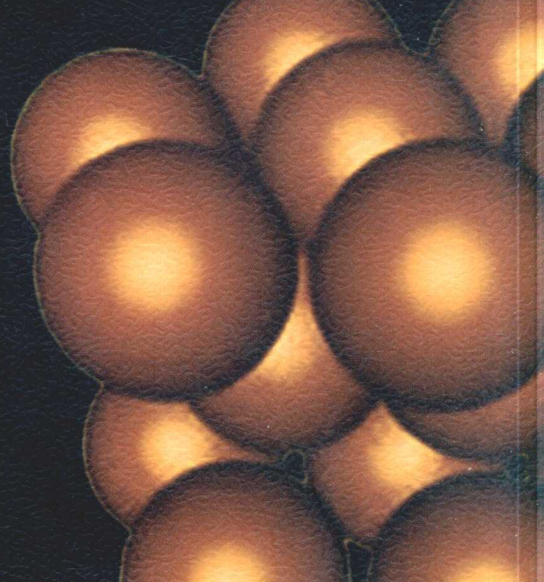
Mechanical Engineering Materials

机械工程材料

陈朝霞 何柏林 ◎ 编著



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应用型人才培养实用教材

普通高等院校机械类“十三五”规划教材

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陈朝霞　何柏林　**编著**

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前　言

本书为“机械工程材料”课程的双语教学配套教材。该课程属于工科院校机械类专业的一门专业基础课。目前，在高校的教学中运用双语教学已成为教学改革的重点和热点。早在2001年，国家教育部发出的《关于加强高等学校本科教学工作提高教学质量的若干意见》的文件，就明确提出在大学推广双语教学。按照“教育要面向现代化、面向世界、面向未来”的要求，为适应经济全球化和科技国际化的挑战，本科教育要创造条件使用英语等外语进行公共课和专业课的教学。本书的编写筹备多年，主要素材来自于多年的双语教学实践过程积累的英语讲义及科研实践中的第一手资料；同时在本书编写过程中，作者也参考了国内外相关教材、著作及文献。

本书的编写，主要强调两大特点。一为英语语言的简单平实，通俗易懂。双语教学的开展，最大的障碍在于语言。我们在准确表达相关专业术语的前提下，力求用科技论文式的论述来表达所述知识点，尽量做到浅显、易懂，避免文中出现大量的复杂句型、生僻字等。二为内容的联系实际、贴近生活。“机械工程材料”课程涵盖的知识面较广，包含了常用工程材料的性能、结构、加工及热处理方面的相关知识。由于“机械工程材料”为学科基础课，学生往往不具有较深厚的实践经验。因此，本书在编写时，相关素材的选取力求与生活紧密相关，从而使学生能更好地去体会和理解所述知识点。

全书共分为13章。第4章、第5章、第6章、第8章、第10章、第12章及第13章由陈朝霞、满华、李力编写；第2章、第3章、第7章及第9章由何柏林、李树桢编写；第11章由匡唐清编写；第1章由徐先锋编写。全书由陈朝霞、何柏林统稿。作者还为本书配备了精美的课件，供购买者免费索取。

