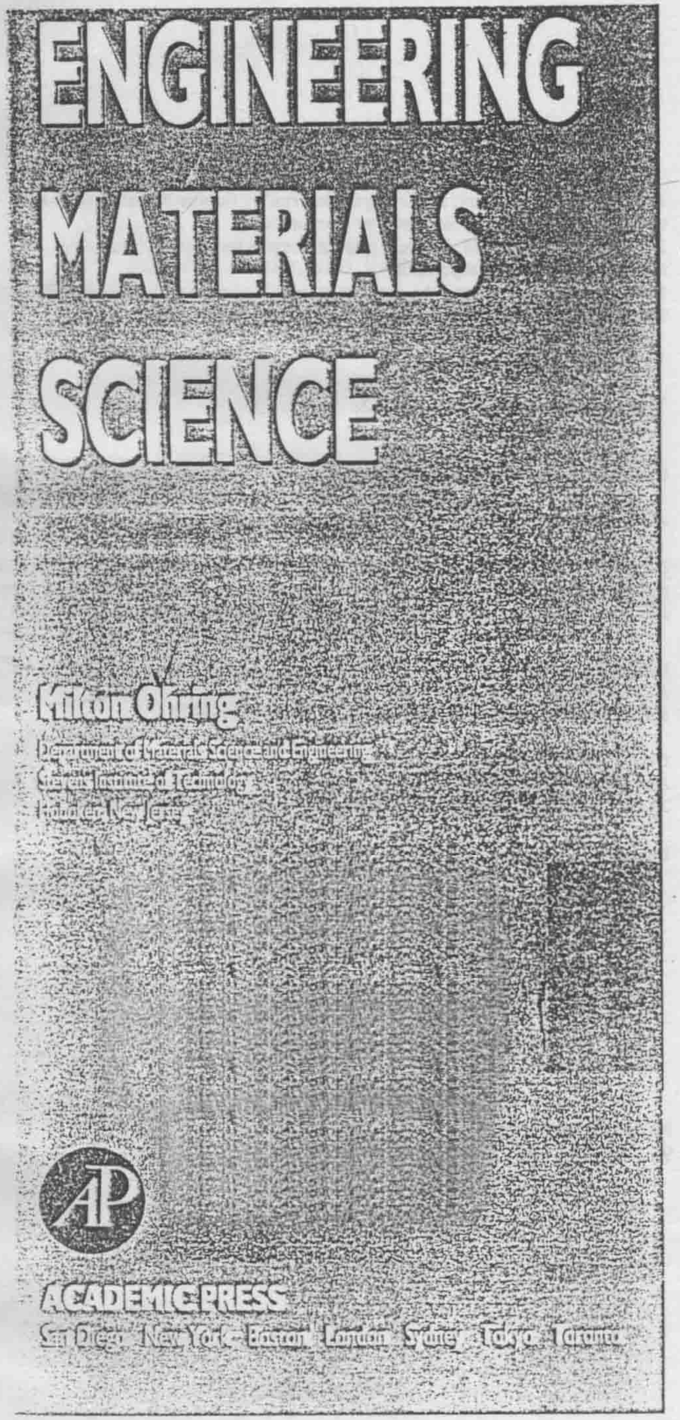
Engineering
Materials Science



ENGINEERING MATERIALS SCIENCE

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ACADEMIC PRESS
San Diego New York Boston London Sydney Tokyo Toronto

Front Cover Photograph: Single crystal superalloy turbine blades used in a jet aircraft engine (courtesy of Howmet Corporation).
Back Cover Photograph: Pentium microprocessor integrated circuit chip (courtesy of INTEL Corporation).
Both products rank among the greatest materials science and engineering triumphs of the 20th century.

