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材料科学与工程基础

Fundamentals of
Materials Science and Engineering

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·北京·

内容简介

本书共分7章，分别阐述了晶体结构与晶体缺陷、金属机械性能、二元合金相图、铁碳合金相图、钢的热处理、碳钢及合金钢、有色金属及合金等机械类专业基础内容。系统地介绍了金属的化学成分、组织结构、机械性能和应用特点方面的基本概念及基础知识。

本书可作为高等工科院校机械类及近机类专业的重要技术基础课程用书，同时可供从事材料研究与应用的工程技术人员作为了解专业知识、提高专业英语水平的阅读材料。

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前　言

随着我国国际交流与合作不断深入，双语教学也逐渐受到各大学的重视并率先在部分基础课和专业基础课中进行了尝试，取得了良好的效果。双语教学与外语教学不同，它是通过外文载体传授学科知识，使学生通过外文而不是中文去理解和掌握专业知识和理论，为学生奠定一个良好的外语环境。工程材料是我校最早被选定作为双语教学的课程之一，在教学内容选择、教学方法研讨、教学理念更新上进行了有益的探索。但是，教材问题长期困扰课程建设，影响该课程教学效果的进一步提高。国外原版教材虽然具有内容先进、信息量大、数据翔实、图表案例丰富、语言纯正、印刷美观等特点，但它存在着教材结构、体系、标准与国内不同的问题，而且有些原版教材篇幅过大，内容与我国现行教学基本要求不太一致。为此，解决工程材料课程的教材问题成为双语教学课程建设的瓶颈。

本书是在参考国外权威教材的基础上，编写的涉及材料科学与工程的发展前沿、内容难易程度适中、概念阐述与具体实例紧密结合、便于学生学习与理解学科知识的工程材料英文教材。全书共分 7 章，分别阐述了晶体结构与晶体缺陷、金属机械性能、二元合金相图、铁碳合金相图、钢的热处理、碳钢及合金钢、有色金属及合金等机械类专业基础内容。系统地介绍了金属的化学成分、组织结构、机械性能和应用特点方面的基本概念及基础知识。

本书具有如下特点：

(1) 为了使学生能够顺畅地与外国专家进行学术交流，同时还能熟练地与国内的工程技术人员进行技术探讨，我们在编写钢的热处理、碳钢及合金钢、有色金属及合金等章节时，详细地叙述了国内外金属材料分类标准、牌号的使用等。

(2) 专业学科知识里出现的英文词汇往往具有音节多、出现频度少、常附有前后缀等特点，为便于学生阅读连贯，对关键词、基本概念、基本定义加上汉语注释。

(3) 重要的基本概念、基本定义列在附录Ⅰ上，便于学生准确掌握，同时，附录Ⅱ列出了欧美计量标准与国际标准换算关系以方便学生阅读。

可以想象，从浩如烟海的材料科学英文文献中筛选出符合本教材要求且能保证章节之间有良好的协调关系的素材并非一件很容易的事情。我们本着一种探索和尝试，在多年使用讲义的基础上组织编写了这本教材。虽然做出了很大的努力并进行了多次修改，但仍然怀着一颗忐忑不安的心来迎接读者的评价。

本教材由黄根哲、朱振华担任主编，黄根哲教授编写第 1 章～第 4 章，朱振华副教授

编写第5章～第7章。本书在编写过程中得到了长春理工大学英国外教John Conroy的悉心指导，部分博士、硕士研究生和实验室人员参与了插图扫描和排版处理等工作，在此一并表示感谢。

作为主要从事机械设计制造的工程技术人员，必须具有合理选择、正确使用工程材料的能力。本书是高等工科院校机械类及近机类专业的重要技术基础课程用书，同时也可供从事材料研究与应用的工程技术人员作为了解专业知识、提高专业英语水平的阅读材料。

编者

2009年8月

CONTENTS

Chapter 1 Crystalline Structures and Imperfections

1.1 Introduction

Materials science and engineering (材料科学与工程) is an interdisciplinary field involving the properties of matter and its applications to various areas of science and engineering. *Materials science* (材料科学) is concerned primarily with the search for basic knowledge about materials. This science investigates the relationship between the structure of materials at atomic or molecular scales and their macroscopic properties. It includes scientific fields of applied physics and chemistry, as well as chemical, mechanical, civil and electrical engineering. It is also an important part of forensic engineering and failure analysis. In addition, *materials engineering* (材料工程) is concerned mainly with using applied knowledge about materials.

