withstand a typical drop of two meters to the pavement.

If you envisioned an automobile, its ultimate demise will probably also be dependent on materials engineering. If a timing belt fails and the valve train gets damaged, you can blame the failure on an engineering materials problem. If the belt were made from the right material it would not fail in the normal life of a car.

Engineering materials are critical to all devices, all machines, all structures. Electrical devices can fail by corrosion; machines can fail by wear; structures can fail by fracture. The annual cost of corrosion and wear in the United States has been estimated to be in excess of $100 billion. The cost of all material failures is many times this number. This is the importance of engineering materials. Some material failures are caused by unexpected incidents. A automobile can inadvertently hit a large pothole. This puts abnormal stresses on a wheel component, and it breaks. However most material failures can be prevented by proper material selection and designs that anticipate material weaknesses—proper materials engineering.

It is the purpose of this text to present information on the nature and properties of materials used in engineering design and to present guidelines to assist the designer in selecting the right material for a given job. The objective is serviceable designs (at least from the materials standpoint). How can this objective be attained by reading this text? The format used presents only the materials information that a designer will need to know to perform the design task.

The theory of materials systems will be minimized, but enough will be presented to provide a foundation for selection information. All the important material systems will be covered: polymers, ceramics, metals, composites, and combinations of these systems. Few machines work well using only polymers or only metals. All material systems should be considered for use. As an introduction to the materials concept, this chapter will review basic chemistry and show how engineering materials are interrelated in concept and properties.

1.1 The Origin of Engineering Materials

Materials engineering is based largely on the pure sciences of chemistry and physics. This text will assume that the reader has a general knowledge of these subjects. Since engineering materials involve many chemical terms, we shall preface our material discussions with a brief review of some of the more important chemical fundamentals and terms.

All materials obey the laws of physics and chemistry in their formation, reactions, and combinations. The smallest part of an element that retains the properties of that element is the *atom*. Atoms are the building blocks for engineering materials. All matter is composed of atoms bonded together in different patterns and with different types of bonds. As shown in Figure 1–1, most substances that we deal with in industry and in everyday life can be categorized as organic or inorganic. *Organic* materials contain the element carbon (and usually hydrogen) as a key part of their structure, and they are usually derived from living things. Petroleum products are organic; crude oil is really the residue of plants that lived millions of years ago, and all plants and animals are organic in nature. *Inorganic* materials are those substances not derived from living things. Sand, rock, water, metals, and inert gases are inorganic materials. Chemistry as a science is usually separated into two fields based on these two criteria. Some chemists specialize in organic chemistry; others specialize in inorganic chemistry. Metallurgists and ceramists deal primarily with inorganic substances. Plastic engineers, on the other hand, deal primarily with organic substances. The field of materials engineering deals with both areas, as does this text.

We shall review the list of basic ingredients that are used to make both organic and inorganic materials, the elements, in order to address engineering materials on a chronological basis. An *element* is a pure substance that cannot be broken down by chemical means to a simpler substance. About 90 elements occur naturally in the earth's crust; some elements are unstable and occur as the result of fission or fusion reactions. Most chemistry texts list 109 elements, but inclusion of laboratory-synthesized elements brings the total number of elements to more than 120.

Many of these elements have little industrial importance, but it is important in engineering materials to recognize the names and chemical symbols for the more useful elements. Figure 1–2 shows a common version of the periodic table. This table lists elements by atomic number. The element hydrogen was assigned an atomic number of 1, and all the other elements derive their atomic number from a comparison of the "size" of atoms to the element hydrogen. The *atomic*

