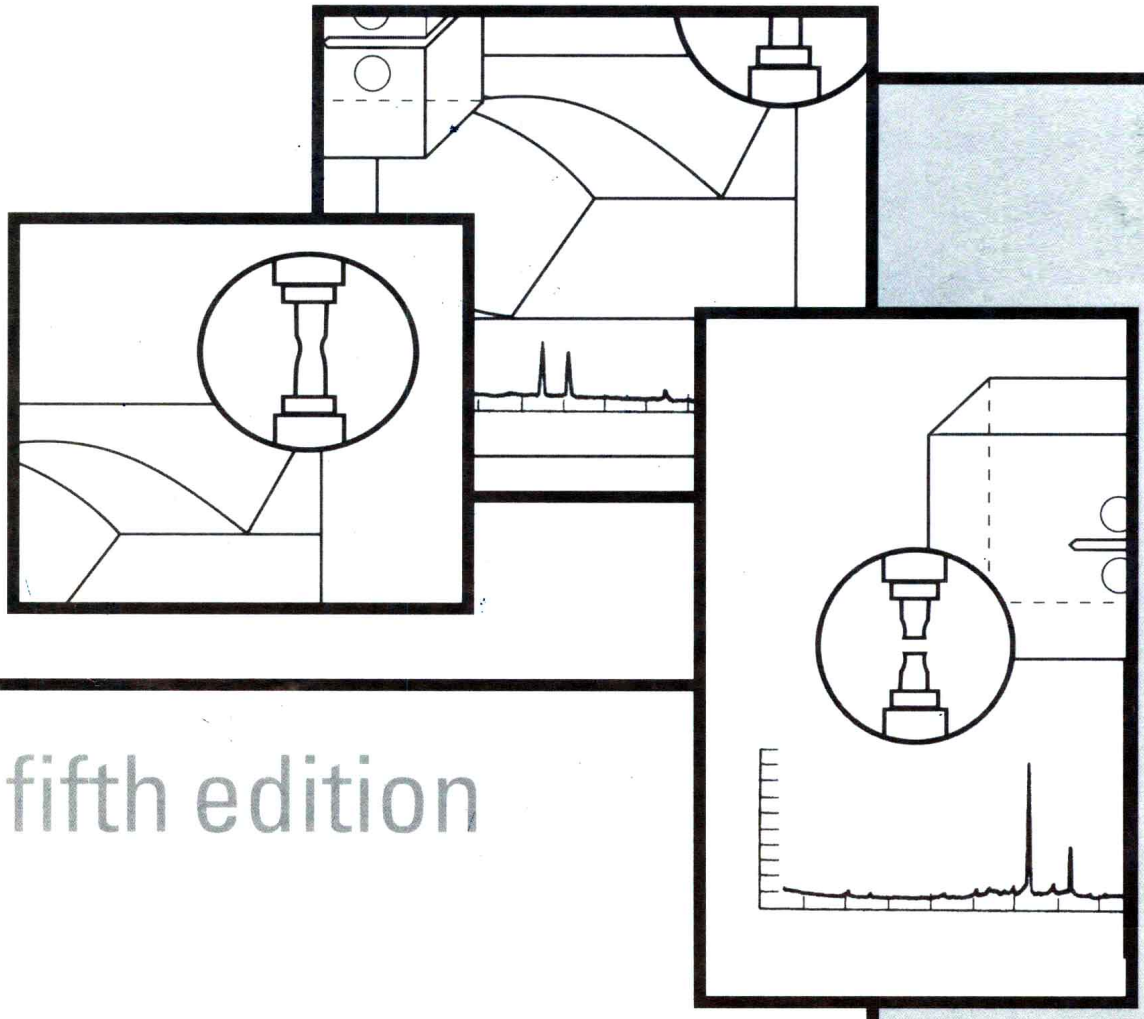
Structure and Properties
of engineering materials



fifth edition

Henkel & Pense

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To my wife, Julie, and my children, Evan and Luke.
Dan Henkel

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PREFACE

The previous fourth edition responded to the ever-expanding field of materials science with the addition of new chapters on engineering polymers and ceramics. At the time, it examined what were considered novel subjects such as directional solidification and splat cooling. However, twenty-three years have passed since the writing of that edition and substantial modernization was clearly overdue. The original premise of the book has not been changed in the fifth edition. It is still intended to be a textbook for intermediate level materials science courses, which would then follow the practicing engineer as an important reference on basic principles and practical information.

