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国外大学优秀教材——材料科学与工程系列（影印版）

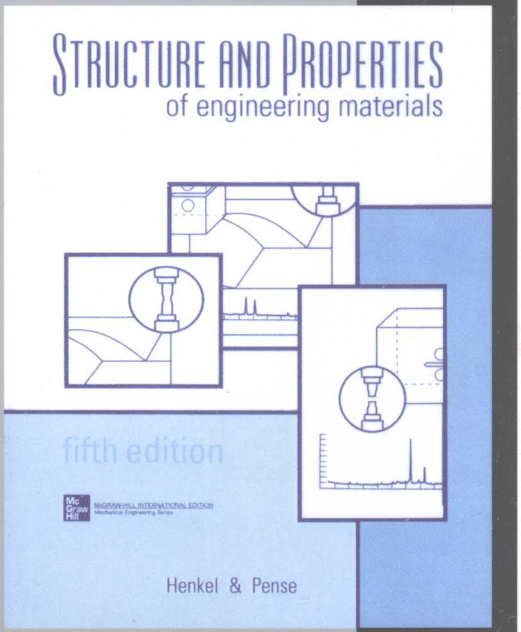
Daniel Henkel, Alan W. Pense

工程材料的结构与性能

（第5版）

Structure and Properties of Engineering Materials

5th Edition



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英文影印版序

“工程材料导论”这门课程是美国大学工学院里许多专业的必修课(比如材料，化工，机械，航空，环境，核工业等)。这门课程一般会分为两类：一类只对材料专业的大二或者大三学生开课；而另一类则面向全部工学院的学生，属于一种基础型公共课程。对于不同的专业，该课程的侧重有所不同。对美国大学材料科学系的学生，一般会根据自己的情况把材料基础课分布在金属、陶瓷、高分子和复合材料等主要方面。在比较传统的美国大学材料科学系里，金属学与陶瓷学仍然具备十分系统性的课程。从导论课开始，然后进行深入的高级课程。近几年来，由于纳米科学与能源材料的发展，材料系已经开始建立许多与新学科相关的课程。比如生物纳米、能源技术、新型复合材料，等等。目前美国大学材料系有一种本科教学上的新趋势。那就是把材料的初级课程归纳综合成为一个统一的基础课，而不再另外分为不同类型材料的导论课 (即：金属导论、陶瓷导论、高分子导论等)。在教学上突出各类材料的共同性质，比如结构原理、化学行为、物理特性，以及在能源、生物、医学等方面的应用。这种方法一是可以避免教学上的重复，二是容易引入许多新的材料概念，比如纳米与能源材料，因为这些概念并不刻意地划分材料的种类。

“工程材料导论”这门课所用的教科书同类型的有许多种。目前在美国流行的至少有数十本。*Structure and Properties of Engineering Materials* 是这门课所用的教科书中较为流行的一部。对于材料工程专业的学生，这本书的教程会较为详细地把重点放在金属材料的章节里。而对于非材料专业的学生，整个课程可以广泛地介绍现代工业应用的一般材料，包括陶瓷、玻璃、高分子，以及复合材料。课时为三个学分（即一周三次课,每课 50 分钟）。一般在大学三年级完成该课程。

这本教科书的特点是体系或结构比较简单，而侧重晶体结构、机械性质、相图与制备、各类重要合金，以及非金属工程材料。它主要分四个部分：第一部分主要阐述晶体结构、点阵缺陷、化学键，以及机械与物理性能，属于基础部分。其中第一章详细讲解了材料的原子结构，如原胞、密勒指数、X-射线结构分析等，在材料学中是最为基础的，也是必须掌握的基本概念。材料的机械性能测量也在第一章做了初步的讨论。该章还介绍了非晶态和高分子材料。这个部分的第二章着重介绍材料性能在环境和应用中的蜕变，包括断裂机理、疲劳和蠕变等。

第二部分主要讨论金属材料的强化理论与制备方法。比如固溶强化（第 3 章)、加工硬化与热处理（第 4 章)、多相强化（第 5 章)、弥散析出强化（第 6 章)，以及马氏体相变强化（第 7 章)。这部分内容结合材料制备的特点，给出了相图的基本概念。比如微结构的控

制、相图分析以及相平衡理论。可以认为，第一和第二部分为本书的主要部分，是材料科学与工程中至关重要的核心和基本概念。所以也是“工程材料导论”教学中的重点。因而，第一、二部分对于材料专业的工科学生，是非常基础性的。