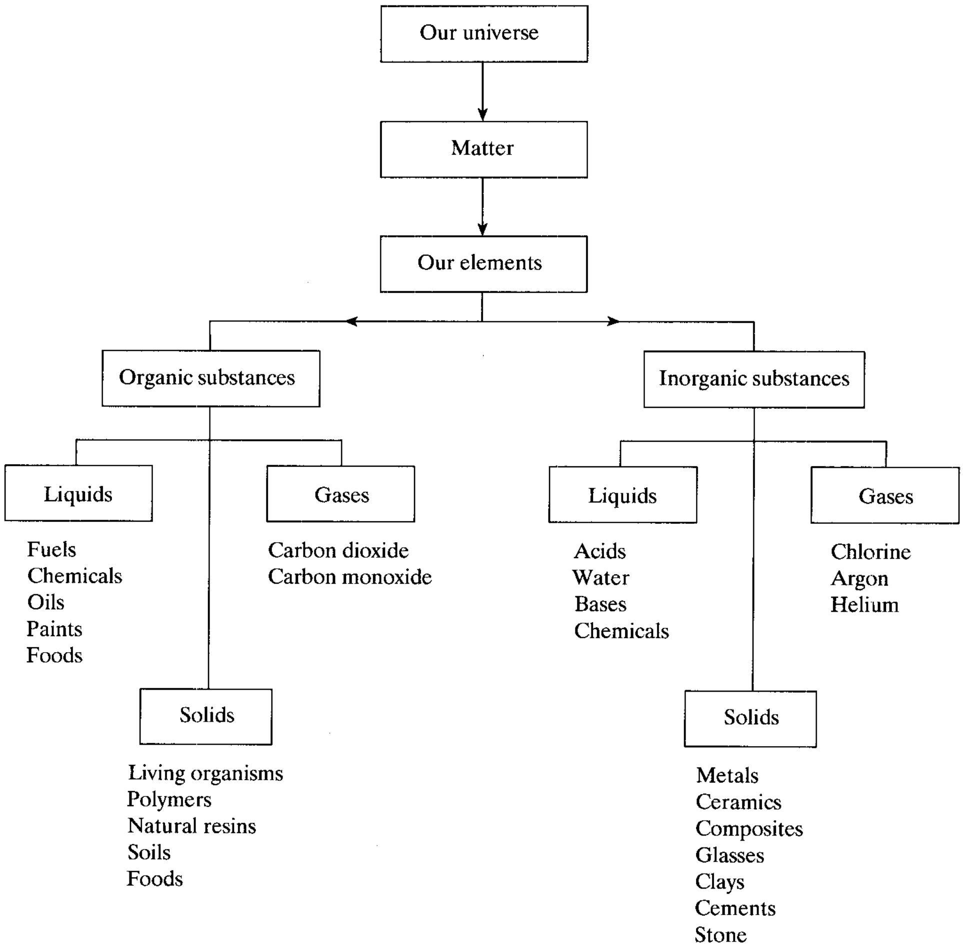

Figure 1–1
The elements are the building blocks for all materials.

number is really the number of protons in the nucleus of an atom. Atoms are far more complicated than we probably even know, but present knowledge characterizes atoms as being composed of *protons* (positively charged particles), *neutrons* (neutral particles), and *electrons*, which orbit the *nucleus*, or core of an atom. For simplicity, atoms are often characterized as a "sun" (nucleus), surrounded by orbiting "planets" (electrons). Electrons have mass. Both neutrons and protons have mass. It is generally agreed that protons have a nominal mass of 1 atomic mass unit (AMU). The neutrons have a slightly larger mass than the protons. Electrons have relatively small mass compared with the protons and neutrons (about 1/1837 the mass of a proton).

Electron "orbits" are not well-defined rings. Quantum mechanics tells us that electrons have properties of particles and properties similar to those of energy waves. The electronic configuration of an atom is defined by quantum numbers. One cannot say that a particular

