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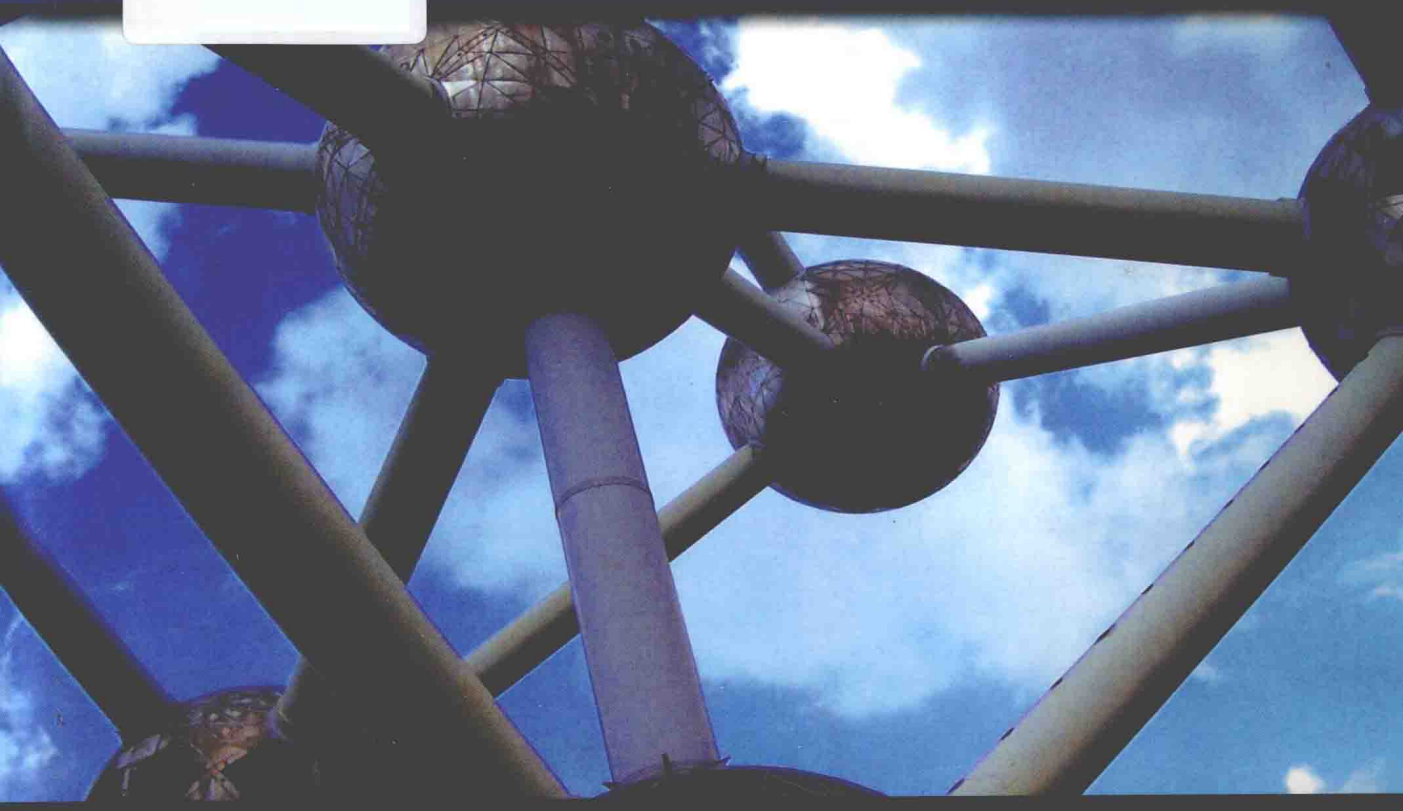

PHYSICAL METALLURGY PRINCIPLES

Fourth Edition

REZA ABBASCHIAN

LARA ABBASCHIAN

ROBERT E. REED-HILL

FOURTH EDITION, SI

Physical Metallurgy Principles

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Preface to the SI Edition

This edition of ***Physical Metallurgy Principles*** has been adapted to incorporate the International System of Units (*Le Système International d'Unités or SI*) throughout the book.

LE SYSTÈME INTERNATIONAL D'UNITÉS The United States Customary System (USCS) of units uses FPS (foot–pound–second) units (also called English or Imperial units). SI units are primarily the units of the MKS (meter–kilogram–second) system. However, CGS (centimeter–gram–second) units are often accepted as SI units, especially in textbooks.