1.2 Classification of Materials

It is convenient to classify materials into broad categories for study. Many of the common characteristics of materials within a category arise from the lowest level of structure, the nature of the atomic bond that holds them together. The three main types of materials are metallic, polymeric, and ceramic materials. Two other types of materials that are very important for modern engineering technology are composite and electronic materials.

Metallic Materials

Metallic materials (金属材料) are inorganic substances that are composed of one or more metallic elements and may also contain some nonmetallic elements. Examples of metallic elements are iron, copper, aluminum, nickel, and titanium etc. Nonmetallic elements such as carbon, nitrogen, and oxygen may also be contained in metallic materials. Metals have a crystalline structure in which the atoms are arranged in an orderly manner. Metals in general are good thermal and electrical conductors. Many metals are

relatively strong and ductile at room temperature, and many maintain good strength even at high temperatures.

Metals and alloys are commonly divided into two classes: ferrous metals and alloys that contain a large percentage of iron such as the steels and cast irons and nonferrous metals and alloys that do not contain iron or contain only a relatively small amount of iron. Examples of nonferrous metals are aluminum, copper, zinc, titanium, and nickel etc.

Ceramics Materials

Ceramic materials (陶瓷材料) are inorganic materials that consist of metallic and nonmetallic elements chemically bonded together. Ceramic materials can be crystalline, noncrystalline, or mixtures of both. Most ceramic materials have high hardness and high-temperature strength but tend to be brittle. Advantages of ceramic materials for engineering applications include light weight, high strength and hardness, good heat and wear resistance, reduced friction, and insulative properties.

The insulative property along with high heat and wear resistance of many ceramics make them useful for furnace linings for heat treatment and melting of metals such as steel. An important aerospace application for ceramics is the use of ceramic tiles for the space shuttle. These ceramic materials thermally protect the aluminum internal structure of the space shuttle during ascent out of and reentry into the earth's atmosphere.

Polymeric Materials (Plastics)

Most *polymeric materials* (聚合物材料) consist of organic (carbon-containing) long molecular chains or networks. Structurally, most polymeric materials are noncrystalline, but some consist of mixtures of crystalline and noncrystalline regions. The strength and ductility of polymeric materials vary greatly. Because of the nature of their internal structure, most polymeric materials are poor conductors of electricity. Some of these materials are good insulators and are used for electrical insulative applications. One of the more recent applications of polymeric materials has been in manufacture of digital video disks. In general, polymeric materials have low densities and relatively low softening or decomposition temperatures.

Composite Materials

Composite materials (复合材料) are mixtures of two or more materials. Most composite materials consist of a selected filler or reinforcing material and a compatible resin binder to obtain the specific characteristics and properties desired. Usually, the components do not dissolve in each other, and they can be physically identified by an interface between them. Composites can be of many types. Some of the predominant types are fibrous (composed of fibers in a matrix) and particulate (composed of particles in a matrix). Many different combinations of reinforcements and matrices are used to produce

composite materials. Two outstanding types of modern composite materials used for engineering applications are fiberglass-reinforcing material in a polyester or epoxy matrix and carbon fibers in an epoxy matrix.

Electronic Materials

Electronic materials (电子材料) are not a major type of material by volume but are an extremely important type of material for advanced engineering technology. The most important electronic material is pure silicon that is modified in various ways to change its electrical characteristics. A multitude of complex electronic circuits can be miniaturized on a silicon chip that is about 3/4 in. square (1.90 cm square). Microelectronic devices have made possible such new products as communication satellites, advanced computers, handheld calculators, digital watches, and welding robots.

The properties of these various classes of materials are usually rather distinct. For instance, metals are opaque to light, and reflective. They are usually ductile, meaning that they can be bent before they break. They are electrically and thermally conducting. On the other hand ceramics and glasses are usually brittle, can be transparent to light, and are good insulators. They are particularly useful at high temperatures or in corrosive environments, since they retain their properties. Most polymers, on the other hand, cannot withstand high temperatures. Most of them are insulators, and many are highly deformable which is the real meaning of the word "plastic", and some have unique elastic properties (rubber bands). Semiconductors, of course, are distinguished by their electrical behavior. All of these property characteristics, and the reasons they exist, are discussed in some detail in the chapters that follow.