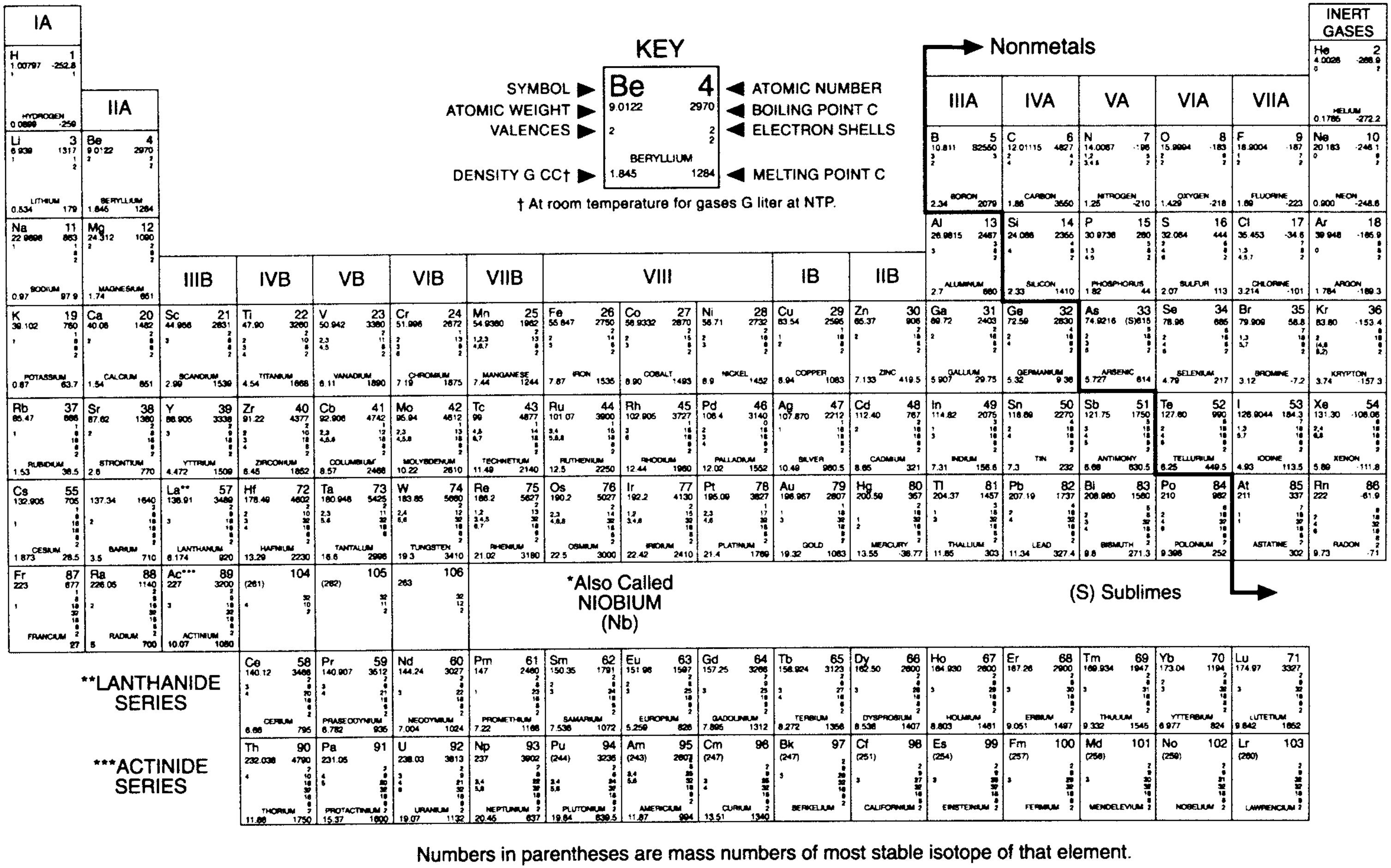

Figure 1–2
Periodic table of the elements

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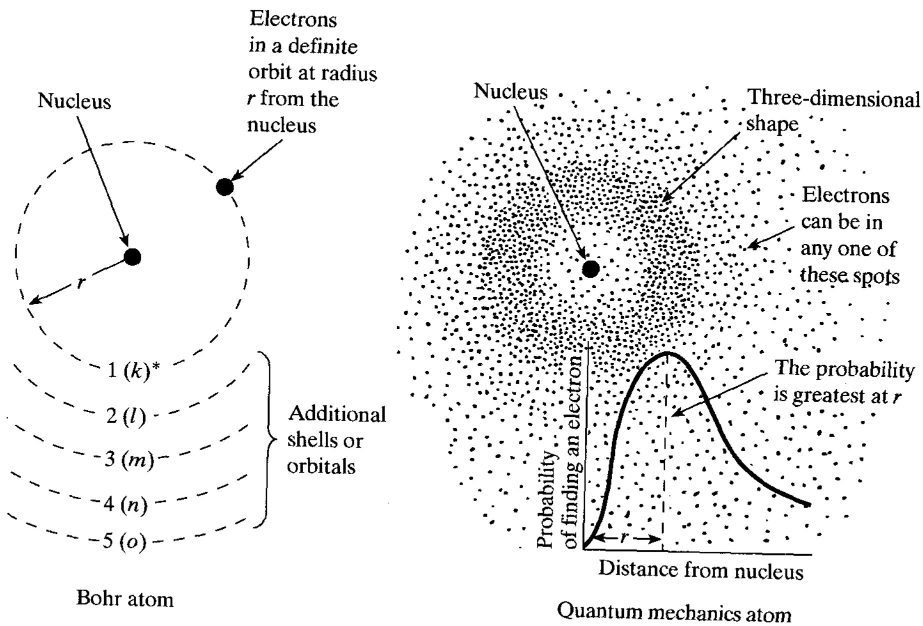

Figure 1–3
The Bohr atom compared with an atom described by quantum mechanics
*Numbers are the most-recent notation system; the letters were formerly used.

electron orbits the nucleus of an atom at, for example, a distance of 1 angstrom from the nucleus. Instead, the position of electrons associated with a particular atom is described by four quantum numbers that essentially state the probability of a particular electron being in a particular relationship with the nucleus of an atom. This concept is illustrated in Figure 1–3.

Quantum numbers and the electron configuration of atoms (Figure 1–4) are used in a variety of ways in engineering materials. For example, the electron configuration of carbon atoms determines molecular bonding characteristics in polymers. In organic chemistry, electron configuration is often related to crystal structure. Electron configurations and available energy levels are extremely important in solid-state physics and electronics. Design engineers may think that they will never use this concept in design engineering, but they may use this material without being aware of it. Advanced analytical techniques that investigate the nature of surface films (XPS and Auger spectroscopy) often analyze 1*s*, 2*s*, 2*p* energy levels to identify surface contaminants, and surface chemical composition. Designers may use these analytical techniques to solve a paint adhesion or welding problem.

Many intricacies are involved in analyzing the nuclear atom. The structure of the atom or of the nucleus of atoms is unimportant in most work in ordinary materials engineering, but it can have some application in deducing bonding tendencies between atoms. Several general rules about the electronic configuration of atoms are worthy of note:

1. Electrons associated with an atom occupy orbitals and subshells within orbitals.
2. The exact location of electrons in orbitals is defined by four quantum numbers that