USING SI UNITS IN THIS BOOK In this book, we have used both MKS and CGS units. USCS units or FPS units used in the US Edition of the book have been converted to SI units throughout the text and problems. However, in case of data sourced from handbooks, government standards, and product manuals, it is not only extremely difficult to convert all values to SI, it also encroaches upon the intellectual property of the source. Also, some quantities such as the ASTM grain size number and Jominy distances are generally computed in FPS units and would lose their relevance if converted to SI. Some data in figures, tables, examples, and references, therefore, remains in FPS units. For readers unfamiliar with the relationship between the FPS and the SI systems, conversion tables have been provided inside the front and back covers of the book.

To solve problems that require the use of sourced data, the sourced values can be converted from FPS units to SI units just before they are to be used in a calculation. To obtain standardized quantities and manufacturers' data in SI units, the readers may contact the appropriate government agencies or authorities in their countries/regions.

INSTRUCTOR RESOURCES A Printed Instructor's Solutions Manual in SI units is available on request. An electronic version of the Instructor's Solutions Manual, and PowerPoint slides of the figures from the SI text are available through *www.cengage.com/engineering*.

The readers' feedback on this SI Edition will be most appreciated and will help us improve subsequent editions.

The Publishers

Preface

THE FIRST EDITION In recent years, introductory physical metallurgy textbooks have attempted to achieve three goals: to explain basic metallurgical phenomena, to identify the compositions and properties of commercial alloys, and to teach principles of metal fabrication. Because all three phases are generally covered in a single course of one or two semesters, none of them receives adequate treatment. A natural question that arises is which of the three is most generally important to the engineering student. In this regard, it should be pointed out that metal fabrication and alloy properties are fields that are characteristically factual in nature. Although, strong arguments can be presented for including these areas of study, it must still be admitted that time spent learning large numbers of apparently unrelated facts is frequently wasted. Information of this sort is easily forgotten and, what is more, today's alloys and methods are not necessarily those of tomorrow. On the other hand, the theoretical approach to physical metallurgy is premised on the belief that the properties of metals and alloys are determined by simple physical laws, and that it is not necessary to consider each alloy as a separate entity. Recent advances in the physics and chemistry of metals have gone far toward finding the needed interrelations.

This book is intended for use as an introductory course (of one or two semesters) in physical metallurgy and is designed for all engineering students at the junior or senior level. A number of chapters dealing with advanced topics, such as Chapters 10, 11, 15, and 19 may be omitted in their entirety when the book is used for a one-semester course. Prerequisites are college physics, chemistry, and strength of materials. An engineering course in thermodynamics or physical chemistry is also considered desirable but not essential. The approach is largely theoretical, but all major phases of metal behavior normally found in physical metallurgy textbooks are covered. In this respect, statistical mechanics and dislocation theory are used to explain plastic deformation and thermal effects in metals. Vacancies are treated in some detail because their study may be used to obtain a true appreciation for the meaning of activation energies in metals. Deformation twinning is given considerable attention not only because this type of deformation has become increasingly more important, but also because twinning theory leads directly into the important subject area of martensite transformations.

On the whole, it is believed that the treatment used in this book is in harmony with current trends toward a more fundamental approach in engineering education.

The author would like to acknowledge that the lectures of Dr. A. S. Nowick and Dr. W. D. Robertson at the Hammond Laboratory, Yale University, were largely instrumental in inspiring the writing of this book. The helpful suggestions from Dr. F. N. Rhines on the subject of creep are also gratefully acknowledged.

THE SECOND EDITION The basic plan and philosophy of the original edition are continued in this volume. The major changes in the new edition are largely the

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result of constructive suggestions and advice by Professor Richard W. Heckel, of Drexel University, Dean Walter S. Owen, of Northwestern University, and Professor Marvin Metzger, of the University of Illinois. One result of these suggestions is the inclusion of a chapter on nucleation and growth kinetics. The outline of this chapter was also inspired by a set of class notes kindly loaned to the author by Professor Heckel. The considerable assistance of Dr. John Kronsbein in revising and expanding Chapter 3, Elementary Theory of Metals, is also gratefully acknowledged.