由于作者水平有限，本书难免存在不当之处，敬请读者批评指正。

作　者

2016年5月10日

Contents

Chapter 1 Introduction ······ 1

1.1 Concepts and sorts of materials and what the function and status of the material are in society revolution ······ 2

1.2 Conteat and Relation of materials science and engineering ······ 5

1.3 Development of materials ······ 7

1.4 Materials and mechanical engineering ······ 10

Chapter 2 The Mechanical Properties Of Metals ······ 13

2.1 Introduction ······ 13

2.2 Static mechanical properties ······ 14

2.3 Hardness tests ······ 22

2.4 Impact toughness ······ 27

2.5 Fracture toughness ······ 30

2.6 Fatigue tests ······ 32

2.7 Test at elevated tempearatures ······ 34

2.8 Variability of material properties ······ 35

Chapter3 Crystal Structure and Crystallizing ······ 37

3.1 Crystal structure of metals ······ 37

3.2 Actual structure of metals ······ 47

3.3 Crystallization of metal ······ 53

3.4 Structure of steel ingot ······ 59

Chapter4 Plastic Deformation and Recrystallization of Metal ······ 62

4.1 Plastic deformation of metal ······ 62

4.2 Effects of plastic deformation on structure and property of metal ······ 67

4.3 The change of structure and property of deformed metal during heating ······ 70

4.4 Hot working of metal ······ 75

4.5 Superplasticity ······ 76

Chapter5 Binary Alloy ··· 78
5.1 Definitions and basic concepts ··· 78
5.2 Phase structure of alloy ··· 80
5.3 Binary alloy diagram ··· 83
Chapter 6 Iron Carbon Alloys ··· 99
6.1 Phase structure and properties of iron carbon alloys ··· 99
6.2 Iron carbon equilibrium diagram ··· 101
6.3 Plain carbon steels ··· 115
Chapter 7 Heat Treatment of Steel ··· 120
7.1 Introduction ··· 120
7.2 Formation of austenite during heating ··· 122
7.3 Decomposition of austenite during cooling ··· 129
7.4 Annealing of steel ··· 140
7.5 Normalising of steel ··· 144
7.6 Hardening of steel ··· 146
7.7 Tempering of steel ··· 159
7.8 The surface quenching of steel ··· 165
7.9 The chemical heat treatment of the steel ··· 170
Chapter 8 Alloy Steels ··· 177
8.1 Effects of alloying elements in steel ··· 177
8.2 Mechanisms of strengthening in metals ··· 183
8.3 Categories and code of alloy steels ··· 186
8.4 Structural alloy steels ··· 186
8.5 Tool steels ··· 195
8.6 Steels for special use ··· 202
Chapter 9 Cast Iron ··· 207
9.1 Introduction ··· 207
9.2 Graphitisation of cast iron ··· 207
9.3 Classify of cast iron ··· 209
9.4 Grey cast iron ··· 211
9.5 Malleable cast iron ··· 214
9.6 Spheroidal cast iron ··· 218
9.7 Vermicular cast iron ··· 223

9.8 Alloy cast iron ······ 224

Chapter10 Nonferrous Metals and Their Alloys ······ 228

10.1 Aluminum and its alloys ······ 229
10.2 Copper and its alloys ······ 237
10.3 Magnesium and its alloys ······ 241
10.4 Titanium and their alloys ······ 243
10.5 Bearing alloys ······ 247

Chapter 11 Polymer ······ 250

11.1 Introduction ······ 250
11.2 Classification of polymers ······ 251
11.3 Structural characteristics of polymers ······ 255
11.4 Properties of polymers and plastics ······ 266
11.5 Additives for plastic materials and compounding ······ 277
11.6 Polymer processes ······ 279
11.7 Properties and utilities of selected polymers ······ 283

Chapter 12 Advanced Materials ······ 285

12.1 Introduction ······ 285
12.2 Information functional materials ······ 285
12.3 Composite materials ······ 286
12.4 Smart materials ······ 292
12.5 Nanomaterials ······ 294
12.6 Biomaterial ······ 300
12.7 Porous materials ······ 301

Chapter 13 Material Selecting for Parts ······ 304

13.1 Failure of mechanical parts ······ 304
13.2 General principles for selecting suitable materials ······ 310
13.3 Selecting suitable material for typical parts and working process ······ 311

References ······ 316

Chapter 1
Introduction

Materials for Mechanical Engineering forms the bedrock of the engineering disciplines, because the structures, components and devices that engineers design and use must be made out of something, and that is the material. The properties of the materials are available to define and limit the capabilities of device or structure, and the techniques that can be used to fabricate the material. Selecting the best material is usually a difficult task, requiring tradeoff between different materials with different properties (including cost). But the repertoire of available materials has expanded considerably in the last few decades and is likely to continue this proliferation trend in the future. In most of mankind's history, the available materials were only a few and essentially natural such as clay for making bricks and pottery, wood and stone for making tools and construction materials, natural fibers (either from plants or animal hair) for cords and textiles, and animal fur for containers and clothing.

Man's abilities to modify natural materials, to extract useful materials from natural resources (which often requires high temperatures), or to combine them in new ways, brings new possibilities. Anthropologists study the material artifacts of the past civilizations to understand how they were fabricated (as there is a field of research called archeo materials), and in turn, to gain insight into the level of technology and sophistication of the culture. The role of materials in the advance of civilization and culture is powerfully summarized by the fact that it is the name of each dominant new material that has been used to describe an era – the Stone Age, the Bronze Age, the Iron Age, and so forth. Articles and editorials frequently appear debating whether our culture is named Silicon age, the Plastic age, or something else. Arguably, we are now in the age of many materials. An appreciation of the important materials characteristics, the connection among the behavior of the material with their intended design settings, and the stuff an object is made from (and how it is made) are important to every engineer, even if they never create a new material but simply choose from standard and widely available ones. Personally, I would like to think that such an appreciation is important to every educated person, since everyone in their daily life constantly uses an enormous variety and range of different objects and will have a better understanding of how many theories work (and why they sometimes fail) by knowing more about the materials from which they are made.