1.3 Structure of Atoms

First of all, let us now review some of the fundamentals of atomic structure since atoms are the basic structural unit of all engineering materials. Atoms consist primarily of three basic subatomic particles: protons, neutrons, and electrons. The current simple model of an atom envisions a very small nucleus of about 10^{-14} m in diameter surrounded by a relatively thinly dispersed electron cloud of varying density, so that the diameter of the atom is of the order of 10^{-10} m. The nucleus accounts for almost all the mass of the atom and contains the protons and neutrons. A proton has a mass of 1.673×10^{-24} g and a unit charge of $+1.602 \times 10^{-19}$ coulombs (C). The neutron is slightly heavier than the proton and has a mass of 1.675×10^{-24} g but no charge. The electron has a relatively small mass of 9.109×10^{-28} g (1/1836 that of the proton) and a unit charge of -1.602×10^{-19} C (equal in charge but opposite in sign from the proton).

The electron charge cloud thus constitutes almost all the volume of the atom (Figure 1-1) but accounts for only a very small part of its mass. The electrons, particularly

the outer ones, determine most of the electrical, mechanical, chemical, and thermal properties of the atoms, and thus basic knowledge of atomic structure is important in the study of engineering materials.

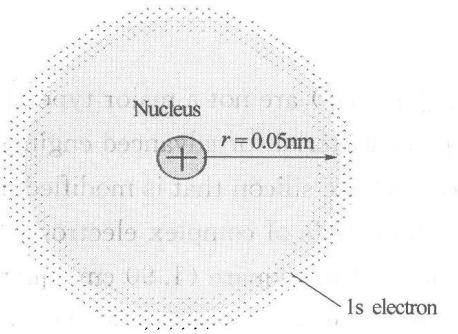


Figure 1-1 Electron charge cloud surrounding the nucleus of a hydrogen atom

1.4 Ideal Crystal, Space Lattice and Unit Cells

From the point of the structure of atoms and bonding system, electrons forming electron clouds revolve around the center points (protons) of the atoms, we can consider the atom a rigid sphere, although there is large empty space between protons and electron clouds because no one can squeeze or extend the radius of electron clouds. If the atoms or ions of a solid are arranged in a pattern that repeats itself in three dimensions, they form a solid that is said to have a crystal structure and is referred to as a crystalline solid or crystalline material (Figure 1-2(a)). Examples of crystalline materials are metals, alloys, and some ceramic materials.

Atomic arrangements in crystalline solids can be described by referring the atoms to the points of intersection of a network of lines in three dimensions such a network is called a space lattice (Figure 1-2(b)), and it can be described as an infinite three-dimensional array of points. Each point in the space lattice has identical surroundings. In an ideal crystal, the grouping of lattice points about any given point is identical with the grouping about any other lattice point in the crystal lattice. Each space lattice can thus

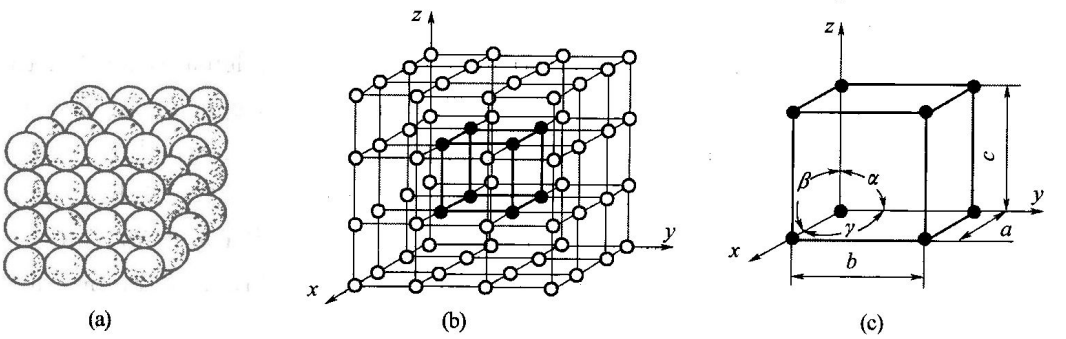


Figure 1-2 (a) Ideal crystal, (b) Space lattice of ideal crystalline solid, (c) Unite cell showing lattice constants

be described by specifying the atom positions in a repeating unit cell, such as the one with black points and heavily outlined in Figure 1 - 2(b). The size and shape of the unit cell can be described by three lattice vectors a, b, and c, originating from one corner of the unit cell (Figure 1 - 2(c)). The axial lengths a, b, and c and the interaxial angles α, β, and γ are the *lattice constants* (晶格常数)of the unit cell.