As a consequence of requests for the inclusion of topics either missing or too lightly covered in the first edition, the new book has been increased in size by about ten percent. In a broad sense, the additional material fits into two classifications. First are the topics that have recently become significant in the field of metallurgy. The second group consists of well-established subjects not covered in the first edition, but which, from use of the text, were found to be needed for a more unified presentation. Among the former subject areas are electron microscopy, fracture mechanics, superconductivity, superplasticity, dynamic recovery, dynamic strain aging, electrotransport, thermal migration, and emissary dislocations. In the latter category belong the new chapter on nucleation and growth kinetics and such topics as magnetism, the zone theory of alloy phases, the five degrees of freedom of a grain boundary, the phase rule, true stress and true strain, coring and homogenization of castings, work hardening, and diffusion in nonisomorphic systems.

The number of problems is substantially increased over that in the original book, in conformity with the current trend in engineering to place more emphasis on problem solving. Problems have been written with the aim of both illustrating points covered in the text and exposing the student to material and concepts not covered directly in the book.

The helpful assistance of Dr. John Hren, Dr. Robert T. DeHoff, Dr. Derek Dove, Dr. Ellis Verink, and Dr. E. N. Rhines, all of the University of Florida, who either reviewed sections of the book or gave suggestions, is acknowledged with thanks.

THE THIRD EDITION The basic philosophy underlying the original edition is retained in the third edition. However, a number of significant improvements have been incorporated in the third edition. The International System of Units is now employed throughout text and problems. A chapter devoted to important nonferrous metal has been added. Fracture mechanics is covered in much greater depth and breadth in a separate chapter. The treatment of solidification has been expanded and brought up to date and includes an extensive coverage of liquid metals as well as the Scheil equation and eutectic freezing. The section on the transmission electron microscope has been expanded and a detailed discussion of the scanning electron microscope has been added. Grain boundaries are now covered in a separate chapter that includes coincident site boundaries. The subject of dislocations has been reorganized and consolidated. Chapter 4 considers the geometrical aspects of dislocations while Chapter 5 treats the relationship of dislocations to plastic deformation. The phase diagrams in the text have been brought up to date. In the steel chapters, the transformations of austenite to peariite, bainite, and martensite, and the tempering of martensite have been modernized. In the deformation twinning and martensite reactions chapter, less emphasis is placed on twinning phenomena per se while the role that twinning can play in the plastic deformation of polycrystalline metals has been added. In the martensite section, thermoelastic deformation and shape memory effects are now covered.

The authors would like to thank Professor William C. Leslie of the University of Michigan and Professor Daniel N. Beshers of Columbia University for their extensive and constructive suggestions concerning material that needed to be corrected or added to the third edition.

The authors would also like to acknowledge the assistance of Professors Paul C. Holloway and Rolf N. Hummel, University of Florida. We are also greatly indebted to all of the following for their constructive reviews of the manuscript of the third edition: Professor William A. Jesser, University of Virginia; Professor William G. Ovens, Rose-Hulman Institute of Technology; Professor Dale E. Wittmer, Southern Illinois University; Professor James C. M. Li, University of Rochester; Professor Alan R. Pelton, University of Notre Dame; and Professor Samuel J. Hruska, Purdue University.

THE FOURTH EDITION The original philosophy of the former editions has been kept in this fourth edition. The text retains its easy-to-read format so that the essence of the information is most successfully communicated. Recent references have been incorporated to complement the remaining original references which provide historic context. Indeed, with electronic search engines limited to more recently published literature, identification and acknowledgment of the pioneers of the field often gets overlooked. To increase the focus of the text, Chapters 22 and 23 were removed, with salient portions incorporated into other chapters. As such, the book is more adaptable for a one or two semester introductory course for juniors or seniors in materials science and engineering. New figures were added to enhance understanding of the text. Sections on nano-structures have been included to demonstrate the applicability of the physical metallurgy principles to current nanotechnology trends; however, the authors leave it to the readers to independently pursue the area more thoroughly.

The authors would like to thank the reviewers whose constructive reviews of the third edition drove the aforementioned changes: Professor Richard B. Griffin, Texas A & M University; Professor Dong-Joo (Daniel) Kim, Auburn University; Professor Anthony P. Reynolds, University of South Carolina; Professor Christopher A. Schuh, Massachusetts Institute of Technology; Professor Jiahong Zhu, Tennessee Technical University. Special thanks to Hilda Gowans, Senior Development Editor, whose assistance was invaluable throughout the revisions, to Chris Carson and the Engineering group at Cengage Learning and to Rose Kernan who managed the production of this new edition. We also thank Dr. Abraham Munitz for providing the pictures for the chapter headings. Finally, we again acknowledge the critical inputs and contributions of all who are listed in the prefaces of the earlier editions.