In general, the book gives an engineering perspective on physical metallurgy with some expansion into polymer science, ceramics and composites. An understanding of the contents will enable the reader to reason out many material selection issues and understand unusual responses to unique environments. The first two sections begin with discussions of atomic level structures and progress through the five fundamental strengthening mechanisms. The final section then provides what is considered the most useful information available on thirteen different classes of materials. It is an unusual combination of reference material in a language that a nonmetallurgical engineer should be able to comprehend.

Consideration was given to the placement of the important chapter on material deterioration, which was previously just an appendix. It does not belong in either the sections on strengthening or specific materials. Therefore, it was decided to place this review of the breakup of structure immediately after the introduction to structure. There was also some needed expansion on the topics of creep and fatigue. A more traditional arrangement of material classes is used than in previous editions with ferrous alloys, followed by nonferrous alloys, followed by nonmetallic materials. To maintain a similar length book, some subjects were reluctantly removed such as beryllium, steelmaking processes, and hardenability while new topics include coatings, composites, and aluminum-lithium alloys.

The book is intended to be a bridge between a theoretical text and an engineering handbook. There is an emphasis on phase transformations and the effects of processing variables that enable the prediction of both structure and properties. Property relationships are presented, usually without derivation, but with enough description to make them useful in actual practice. Many new references have been included on each subject to direct the reader to the theoretical sources. Updated problems are provided to stimulate some discussion and review of the text but they are not as extensive as those that may appear in an introductory materials science book. A final point of modernization involved replacement of most of the English units with the metric system.

We want to gratefully acknowledge the many contributors noted in previous editions that made this book a collection of more than fifty years of practical knowledge. Finally, Dr. Henkel wants to express his appreciation to Julie Klement Henkel for the motivation to pursue the tough projects and for her continuous inspiration.

Daniel P. Henkel Alan W. Pense

ABOUT THE AUTHORS

DANIEL P. HENKEL

Dr. Dan Henkel has twenty-five years of combined experience as a professional metallurgical engineer, materials research scientist, and college professor. He is presently the Senior Manager for Materials Development at Pall Corporation in Cortland, New York. Dr. Henkel received both his masters in metallurgy and material engineering and his doctorate in materials science from Lehigh University, and he received his bachelors in electrical engineering from the Pennsylvania State University. He was formerly president of Henkel Metallurgical Technologies, which performed surface science research and provided materials consulting to industry and government. Before HMT, Dr. Henkel was a Senior Research Scientist at NASA Langley Research Center. His specialty is the relationship between microstructure and the physical/mechanical properties of materials. While at NASA, he was also an adjunct professor in the Applied Science Program at the College of William and Mary, teaching courses in advanced microscopies and microstructural characterization. He holds two state licenses in metallurgical engineering, has three U.S. Patents and a list of archival publications, and is a member of ASM International. He was the recipient of an NSF research scholarship, a NASA research training grant, and a Department of Energy research grant.

ALAN W. PENSE

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Dr. Alan W. Pense has been a member of the Lehigh University faculty since 1960, serving as professor, department chair, dean, provost, and vice president of academic affairs. In 1987, he co-authored the proposal that led to the Advanced Technology Center for Large Structural Systems (ATLSS), an NSF-sponsored engineering research center at Lehigh. A specialist in physical and mechanical metallurgy and welding, Dr. Pense has been teaching and conducting published research for forty years. In addition to several prestigious teaching awards, he was elected as a fellow of ASM International in 1989 and the National Academy of Engineering in 1993. He is also listed in *American Men and Women of Science, Who's Who in America, Who's Who in the World,* and *Who's Who in Technology Today.* In 1997, he retired and became professor and provost emeritus. Today, Dr. Pense continues to advance the field of welding as an ATLSS research associate and a consultant to government and private industry.

