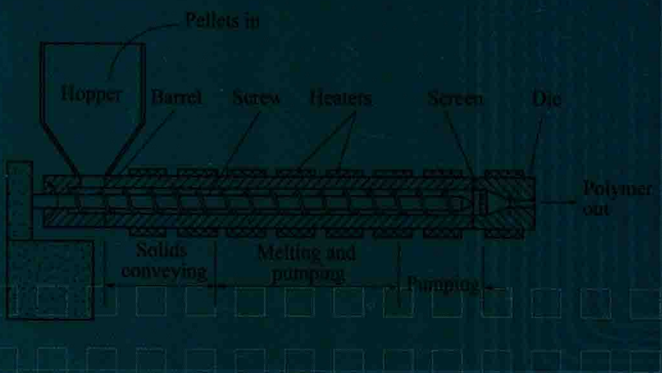
Materials Introduction

材料导论

王者辉　编著



化学工业出版社

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·北京·

《Materials Introduction（材料导论）》共分为两部分：第一部分分别介绍了金属材料、陶瓷材料、水泥混凝土材料、高分子材料、复合材料、半导体材料、能源材料的基本结构特征、性能、用途、合成制造和加工方法；第二部分为各种材料的实验操作内容。本书不仅详述材料科学基础理论，同时兼顾材料工程生产实践，注重理论与生产生活实践相结合，提高读者的知识面及阅读兴趣。

《Materials Introduction（材料导论）》可供从事材料科学与工程方面的科研人员、生产技术人员等参考阅读。

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前言

大千世界中，材料无处不在。吃、穿、住、行，每个人每天都会碰到诸如金属、橡胶、磁性、光电等众多材料，小到一根针、一张纸、一个塑料袋、一件衣服，大到交通工具、医疗器械、工程建筑、信息通讯、航天航空，处处都有材料科学与工程的身影。

材料科学与工程以材料学、化学、物理学为基础，主要研究材料成分、结构、加工工艺与其性能和应用。人类文明的发展史事实上就是一部如何更好地利用材料和创造材料的历史，材料的不断创新和发展，反过来又极大地推动了社会经济的发展。

材料科学与工程囊括了金属材料工程、无机非金属材料工程、高分子材料与工程、复合材料与工程等。随着人类进入新世纪以及科学技术的不断发展，无论是工业领域、建筑领域、医疗领域还是航空领域，材料学都面临着技术突破和重大产业发展机遇。以高分子材料、纳米材料、光电子材料、生物医用材料及新能源材料等为代表的新材料技术创新也显得非常活跃。很多日用化工类、机械加工类、石油化工、钢铁制造类企业都离不开材料及相关工程方面的人才，如材料及高分子复合材料成型加工、高分子合成、化学纤维、新型建筑装饰材料、现代喷涂与包装材料、陶瓷、水泥、家用电器、电子电气、汽车厂、钢铁企业、石油化工、制造企业、航天航空等企业中从事设计、新产品开发、生产管理、市场经营及贸易部门工作的人员，高等学校、科研单位从事材料科学研究与教学工作的学者和研究人员，政府部门从事行政管理、质量监督等工作的行政人员等，都也离不开材料及相关工程方面的知识和技能。

按照材料的种类，本书共涉及七种材料：金属材料、陶瓷材料、水泥混凝土材料、高分子材料、复合材料、半导体材料、能源材料，分别介绍各种材料的基本结构特征、性能、用途、合成制造、加工方法和相关实验操作。本书在注重材料科学基础理论的同时，兼顾材料工程生产实践，注重理论与生产生活实践相结合，提高读者的阅读兴趣。

由于作者水平有限，疏漏和不足之处在所难免，敬请读者指正。

作者

2017 年 5 月

Preface

Materials Science and Engineering encompasses all natural and man-made materials——their extraction, synthesis, processing, properties, characterization, and development for technological applications. Advanced engineering activities that depend upon optimized materials include the medical device and healthcare industries, the energy industries, electronics and photonics, transportation, advanced batteries and fuel cells, and nanotechnology. Professionals in materials science and engineering develop a fundamental understanding of materials at the nano, micro and macro scales, leading to specialization in such topics as: biomaterials; chemical and electrochemical materials science and engineering; computational materials science and engineering; electronic, magnetic and optical materials; and structural materials. As in the past, today's materials advancements enables new technological breakthroughs across all engineering disciplines.