Robert E. Reed-Hill
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Lara Abbaschian

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CHAPTER 1

The Structure of Metals

The most important aspect of any engineering material is its structure, because its properties are closely related to this feature. To be successful, a materials engineer must have a good understanding of this relationship between structure and properties. By way of illustration, wood is a very easy material in which to see the close interaction between structure and properties. A typical structural wood, such as southern yellow pine, is essentially an array of long hollow cells or fibers. These fibers, which are formed largely from cellulose, are aligned with the grain of the wood and are cemented together by another weaker organic material called lignin. The structure of wood is thus roughly analogous to that of a bundle of drinking straws. It can be split easily along its grain; that is, parallel to the cells. Wood is also much stronger in compression (or tension) parallel to its grain than it is in compression (or tension) perpendicular to the grain. It makes excellent columns and beams, but it is not really suitable for tension members required to carry large loads, because the low resistance of wood to shear parallel to its grain makes it difficult to attach end fastenings that will not pull out. As a result, wooden bridges and other large wooden structures are often constructed containing steel tie rods to support the tensile loads.

1.1 THE STRUCTURE OF METALS

The structure in metals is of similar importance to that in wood, although often in a more subtle manner. Metals are usually crystalline when in the solid form. While very large single crystals can be prepared, the normal metallic object consists of an aggregate of many very small crystals. Metals are therefore *polycrystalline*. The crystals in these materials are normally referred to as its grains. Because of their very small sizes, an optical microscope, operating at magnifications between about 100 and 1000 times, is usually used to examine the structural features associated with the grains in a metal. Structures requiring this range of magnification for their examination fall into the class known as *microstructures*. Occasionally, metallic objects, such as castings, may have very large crystals that are discernible to the naked eye or are easily resolved under a low-power microscope. Structure in this category is called *macrostructure*. On the other hand, there are materials whose grains or sizes are much finer and in the nanoscale range. These microstructures are commonly referred to as *nanostructures*, with scales on the order of one billionth of a meter. It should be noted that nanoscale features can be in one dimension, as in nanosurfaces or nanofilms; in two dimensions, as in nanotubes or whiskers; or in three dimensions, as in nanoparticles. Nanoprecipitates such as Guinier and Preston (GP) Zones have been used for decades for precipitation hardening of aluminum alloys, as discussed in Chapter 16. Finally, there is the basic structure inside the grains themselves: that is, the atomic arrangements inside the crystals. This form of structure is logically called the *crystal structure*.

Of the various forms of structure, microstructure (that visible under the optical microscope) has been historically of the greatest use and interest to the metallurgist. Because the metallurgical microscope is normally operated at magnifications where its

depth of field is extremely shallow, the metallic surface to be observed must be very flat. At the same time, it must reveal accurately the nature of the structure inside the metal. One is therefore presented with the problem of preparing a very smooth flat and undistorted surface, which is by no means an easy task. The procedures required to obtain the desired goal fall under the general heading of metallographic specimen preparation. Detailed description of metallographic sample preparation techniques and examples of microstructures can be found in Reference 1.

A *crystal* is defined as an orderly array of atoms in space. There are many different types of crystal structures, some of which are quite complicated. Fortunately, most metals crystallize in one of three relatively simple structures: the face-centered cubic, the body-centered cubic, and the close-packed hexagonal.

1.2 UNIT CELLS

The *unit cell* of a crystal structure is the smallest group of atoms possessing the symmetry of the crystal which, when repeated in all directions, will develop the crystal lattice. Figure 1.1A shows the unit cell of the body-centered cubic lattice. It is evident that its name is derived from the shape of the unit cell. Eight unit cells are combined in Fig. 1.1B in order to show how the unit cell fits into the complete lattice. Note that atom *a* of Fig. 1.1B does not belong uniquely to one unit cell, but is a part of all eight unit cells that surround it. Therefore, it can be said that only one-eighth of this corner atom belongs to any one-unit cell. This fact may be used to compute the number of atoms per unit cell in a body-centered cubic crystal. Even a small crystal will contain billions of unit cells, and the cells in the interior of the crystal must greatly exceed in number those lying on the surface. Therefore, surface cells may be neglected in our computations. In the interior of a crystal, each corner atom of a unit cell is equivalent to atom *a* of Fig. 1.1B and contributes one-eighth of an atom to a unit cell. In addition, each cell also possesses an atom located at its center that is not shared with other unit cells. The body-centered cubic lattice thus has two atoms per unit cell; one contributed by the corner atoms, and one located at the center of the cell, as shown in Fig. 1.1C.