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SECTION

1

INTRODUCTORY MATERIALS CONCEPTS

chapter

1

Structure and Properties

1.1 ATOMIC PACKING

Think of atoms in a solid as hard, round spheres that exert attractive forces in all directions. Given a number of these hard, spherical bodies, how can they be arranged to be as close-packed as possible, i.e., to occupy a minimum volume? It is easiest to consider the two-dimensional case first. When a given number of atoms are fitted together in a hexagonal pattern like the cells of a honeycomb, this criterion is achieved and they cover a minimum area.

Because they have relatively high densities, metals must consist of atoms that are packed very closely together as patterned in Fig. 1.1. It represents the closest possible packing of spheres on a flat sheet. To make a three-dimensional array of spheres occupying a minimum volume, it is necessary to place the centers of the atoms of the second sheet over the holes between the atoms of the first sheet. In Fig. 1.2, crosses show the locations of the centers of the atoms of the second sheet. Note that the atoms of the second sheet cover only half the holes in the first sheet. The other set of holes, the ones not marked by crosses, could have equally been used for the atom centers of the second sheet. The atomic structure of the two layers would look the same in either case.

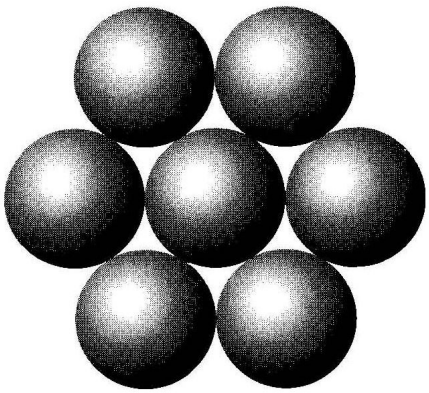

Figure 1.1 Packing of equal-sized spheres on a single plane to occupy a minimum area.

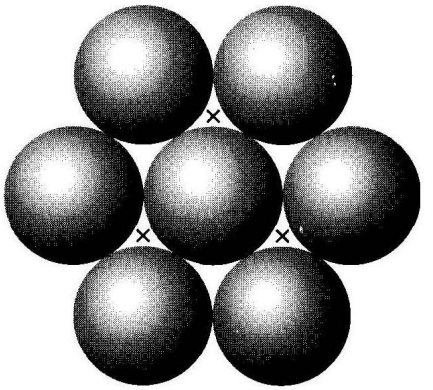

Figure 1.2 Location of the centers of the atoms in positions marked **x** of a second layer similar to Fig. 1.1.

The metal crystal that has been constructed by stacking up hard spheres is only two atomic layers thick. A third layer introduces a slight complication because there are two different ways in which it can be added. One way is to put the centers of the atoms of the third layer over the holes of the first layer that are not marked by crosses. In order to describe this structure, let the first layer be called *A*, the second layer, with its atom centers at the **x** positions, be called *B*, and the third layer, with its atom centers over the unmarked holes in *A*, be called *C*. The stacking sequence of close-packed layers is then *ABC* in this case. All the possible alternative positions for close-packed layers have been used up in this stack of three layers of atoms, but the fourth layer can be added in the *A* position again. In this way a sequence of layers *ABCABCA* can be built up to any desired thickness. The result is a three-dimensional array of spheres packed as closely as possible. Figure 1.3 shows a plane view of this structure.