Structural Materials focus on the relationships between the chemical and physical structure of materials and their properties and performance. Regardless of the material class metallic, ceramic, polymeric or composite, an understanding of the structure-property relationships provides a scientific basis for developing engineering materials for advanced applications. Fundamental and applied research in structural materials responds to an ever-increasing demand for improved or better-characterized materials.

This book treats the important properties of seven primary types of materials——metals, ceramics, concrete, polymers, composite materials, semiconductors, as well as energy. Describes the relationships that exist between the structural elements of these materials and their characteristies. Emphasizes mechanical behavior and failure along with techniques used to improve the mechanical and failure properties in terms of alteration of structural elements. Individual chapters discuss each of the corrosion, electrical, thermal, magnetic, and optical properties plus economic, environmental, and societal issues. Features a design component which includes design examples, case studies, and design type problems and questions.

The author would like to acknowledge with appreciation the numerous and valuable comments, suggestions, constructive criticisms and praise from evaluators and reviewers.

Author
May 2017

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Part 1

Materials Introduction

Chapter 1 Metals

【Objective】

Students will develop an understanding of the relationship between the structure and composition of metals and their observable macroscopic properties. They will discover how these properties determine applications, and gain an appreciation of the historical impact of metals and the role they will play in the future.

【Key Concepts】

- Metallic bonding
- The effect of cold working metals
- Annealing and quenching and the effect of heat treating
- Alloys
- Corrosion and its impact
- The value of recycling metals

【Prerequisites】

It is assumed that students have some familiarity with the following concepts:

- Measurement of mass and length
- Presenting data in graphic form
- Considerations of matter as atoms
- Differences between chemical and physical changes
- The importance of electrons in atomic bonding

1.1 What are Metals?

Metals are opaque, lustrous elements that are good conductors of heat and electricity. Most metals are **malleable** and **ductile** and are, in general, denser than the other elemental substances.

Metals are used in various aspects:

(1) Transportation, such as cars, buses, trucks, trains, ships, and airplanes;

(2) Aerospace, such as unmanned and manned rockets and the space shuttle;

(3) Computers and other electronic devices that require conductors (TV, radio, stereo, calculators, security devices, etc.)

(4) Communications including satellites that depend on a tough but light metal shell.

(5) Food processing and preservation, such as microwave, conventional ovens, refrigerators and freezers.

(6) Construction, for example nails in conventional lumber construction and structural **steel** in other buildings.

(7) Biomedical applications, act as artificial replacement for joints and other prostheses.

(8) Electrical power production and distribution, for example boilers, turbines, generators, transformers, power lines, nuclear reactors, oil wells, and pipelines.

(9) Farming, such as tractors, combines, planters, etc.

(10) Household conveniences, such as ovens, dish and clothes washers, vacuum cleaners, blenders, pumps, lawn mowers and trimmers, plumbing, water heaters, heating/cooling, etc.