1.1 Concepts and sorts of materials and what the function and status of the material are in society revolution

1.1.1 Conception and types of materials

Materials can be classified as structural materials and functional materials by usage. On one hand, Structural materials are a sort of material which, for example, applies its mechanical, physical and chemical properties in mechanical production, engineering construction, transportation and every other industry department. On the other hand, functional materials are a sort of material which applies its thermal optical and magnetic properties in electronics, laser, communication energy resources, biological engineering and so on. The latest development of functional material is intelligence material, which can estimate circumstances and self-repair, therefore people regard it as the material of the 21^{st} century.

Materials can also be classified as metal materials, ceramic materials, high polymer materials and composite materials by components and identity. Metal materials can be divided into ferrous metal materials and nonferrous metal materials. Ferrous metals generally include iron, manganese, chromium and their alloy, which are the most widely used structural materials. All metals apart from ferrous metals are called nonferrous metal materials. Nonferrous metal material has wide varieties, which can be divided into light metal, heavy metal, high-melting metal, rare earth metal, dissipated metal, noble metal and so on. The strength of pure metal is lower than that of other metal, thus most metals commonly used are alloys which is formed by melting two or more kinds of metals or nonmetals, mixing and cooling them at low temperature. For instance, the bronze (which is composed of copper and tin), and the duralumin (which is composed of aluminum, copper and magnesium) are all alloys. Alloys may also be composed of metal elements and nonmetal elements, for instance, carbon steel is composed of carbon and iron. Mechanical properties of alloy are generally better than that of pure metals. To meet the demands of developing aviation, rocket, naval vessels, to accelerate the development of the fields of energy resource industry, metal structure materials which possess special properties should be developed, so, the core of the metal materials research is the development of new metal materials.

Ceramic material is the earliest material that has been utilized. Traditional ceramic materials are silicate materials which mainly are silicon and aluminum oxides. The components of the newly fields of developed special ceramic or fine ceramic extend to pure oxide, carbide, silicide and so on, so it can be called inorganic nonmetallic material.

Macromolecular material is one kind of composite materials, which mainly includes plastic, synthetic fibre and synthetic rubber. Besides those, there are paint and adhesive. Such materials have excellent properties, such as high strength, good plasticity, high corrosion resistance and effective insulativity. Their development is fast and they partially replace metal materials now.

Composite macromolecular materials with special properties indicates the direction of development of polymer materials.

Composite materials consist of metal material, ceramic materials and macromolecular materials. The strength, rigidity and corrosion resisting abilities of composite materials are better than single-component material, and it is a new material with great developing prospects.

Materials can also be divided into traditional materials and new materials, the manufacture process of traditional materials is already ripe. Materials that are developing or developed recently are called new materials. Materials like high-temperature superconducting materials, engineering ceramics and functional polymeric materials are new materials. The features of new materials are as follows.

(1) New materials are composite materials designed, studied, experimented and composited based on the command of matter structure and variation. The special features of new materials can meet the needs of top technology and manufacture. For example, ultra-temperature, ultra-high pressure, extra low pressure, corrosion resisting and rubresistance materials can perform in almost extreme conditions.

(2) The development of new materials is the result of comprehensive study in multi disciplinary. It requires advanced science, often relates to physics, chemistry, metallurgy and so on. With out the development of multi fields, it is impossible to design and develop a new material.

(3) From designation to production, manufacture of a new material requires special, complex equipments and technology, which form a unique field itself, called new material technology. New material technology has a special statu in high-tech fields, and becomes the foundation of high-tech implementation.

1.1.2 What the function and status of material are in society revolution

1. Material is the milestone in the progress of human society

Every discovery and application of new materials levers human's ability to a higher level. Every breakthrough in material science leads to a revolution in manufacture technology, even can bring a worldwide technological change. The partition of human civilization is based on material development, for exemple, there are Stone Age and the Bronze Age. Nowadays, we are entering a synthetic material new age.

It should be said, the application of metals (bronze and iron) is the sign of human civilization. Earliest civilizations have entered the Bronze Age early or later. Bronze is the metal human used earliest, in the Bronze Age, while iron is more valuable than bronze, that is because copper refinement is much easier than iron making in that age; and copper always exists in earth surface, which means it is easier to be discovered and mined.