This book is printed on acid-free paper. ♾

Academic Press, Inc.
A Division of Harcourt Brace & Company
525 B Street, Suite 1900, San Diego, California 92101-4495

United Kingdom Edition published by
Academic Press Limited
24-28 Oval Road, London NW1 7DX

Library of Congress Cataloging-in-Publication Data

Ohring, Milton, date.
Engineering materials science / by Milton Ohring.
p. cm.
Includes index.
ISBN 0-12-524995-0
1. Materials science. 2. Materials. I. Title.
TA403.037 1995
620.1'1--dc20 94-40228
CIP

PRINTED IN THE UNITED STATES OF AMERICA
95 96 97 98 99 00 DO 9 8 7 6 5 4 3 2 1

This book is dedicated to the women in my life:

Ahrona,
Feigel, Rochelle, and Yaffa,
and to the memory of my mother, Mollie.

> Human existence depends on compassion and knowledge. Knowledge without compassion is inhuman; compassion without knowledge is ineffective.
>
> Victor F. Weisskopf

PREFACE

The title *Engineering Materials Science* concisely describes the contents of this book and reflects its point of view. Long before there was a *science* to characterize them, man-made *engineering* materials were used for structural applications, to ease the drudgery of existence, and to enrich life. It was only in the late 19th century that scientific methods allowed a better understanding of engineering materials already in use for millennia. The result was improvement in their properties and more reliable ways of producing them. But science constantly advances, and it was not long before totally new materials like polymers, nuclear materials, semiconductors, and composites—and innovative ways to process and characterize them—were developed. Today, materials engineering and science advances are more closely synchronized. Often, however, science surges ahead, as with the discovery of high-temperature superconductors, making it necessary to establish engineering goals for their exploitation. Conversely, engineering progress frequently raises scientific questions that must be answered to advance the state of the art, for example, in the manufacture of integrated circuits. As reflected in the book's title, these divisions between the science and the engineering are often blurred and sometimes seamless.

This book has three broad objectives and missions. The first is to present a panoramic sweep of the materials field in order to frame it within the borders of the larger scientific and engineering disciplines. By introducing the vocabulary of materials, the way they are characterized, and the concerns involved in producing myriad reliable products from them, I hope to foster a cultural appreciation of the role materials play in technology and society.

The second is to use the subject of materials as the vehicle for connecting the prior freshman/sophomore science courses to the engineering courses that follow. Because the materials field lies at the interface between the science and engineering disciplines, it is admirably suited to serve as the connection in engineering curricula. Therefore, the book aims to expose the practical implications of abstract scientific formulas, to provide realistic limits to ideal models and systems, and to bolster the engineering design process. The transition from theory to practice is evident in the many practical applications presented.

Finally, I have attempted to better prepare those of you who will grapple with day-to-day materials problems in your professional engineering careers. The issues will most likely involve designing the properties needed for a particular component or application, selecting the best material for the job, choosing a manufacturing process to make it, and analyzing why it failed or broke in service. You may then find, as I have, that virtually every engineering problem is ultimately a materials problem. The best preparation for confronting problems that materials pose is a thorough grounding in the scientific fundamentals that underscore their nature. These invariant principles are also the basis for developing totally new materials and addressing the host of future challenges and opportunities they present.

This book is intended to be an introductory text for engineering undergraduates of all disciplines. The only prerequisites assumed are typical preengineering courses: freshman chemistry, physics, and mathematics. The introductory chapter, which I hope will not be glossed over, defines the roles of materials within broad engineering and societal contexts. Chapter 2 provides a modern view of the *electronic* structure of solids and how atoms are bound in them. The *physical* structure or location of atoms in the important engineering solids—metals, polymers, ceramics, and semiconductors—is the primary subject of Chapters 3 and 4. Minimization of energy and the consequences of thermodynamic equilibrium are overriding constraints that govern the stability of material systems. They are dealt with in Chapter 5, while its companion, Chapter 6, is concerned with time-dependent processes involving atom movements that enable structural and chemical modification of materials. The scientific underpinning provided by Chapters 2–6 is part of the core subject matter that will, to a greater or lesser extent, be part of the syllabus of all introductory materials courses.

Chapters 7–10 are devoted to the *mechanically* functional materials—their properties and behavior, how they are processed, how they can be strengthened and toughened, and how they degrade and fail in service. Similarly, Chapters 11–15 focus on the behavior, processing, and reliability of *electrically, optically*, and *magnetically* functional materials and devices. The properties and performance of these electronic materials are a testament to the exploitation of their structures through highly controlled processing. These last nine chapters present two broad avenues of occasionally linked engineering applications.