The unit cell of the face-centered cubic lattice is shown in Fig. 1.2. In this case, the unit cell has an atom in the center of each face. The number of atoms per unit cell in the face-centered cubic lattice can be computed in the same manner as in the body-centered

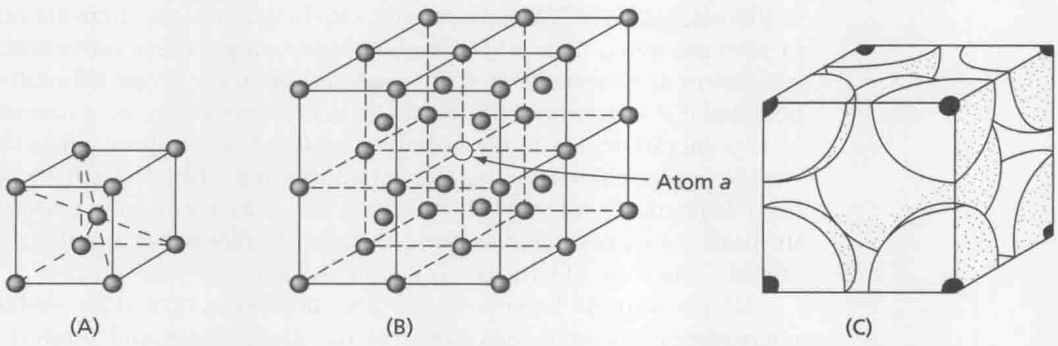

FIG. 1.1 (A) Body-centered cubic unit cell. **(B)** Eight unit cells of the body centered cubic lattice. **(C)** Cut view of a unit cell

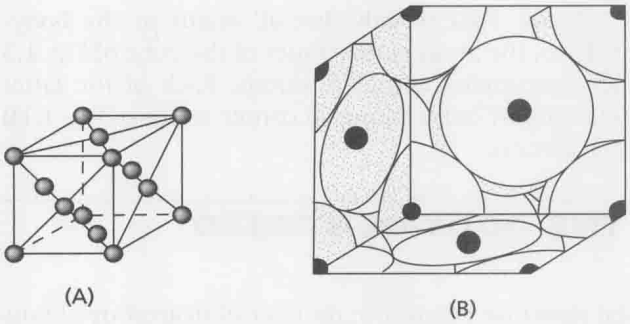

FIG. 1.2 (A) Face-centered cubic unit cell. **(B)** Cut view of a unit cell

cubic lattice. The eight corner atoms again contribute one atom to the cell, as shown in Fig. 1.2B. There are also six face-centered atoms to be considered, each a part of two unit cells. These contribute six times one-half an atom, or three atoms. The face-centered cubic lattice has a total of four atoms per unit cell, or twice as many as the body-centered cubic lattice.

1.3 THE BODY-CENTERED CUBIC STRUCTURE (BCC)

It is frequently convenient to consider metal crystals as structures formed by stacking together hard spheres. This leads to the so-called *hard-ball model* of a crystalline lattice, where the radius of the spheres is taken as half the distance between the centers of the most closely spaced atoms.

Figure 1.3 shows the hard-ball model of the body-centered cubic (bcc) unit cell. A study of the figure shows that the atom at the center of the cube is colinear with each corner atom; that is, the atoms connecting diagonally opposite corners of the cube form straight lines, each atom touching the next in sequence. These linear arrays do not end at the corners of the unit cell, but continue on through the crystal much like a row of beads strung on a wire (see Fig. 1.1B). These four cube diagonals constitute the close-packed directions of the body-centered cubic crystal, directions that run continuously through the lattice on which the atoms are as closely spaced as possible.

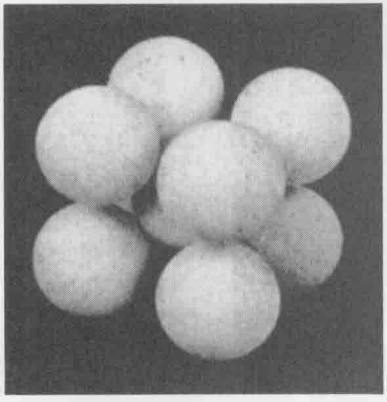

FIG. 1.3 Hard-ball model of the body-centered cubic unit cell

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