Unearthed cultural relics indicate that, iron has existed since 3000B.C.; in 2000B.C., human has learnt cast iron processes. Among them, Chinese people made a significant contribution to human civilization in the Iron Age.

Iron and steel industry has developed until the latter half of the 19^{th} century, that was because of the development in social productive force and steelmaking technologies. Especially in 1950s, thanks to L-D process, the production was booming. From the early 1950s to the late 1970s, worldwide steel production increased from 2.1 hundred millions to 7.5 hundred millions.

During this period, steel and non-ferrous metals were developing. C.M. Hall developed electrolytic aluminum in 1866, the amount of aluminum is just lower than steel till now. In 1910, sodium reduction out pure titanium, it meets the need in aviation industry. The needs of nuclear industry promote the developments of uranium and other nuclear fuels, at the same time, electronic industry and semiconductor industry facilitate the development of ultrapure materials.

Moreover, in nonmetal material field, especially in 20^{th} century, great developments were achieved. Synthetic polymer materials are compatible to steel materials in huge wide applications since 1920s. Production of synthetic polymer materials which include plastics, synthetic rubber and synthetic fiber from all over the world has already reached 1 hundred million tons per year. Date from 1970, the production of synthetic polymer materials was forty millions tons, besides thirty millions tons of plastics. The amount of synthetic rubber is five million tones, which was already beyond the production amount of natural rubber; the amount of synthetic fiber is four million tons, which is equal to the production amount of natural fiber in that year. Such a high developing speed is unparalleled.

Ceramic is a symbol of human civilization. Five hundred thousand years ago, after human have learnt how to use fire, human began to make ceramics, which is the beginning of changing material property with heat treatment. In the New Stone Age, brownware was made around the world. As for glass production, it begin as early as 1600B.C. in Egypt.

In the last two decades, with the development of material science and technology, ceramic has became the main source of heat-resistant materials, corrosion-resistant materials and all kinds of functional materials in metallurgy, construction, chemical industry and frontier field. For example, alumina is a heat-resistant, corrosion-resistant materials; lithium niobate can translate electronic signal into optical signal; silicon nitride is applied in cutting tool.

Recently, European Space Agency declares: human will emigrate to the moon in 40 years. Main material of lunar landing spacecraft will be ceramic materials. So, ceramic is both the oldest material, and the newly developed material. Ceramic materials, metal materials and Synthetic materials are the three pillars of engineering materials.

2. Material is the foundation and guide of the development of society and economic

All the industry revolutions are guided by invention and wide application of new materials. In the first industrial revolution, the development of steelmaking contributed to the material foundation of invention of steam engine; in the second industrial revolution, monocrystal silicon played an important role in electronic technology prosperity. High-tech field is closely related to the development of material.

1.2 Content and Relation of materials science and engineering

For a long time, people used materials to make tools, to accumulate a wealth of knowledge, including material performance, processing technique and applicability. The knowledge was based on practice and experience. After people knowing properties and processing technique, materials were used to meet the needs of society. According to the history of material development, material processing was in "skill" level before industry revolution.

Since the industry revolution, the application and development of materials had become a discipline called "material science and engineering". The basis of materials science and engineering involves studying the structure of materials, and relating them to their properties. The major determinants of the structure of a material and thus of its properties are its constituent chemical elements and the way in which it has been processed into its final form. Fig. 1-1 depicts the content of material science and engineering and relationship of them. Structure/component, property, synthesis/process, efficiency (usability) were four elements of materials science and engineering.

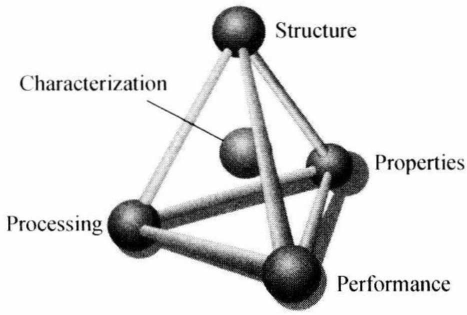

Fig. 1-1 Content of material science and engineering and relationship

The property can be divided into two sorts: mechanical property and physical property.

Normally, mechanical properties of material are strength, plasticity and rigidity. However, there are always situations like this, material can bear suddenly, strongly impacts (impact ductility); continuously, periodically bear alternant force (fatigue property); some conditions bear high temperature (creep property) and can operate in frication condition (abrasion resistance). The strength property of material is not only to meet the operate condition, but also its machinability. Forging metal parts must bear force suddenly imposed during forming process, in this process, flows should not appear. Normally, slightly change in component could lead to notable change in property.