It is customary for textbooks to include more material than can be covered in a one-semester course, and the same is true here. This should enable instructors to tailor the subject matter to courses with different student audiences. Importantly, it will allow interested readers to explore topics that range beyond the confines of the course syllabus. Regardless of the intended student population, however, the book emphasizes fundamentals. Frequently, the focus is on a single class of materials that display unique properties, but just as often properties of different materials are compared. Therefore, "all you ever wanted to know about ceramics" will not be found in a single chapter but is distributed throughout several relevant chapters. The same is true for metals, polymers, and semiconductors. This comparative approach enables parallels in material behavior to be recognized amid clear differences in their individual natures. Conversely, it allows important distinctions among outwardly similar behaviors to be made. The continual juxtaposition of microscopic and macroscopic points of view sharpens and illuminates these issues. Thus, at times (microscope-like) examination of phemomena at atomic and even subatomic levels is required, but often the unaided eye is fully capable of discerning and analyzing bulk (macroscopic) material behavior. Throughout I have tried to promote the subject matter and above viewpoint in as lively a manner as possible.

More than 80 illustrative examples are fully worked out in the text. In addition there are over 500 problems and questions for student assignments dealing with analysis, materials design, and materials selection. Answers to a selected number of problems are also included.

The copyrighted interactive software that accompanies this book contains modules on different materials topics and is both computationally and graphically oriented. It runs on IBM-compatible computers and, once learned, can help solve many numerical problems presented in this as well as other texts on the subject.

ACKNOWLEDGMENTS

Authors fear that they may not show sufficient awareness of their debt to the people who make their books possible. In this vein I hope that I will be forgiven by the many for citing only the few. Among my colleagues I would like to thank Professor Edward Whittaker for conscientiously reading and reviewing several chapters on electronic properties. I am additionally grateful to Dr. W. Moberly, and Professors W. Carr, D. Smith, and A. Freilich for their critical comments. However, the bulk of the review process was performed by many excellent but anonymous reviewers who are the unsung heroes of this book. They offered encouragement, and much good criticism and advice which I tried to incorporate. I am solely responsible for any residual errors in my understanding of concepts and wording of text.

Some very special people to whom I am indebted sent me the beautiful photographs that elevate and give life to the text. In particular, the contribution of George Vander Voort must be singled out. This exceptional metallographer not only provided many excellent micrographs but taught me a bit of metallurgy as well. I also wish to acknowledge Dr. R. Anderhalt and Mr. Jun Yeh for their respective scanning electron and optical micrographs.

The software was the result of a multi-man-year team effort in which major contributions were made by Dmitry Genken, Tom Harris, Dr. Dan Schwarcz,

and Eugene Zaremba. Professors W. Carr and D. Sebastian are owed thanks for evaluating the software.

I am grateful to all of those at Academic Press who had a part in producing this book including Jane Ellis who encouraged me to undertake its writing, Dr. Zvi Ruder for his support of this project, and Deborah Moses who so capably guided and coordinated the complex publishing process. Others who deserve thanks for many favors are Noemia Carvalho, Pat Downes, Dick Widdecombe, and Dale Jacobson.