1.2 Historical Timeline of Metals

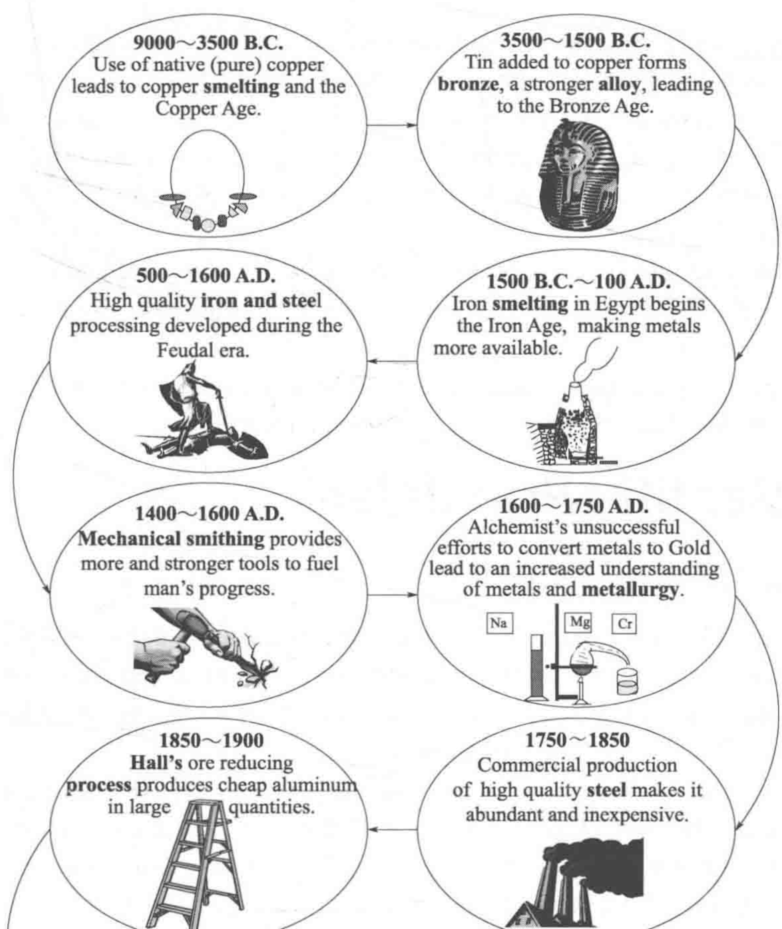


Figure 1.1

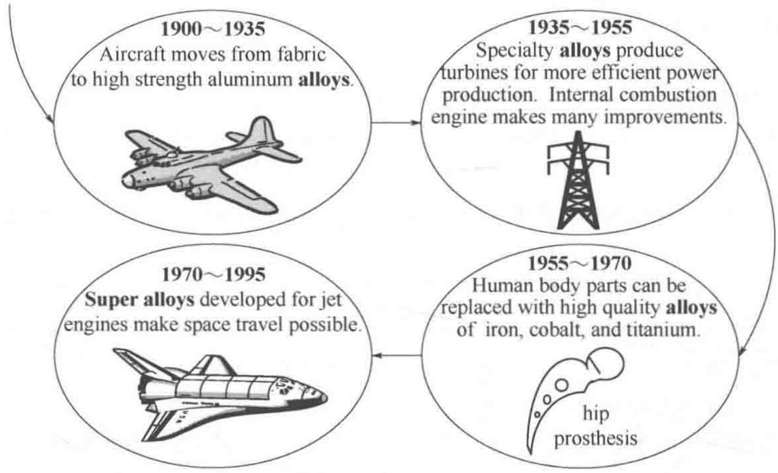


Figure 1.1 Metals history timeline from 9000 B.C. to present.

1.3 Future Trends

In the future, we will continue to depend heavily on metals. Lightweight aluminum alloys will be utilized more in automobiles to increase fuel efficiency. New, heat resistant super alloys will be developed so that engines can operate more efficiently at higher temperatures. Similarly, ceramic coatings will be used more to protect metals from high temperatures, and to increase the lifetime of tools. New, radiation-resistant alloys will allow nuclear power plants to operate longer, and thus lower the cost of nuclear energy.

Steel will continue to be the most commonly used metal for many years to come, due to its very low cost (approximately 20 cents/pound) and the ability to customize its properties by adding different alloying elements.

Finally, as easily-mined, high grade **ores** are depleted, recycling will become more important. Already, half of all aluminum, copper, and steels are being recycled.

1.4 Scientific Principles

1.4.1 Structure of Metals

Metals account for about two thirds of all the elements and about 24% of the mass of the planet. They are all around us in such forms as steel structures, copper wires, aluminum foil, and gold jewelry. Metals are widely used because of their properties: **strength**, ductility, high melting point, thermal and electrical conductivity, and **toughness**.

These properties also offer clues as to the structure of metals. As with all elements, metals are composed of atoms. The strength of metals suggests that these atoms are held together by strong bonds. These bonds must also allow atoms to move; otherwise how could metals be hammered into sheets or drawn into wires? A reasonable model would be one in which atoms are held together by strong, but delocalized bonds.

(1) Bonding

Such bonds could be formed between metal atoms that have low electronegativities and do not attract their valence electrons strongly. This would allow the outermost electrons to be shared by all the surrounding atoms (Figure 1.2), resulting in positive ions (**cations**) surrounded by a sea of electrons (sometimes referred to as an electron cloud).

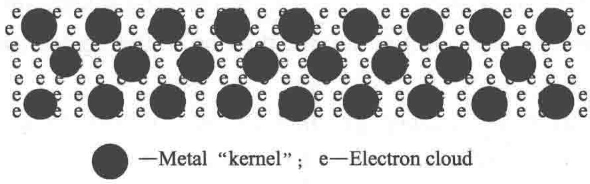


Figure 1.2 Metallic bonding.