There is a second way in which the close-packed layers of Fig. 1.1 can be stacked up to make a close-packed crystal. The first two layers are stacked as in Fig. 1.2, but the third layer is now added so that it is directly over the first. This structure is obviously close-packed, like the one derived above, but the stacking sequence is *ABABA*. Many metals are found to have either the *ABCABCA* or the *ABABA* type of close-packed structure. Some metals have more complicated structures; these will be described later.

For many purposes it is convenient to think of the close-packed structures as stacks of close-packed layers according to the description given above. Sometimes, however, it is convenient to single out a small group of atoms in the stack and then describe the atom arrangement in this group. The group of atoms chosen for this purpose is called a unit cell of the structure. One can choose a number of equally accurate ways of representing the unit cell, but experience has shown that, for each structure, there is one cell which is most easily visualized. This one best shows the symmetry of the atom arrangement.

For the close-packed structure of the *ABCABCA* type, the group of atoms forming the unit cell is shown in Fig. 1.4*b*. Note that the close-packed layers are in an

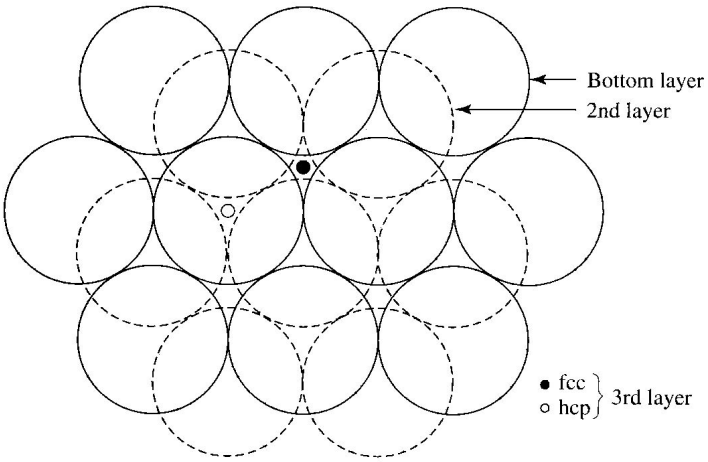

Figure 1.3 Solidly outlined circles represent a bottom plane of atoms, and dash-outlined circles represent a second plane nested on the first. In a close-packed structure, the third layer can be centered at the position of either the closed dot (*C* layer) or the open dot (another *A* layer).

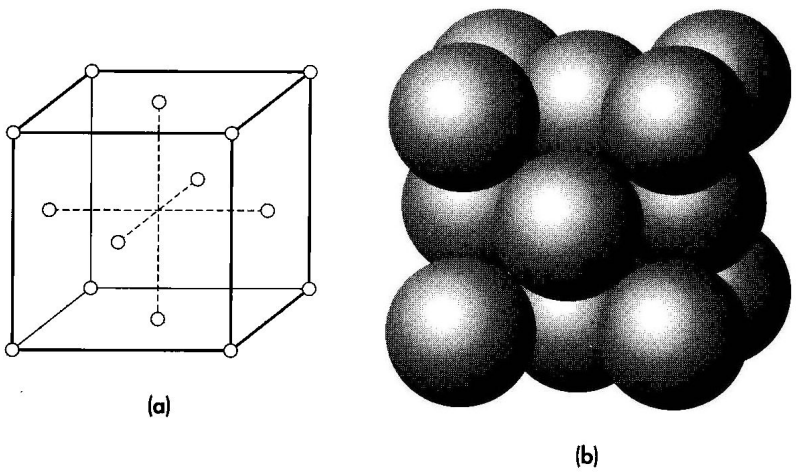

Figure 1.4 (*a*) The positions of the centers of the atoms in one unit cell of the fcc structure. (*b*) The packing of atoms in a unit cell of the fcc structure. Each atom on a face center touches each of the nearest corner atoms as well as the face-centered atoms in front and in back of it, making 12 nearest neighbors. There are four atoms in this unit cell (one-half of each face-centered atom plus one-eighth of each corner atom).

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