CONTENTS

1

INTRODUCTION TO MATERIALS SCIENCE AND ENGINEERING

2

ELECTRONS IN ATOMS AND SOLIDS: BONDING

3

STRUCTURE OF SOLIDS

4

POLYMERS, GLASSES, CERAMICS, AND NONMETALLIC MIXTURES

5

THERMODYNAMICS OF SOLIDS

6 KINETICS OF MASS TRANSPORT AND PHASE TRANSFORMATIONS

7 MECHANICAL BEHAVIOR OF SOLIDS

8 MATERIALS PROCESSING AND FORMING OPERATIONS

9

HOW ENGINEERING MATERIALS ARE STRENGTHENED AND TOUGHENED

10

DEGRADATION AND FAILURE OF STRUCTURAL MATERIALS

11

ELECTRICAL PROPERTIES OF METALS, INSULATORS, AND DIELECTRICS

12

SEMICONDUCTOR MATERIALS AND DEVICES: SCIENCE AND TECHNOLOGY

13

OPTICAL PROPERTIES OF MATERIALS

14

MAGNETIC PROPERTIES OF MATERIALS

15

FAILURE AND RELIABILITY OF ELECTRONIC MATERIALS AND DEVICES

1

INTRODUCTION TO MATERIALS SCIENCE AND ENGINEERING

1.1. MATERIALS RESOURCES AND THEIR IMPLICATIONS

1.1.1. A Historical Perspective

The designation of successive historical epochs as the Stone, Copper, Bronze, and Iron Ages reflects the importance of materials to mankind. Human destiny and materials resources have been inextricably intertwined since the dawn of history; however, the association of a given material with the age or era that it defines is not only limited to antiquity. The present nuclear and information ages owe their existences to the exploitation of two remarkable elements, uranium and silicon, respectively. Even though modern materials ages are extremely time compressed relative to the ancient metal ages they share a number of common attributes. For one thing, these ages tended to define sharply the material limits of human existence. Stone, copper, bronze, and iron meant successively higher standards of living through new or improved agricultural tools, food vessels, and weapons. Passage from one age to another was (and is) frequently accompanied by revolutionary, rather than evolutionary, changes in technological endeavors.

It is instructive to appreciate some additional characteristics and implications of these materials ages. For example, imagine that time is frozen at 1500 BC and we focus on the Middle East, perhaps the world's most intensively excavated region with respect to archaeological remains. In Asia Minor (Turkey) the ancient Hittites were already experimenting with iron, while close by to the east in Mesopotamia (Iraq), the Bronze Age was in flower. To the immediate north in Europe, the south in Palestine, and the west in Egypt, peoples were enjoying the benefits of the Copper and Early Bronze Ages. Halfway around the world to the east, the Chinese had already melted iron and demonstrated a remarkable genius for bronze, a copper–tin alloy that is stronger and easier to cast than pure copper. Further to the west on the Iberian Peninsula (Spain and Portugal), the Chalcolithic period, an overlapping Stone and Copper Age held sway, and in North Africa survivals of the Late Stone Age were in evidence. Across the Atlantic Ocean the peoples of the Americas had not yet discovered bronze, but like others around the globe, they fashioned beautiful work in gold, silver, and copper, which were found in nature in the free state (i.e., not combined in oxide, sulfide, or other ores).

Why materials resources and the skills to work them were so inequitably distributed cannot be addressed here. Clearly, very little technological information diffused or was shared among peoples. Actually, it could not have been otherwise because the working of metals (as well as ceramics) was very much an art that was limited not only by availability of resources, but also by cultural forces. It was indeed a tragedy for the Native Americans, still in the Stone Age three millennia later, when the white man arrived from Europe armed with steel (a hard, strong iron–carbon alloy) guns. These were too much of a match for the inferior stone, wood, and copper weapons arrayed against them. Conquest, colonization, and settlement were inevitable. And similar events have occurred elsewhere, at other times, throughout the world. Political expansion, commerce, and wars were frequently driven by the desire to control and exploit materials resources, and these continue unabated to the present day.

When the 20th century dawned the number of different materials controllably exploited had, surprisingly, not grown much beyond what was available 2000 years earlier. A notable exception was steel, which ushered in the Machine Age and revolutionized many facets of life. But then a period ensued in which there was an explosive increase in our understanding of the fundamental nature of materials. The result was the emergence of polymeric (plastic), nuclear, and electronic materials, new roles for metals and ceramics, and the development of reliable ways to process and manufacture useful products from them. Collectively, this modern Age of Materials has permeated the entire world and dwarfed the impact of previous ages.

Only two representative examples of a greater number scattered throughout the book will underscore the magnitude of advances made in materials within a historical context. In Fig. 1-1 the progress made in increasing the strength-to-density (or weight) ratio of materials is charted. Two implications of these advances have been improved aircraft design and energy savings in transportation systems. Less visible but no less significant improvements made in abrasive and cutting tool materials are shown in Fig. 1-2. The 100-fold tool cutting speed increase in this century has resulted in efficient machining and manufacturing