1.5 Crystal Structures and Bravais Lattices

Crystal structures are different from Bravais lattices. A. J. Bravais (1811—1863), French crystallographer, calculated mathematically the number of the space lattices according to the principle on which geometric and chemical environment is same at the every lattice point, it concluded that, only 14 standard unit cells could describe all possible lattice networks. But because crystal structures are referred to as specific arrangements of real atoms, they can constitute any kind of arrangements, so there are an infinite number of crystal structures. These Bravais lattices are illustrated in Figure 1 - 3, and they can be included to seven different types of crystal system (Table 1 - 1).

Table 1 - 1 Classification of space lattices by crystal system

Space lattice	Axial lengths and interaxial angles	Crystal system
Simple cubic	Three equal axes at right angles $A = b = c$, $\alpha = \beta = \gamma = 90°$	Cubic
Body-centered cubic		
Face-centered cubic		
Simple tetragonal	Three axes are right angles, two equal $A = b \neq c$, $\alpha = \beta = \gamma = 90°$	Tetragonal
Body-centered tetragonal		
Simple orthorhombic	Three unequal axes at right angles, two equal $a \neq b \neq c$, $\alpha = \beta = \gamma = 90°$	Orthorhombic
Body-centered orthorhombic		
Base-centered orthorhombic		
Face-centered orthorhombic		
Simple rhombohedral	Three equal axes, equally inclined $a = b = c$, $\alpha = \beta = \gamma \neq 90°$	Rhombohedral
Simple hexagonal	Two equal axes at 120°, third axis at right angles, $a = b \neq c$, $\alpha = \beta = 90°$, $\gamma = 120°$	Hexagonal
Simple monoclinic	Three equal axes, one pair not at right angle $a \neq b \neq c$, $\alpha = \gamma = 90° \neq \beta$	Monoclinic
Base-centered monoclinic		
Simple triclinic	Three unequal axes, unequally inclined and none at right angles $a \neq b \neq c$, $\alpha \neq \beta \neq \gamma \neq 90°$	Triclinic