Because these valence electrons are shared by all the atoms, they are not considered to be associated with any one atom. This is very different from ionic or covalent bonds, where electrons are held by one or two atoms. The metallic bond is therefore strong and uniform. Since electrons are attracted to many atoms, they have considerable mobility that allows for the good heat and electrical conductivity seen in metals.

Above their melting point, metals are liquids, and their atoms are randomly arranged and relatively free to move (Figure 1.3). However, when cooled below their melting point, metals rearrange to form ordered, crystalline structures.

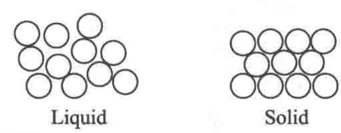


Figure 1.3 Arrangement of atoms in a liquid and a solid.

(2) Crystals

To form the strongest metallic bonds, metals are packed together as closely as possible. Several packing arrangements are possible. Instead of atoms, imagine marbles that need to be packed in a box. The marbles would be placed on the bottom of the box in neat orderly rows and then a second layer begun. The second layer of marbles cannot be placed directly on top of the other marbles and so the rows of marbles in this layer move into the spaces between marbles in the first layer. The first layer of marbles can be designated as A and the second layer as B giving the two layers a designation of AB (Figure 1.4).

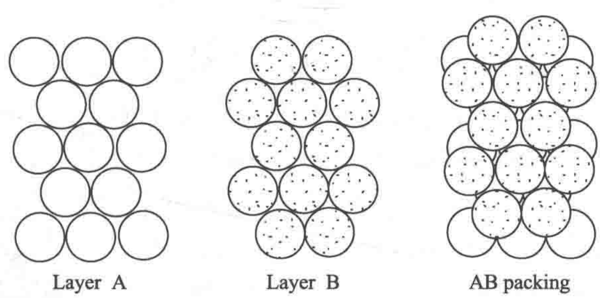


Figure 1.4 AB packing of spheres (notice that layer B spheres fit in the holes in the A layer).

Packing marbles in the third layer requires a decision. Again rows of atoms will nest in the hollows between atoms in the second layer but two possibilities exist. If the rows of marbles are packed so they are directly over the first layer (A) then the arrangement could be described as ABA. Such a packing arrangement with alternating layers would be designated as ABABAB. This ABAB arrangement is called **hexagonal close packing (HCP)**.

If the rows of atoms are packed in this third layer so that they do not lie over atoms in either the A or B layer, then the third layer is called C. This packing sequence would be designated ABCABC, and is also known as **face-centered cubic (FCC)**. Both arrangements give the closest possible packing of spheres leaving only about a fourth of the available space empty.

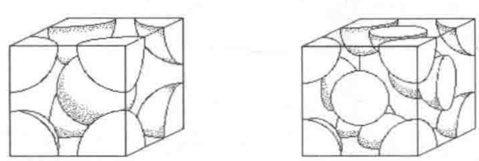
The smallest repeating array of atoms in a crystal is called a **unit cell**. A third common packing arrangement in metals, the body-centered cubic (BCC) unit cell has atoms at each of the eight corners of a cube plus one atom in the center of the cube. Because each of the corner atoms is the corner of another cube, the corner atoms in each unit cell will be shared among eight unit cells. The BCC unit cell consists of a net total of two atoms, the one in the center and eight eighths from the corners.

In the FCC arrangement, again there are eight atoms at corners of the unit cell and one atom centered in each of the faces. The atom in the face is shared with the adjacent cell. FCC unit cells consist of four atoms, eight eighths at the corners and six halves in the faces. Table 1.1 shows the stable room temperature crystal structures for several elemental metals.

Table 1.1 Crystal Structure for Some Metals (at room temperature)

Metals	Crystal Structure	Metals	Crystal Structure
Aluminum	FCC	Nickel	FCC
Cadmium	HCP	Niobium	BCC
Chromium	BCC	Platinum	FCC
Cobalt	HCP	Silver	FCC
Copper	FCC	Titanium	HCP
Gold	FCC	Vanadium	BCC
Iron	BCC	Zinc	HCP
Lead	FCC	Zirconium	HCP
Magnesium	HCP		

Unit cell structures determine some of the properties of metals. For example, FCC structures are more likely to be ductile than BCC (body-centered cubic) or HCP (hexagonal close packed). Figure 1.5 shows the BCC and FCC unit cells.