第三部分是对各类金属工程材料的分类与介绍。其中详细讨论了各种钢材，例如低碳钢、中碳钢与高碳钢的特性、制备，以及应用。同时系统地介绍了各类合金钢，比如不锈钢、铝合金、铜合金、镁合金、钛合金，以及高温合金等。该书从第 8 章到第 17 章利用大量的篇幅十分详细地介绍了工程合金材料的各种特殊性质、物理行为和制备工艺。对于金属冶金专业的学生来说，这个部分是至关重要的。

第四部分囊括了工业应用中其他大部分非金属材料，比如高分子材料、陶瓷材料，以及复合材料。这些章节不仅给出了这些重要材料的标定、规格和类型，而且阐述了它们的特性、应用范围和制备条件。比如陶瓷纤维的特殊性质、复合材料的微结构特征，以及这些材料的热加工过程。对于工业应用中的重要材料：高分子，该部分也做了十分详尽的描述，包括高分子材料的结构特点，合成方法、温变行为，以及力学变形机制。因而，第四部分对于非材料专业的工科学生，在掌握工程材料的一般知识方面有着极为重要的意义。尤其对于那些需要在工程实践中广泛接触材料应用的专业，比如航空、机械、土木、环境和化工等专业。

本书条理有序，结构清晰，内容丰富，浅显易懂，十分适用于一般工学院的材料导论课程。同时，它也适用于材料专业的初级课程。尤其本书所出的作业题，内容十分广泛，而且重点突出，切题实用。在为其他非材料专业开设的“材料科学与工程导论”一课中，教学大纲一般会包括第一、二、四部分的一些主要内容，比如晶体结构、点阵缺陷、力学性质、相图分析和微结构控制，以及第三部分的某些内容。对美国十一周、三学分课时的学期建制，选择这些内容是比较合适的。正是由于学时的限制，单一的课程无法囊括本书的所有部分和章节。所以，第一、二部分应该是材料学初级课程的重点。第三部分的选用，应该根据学生专业的特点和区别择重取用。

本书的作者 Daniel Henkel 和 Alan W.Pense 博士是材料领域十分著名的专家。他们在本书中不仅对金属材料部分的介绍有独到的见解和非常精彩的阐述，而且对陶瓷、玻璃、高分子和复合材料等领域也作了极为详尽的描述。作者以他们博学的知识和深厚的研究经历对工程材料的结构与性质给出循序渐进地讲解和较为深刻的理论探讨。更为可贵的是本书引入大量现代科技最新发展的成果。这为开拓学生眼界，熟悉相关领域动态，掌握现代工业发展有着极为积极的意义。

清华大学出版社在中国高科技工业飞速发展的今天，十分及时地选择 *Structure and*

Properties of Engineering Materials 一书并作为中国大学工科的材料学英文原版教科书并引进该书的版权，有着非常重要的现实意义。它不仅可以在国内英文教学方面树立一个具有国际工程院系的教学标准，也为大专院校和科技单位的研究工作者也提供了一本内容丰富又极具科研价值的参考书。我衷心祝愿本书的英文影印版受到国内师生以及科研同行的欢迎，并在教学和科研中发挥较大的作用。

时东陆
化工与材料工程系教授
美国俄亥俄州立辛辛那提大学
2008 年

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

Professor and Provost Emeritus, Lehigh University

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.

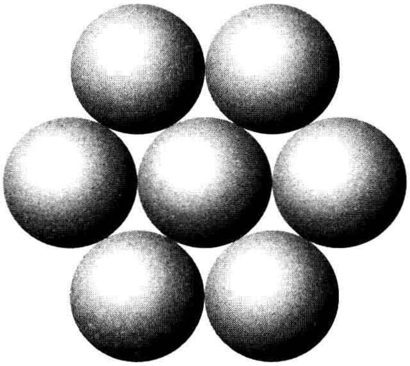

Figure 1.1 Packing of equal-sized spheres on a single plane to occupy a minimum area.

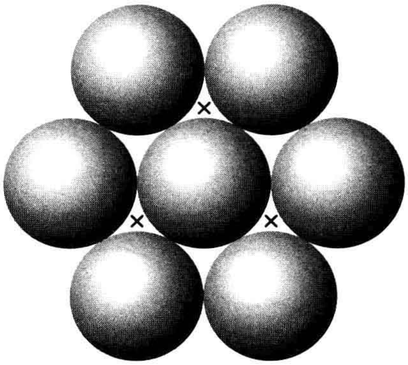

Figure 1.2 Location of the centers of the atoms in positions marked **x** of a second layer similar to Fig. 1.1.

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