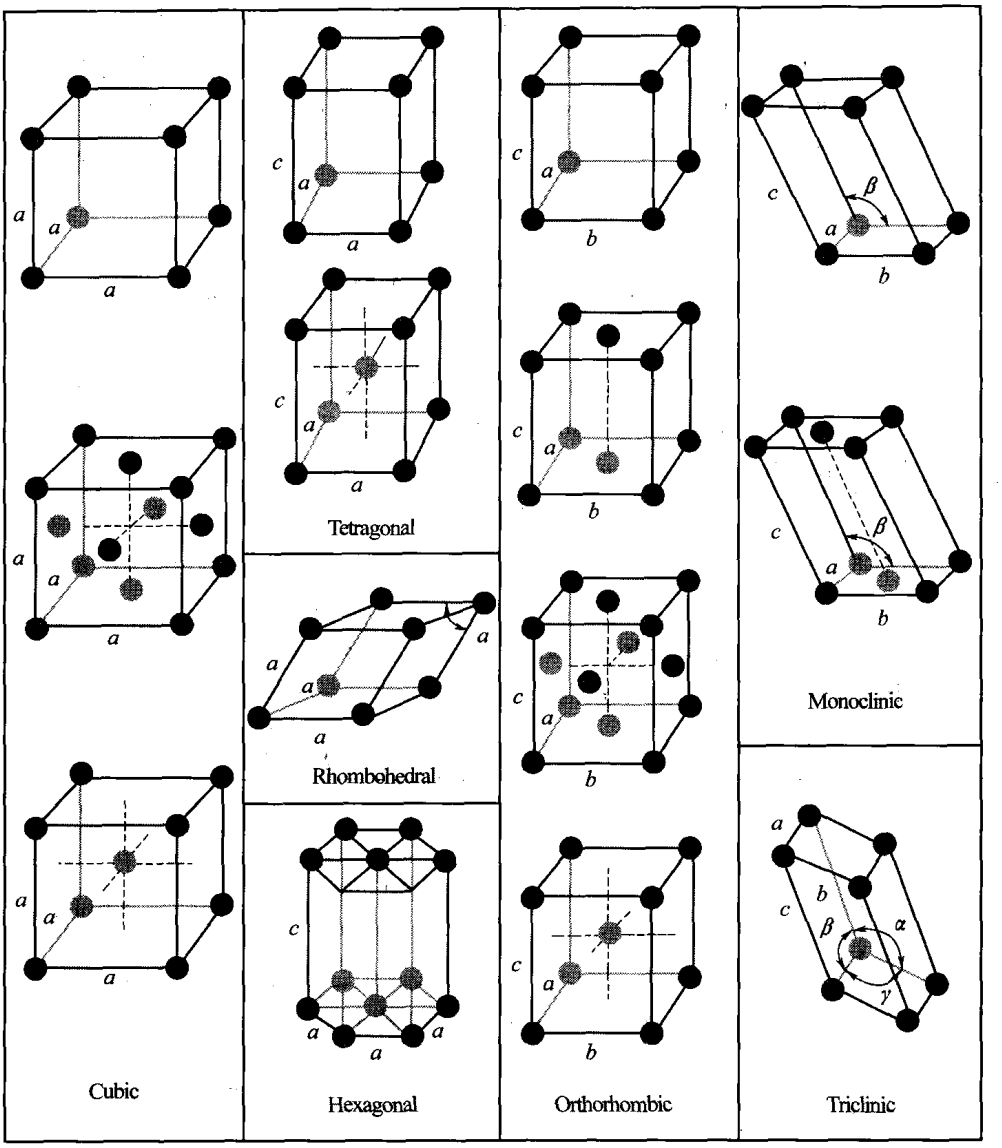


Figure 1－3 The 14 Bravais conventional unit cells grouped according to crystal system

1.6 Cubic Unit Cells

The term *unit cell* (单位晶胞) is used to describe the basic building block or basic geometric arrangement of atoms in a crystal. You can compare a unit cell to a single brick in a brick wall. Knowing that atoms are located at each corner of the single brick, it is easy to picture that atomic structure of a crystal, with such a unit cell repeating itself in three-dimensional space. If you repeat the unit cell in all three dimensions, you create a crystalline structure with a definite pattern. This larger pattern of atoms in a single crystal is known as a *space lattice* (空间点阵) or *crystal lattice* (晶体点阵). A space lattice is three sets of straight lines at angles to each other, constructed to divide space into small volumes of equal size, with atoms (ions or molecules) located at the in-

tersections of these lines or between the various lines. We must remember that the lines and points in a space lattice are only imaginary. The lattice concept is used to show the positions of atoms, molecules, or ions in relation to each other.

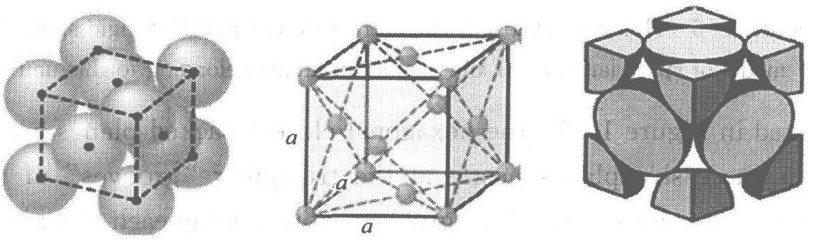
Cubic unit cells come in three categories—simple cubic (SC), body-centered cubic (BCC) and face-centered cubic (FCC). Since all directions and faces are the same, this geometry has the most symmetry and the calculations are the most straightforward. Many atoms bond in ways that utilize the cubic structure. On ionic and covalent bonding, we will see examples in which groups of atoms are associated with each lattice point. However, for many common metals, the "basis" of the unit cell (the number of atoms per lattice point) is one, and the simplicity of the cubic arrangement is particularly apparent. If all of the atoms are identical, then the *coordination number* (配位数), which was defined as the total number of nearest neighbors of one atom, is six for SC, eight for BCC, and twelve for FCC. The coordination number determines the quantity of the nearest equidistant elementary particles, in another words, the number of neighboring atoms directly surrounding each atom.

1.7 Basic Crystalline Structures in Metals

The elementary space-elements can be filled in the following manners for metals:

Face Centered Cubic Lattice (FCC)

There is one host atom at each corner, one host atom in each face, and the host atoms touch along the face diagonal ($a = 2\sqrt{2}r$, number of atoms per unit cell = 4). This lattice is "closest packed", because spheres of equal size occupy the maximum amount of space in this arrangement (Figure 1-4(a)—(c)). It appears at Cu, Ag, Au, Ni, Pb and γ-Fe etc.



(a) (b) (c)

Figure 1-4 Face-centered cubic structure (a) model of rigid spheres, (b) model of space lattice, (c) the number of atoms belonging to this unit cell

Body Centered Cubic lattice (BCC)

There is one host atom at each corner of the cubic unit cell and one atom in the cell center. Each atom touches eight other host atoms along the body diagonal of the cube