Body-Centered Cubic(BCC) Face-Centered Cubic(FCC)

Figure 1.5 Unit cells for BCC and FCC.

As atoms of melted metal begin to pack together to form a crystal lattice at the freezing point, groups of these atoms form tiny crystals. These tiny crystals increase in size by the progressive addition of atoms. The resulting solid is not one crystal but actually many smaller crystals, called **grains**. These grains grow until they impinge upon adjacent growing crystals. The interface formed between them is called a **grain boundary**. Grains are sometimes large enough to be visible under an ordinary light microscope or even to the unaided eye. The spangles that are seen on newly galvanized metals are grains. Figure 1.6 shows a typical view of a metal surface with many grains, or crystals.

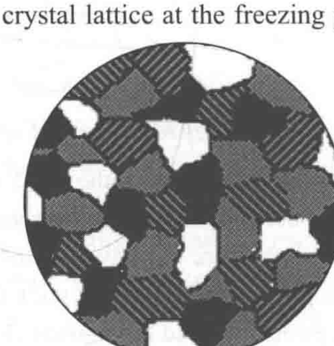


Figure 1.6 Grains and grain boundaries for a metal.

(3) Crystal Defects

Metallic crystals are not perfect. Sometimes there are empty spaces called **vacancies**, where an atom is missing. Another common defect in metals are **dislocations**, which are lines of defective bonding. Figure 1.7 shows one type of dislocation.

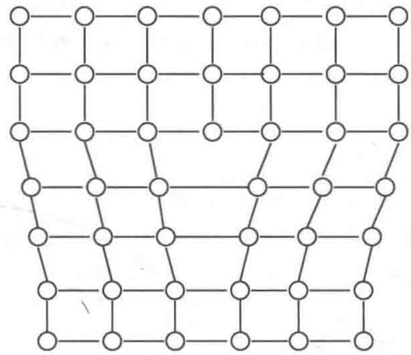


Figure 1.7 Cross-section of an edge dislocation, which extends into the page (Note how the plane in the center ends within the crystal).

These and other imperfections, as well as the existence of grains and grain boundaries, determine many of the mechanical properties of metals. When a **stress** is applied to a metal, dislocations are generated and move, allowing the metal to deform.

1.4.2 Mechanical Properties

When small loads (stresses) are applied to metals they deform, and they return to their original shape when the load is released. Bending a sheet of steel is an example where the bonds are bent or stretched only a small percentage. This is called **elastic deformation** (Figure 1.8) and involves temporary stretching or bending of bonds between atoms.

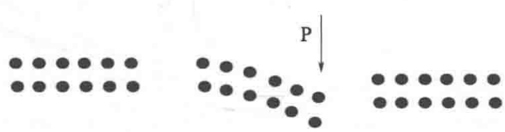


Figure 1.8 Elastic deformation in a bar of metal.

When higher stresses are applied, permanent (plastic) deformation occurs. For example, when a paper clip is bent a large amount and then released, it will remain partially bent. This **plastic deformation** involves the breaking of bonds, often by the motion of dislocations. See Figure 1.9, dislocations move easily in metals, due to the delocalized bonding, but do not move easily in ceramics. This largely explains why metals are ductile, while ceramics are brittle.

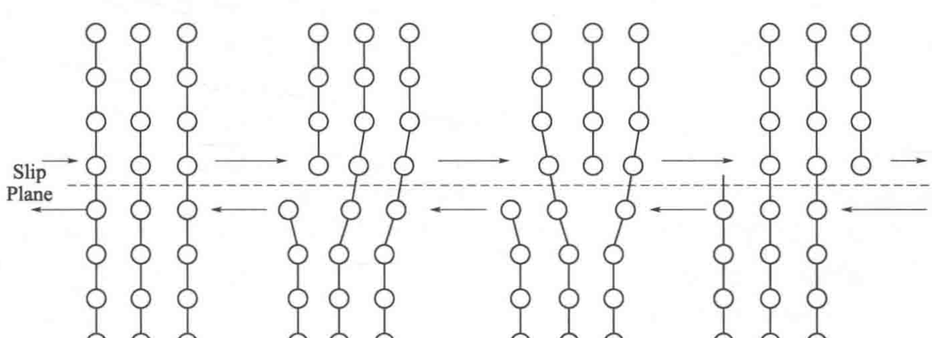


Figure 1.9 Dislocation movement in a crystal.

If placed under too large of a stress, metals will mechanically fail, or fracture. This can also