Physical properties include electrical, magnetic, thermology and chemical performance. Physical properties depend on structure and processing technic. Even slightly change in component could lead to notable change in the electrical conductivity of semi-conductor and ceramic. High calcination temperature will significantly reduce the insulation properties of ceramics. Slightly impurities will change the color of glasses and plastics.

The structure of materials can be analysed from several levels. No matter change happened in which level, properties will change.

The first level is the slightest level. Atoms consist material in this level. The arrangement of electron around atom nucleus has great impact on electricity, magnetic, calorific, optical even corrosion resisting properties. Especially, the arrangement of electron will have impact on atom bonding, thus materials can be divided into metal, ceramic and high polymer materials.

The second level is the arrangement of atoms in space. Metals, many ceramics and some high polymer materials have regular arrangement of atom in space, or crystal structure. Crystal structure will impact mechanical properties of metals, such as strength, plasticity and seismic resistance property. Other ceramic materials and most of high polymer materials don't have regular arrangement of atoms. Materials which are in amorphous state are very different from materials which are in crystalline state. For example, glassy polyethylene is transparent; but polyethylene in crystal state is semi-transparent. Because of flow exist in arrangement of atom, properties changes significantly.

The third level is crystal structure of material. Crystal structures exist in most of the metal materials, some ceramic materials and a few of high polymer materials. In these crystal grain, because of the arrangement of atoms altering their direction, properties are impacted and change accordingly. At the level of crystal structure, size and shape of crystal grain play key roles in properties.

The forth level is multiphase structure of materials. In most materials, there are more than one phase, each phase has unique arrangement of atoms and properties. Controlling the form, size, distribution and amount of material substrate are valid measures to improve macroscopic properties.

Material processing technology is the important part of material science and engineering. And in fact it is material engineering. Material processing has great influence on structure and property of material. The relationship of material structure, property, and processing is shown in Fig. 1-2. Besides, using and processing circumstance can influence properties of material.

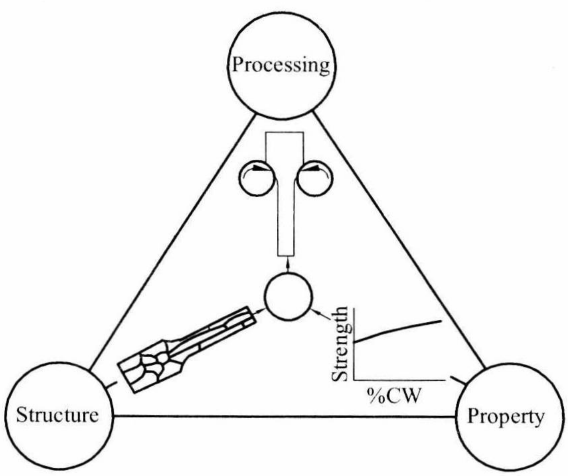

Fig. 1-2 Relationship of material structure, property, and processing

The goal of material science and engineering is: according to the required performance, design the composition of atoms or molecules, establish corresponding process technology in order to get ideal structure, and to apply known scientific laws to improve performance, efficiency and service life of existing materials greatly.

1.3 Development of materials

Materials themselves are foundations and supports of material civilization, and they also support the developments of other new technology in the exploitation, refinement, transformation and transportation of energy resource and the transmission, storage application and control of information cannot be apart from material technology; and structure materials and functional material are necessary for space technology, ocean engineering, biological engineering and system engineering.

Materials are always faced with the choice of society, and this choice depends on the requirement of society. Five criterions are required to decide whether one material can be accepted by society: resource, energy resource, environmental protection, economic and performance. When the restrictions of resource, energy resource, environment are satisfied, the property and economic efficiency material should also be concerned.

The development of material is in competitive conditions all the time. One of them is the competition between metal materials, ceramic materials and high polymer materials; the other one is different types of competition in the categories of materials, such as competition between ferrous metals and nonferrous metals, but they all belong to the metal. The average weight of a car in America was 1 500 kg in 1980 and reduced to 1 020 kg in 1990. The proportion of cast iron dropped from 15% to 11%. The amount of cast iron in one car dropped from 225 kg to 112 kg; the proportion of aluminum alloy rose from 4% to 9%; the proportion of high polymer materials rose from 6% to 9%. Automobile engines which adopt ceramic materials replaced automobile engines which adopt metal materials, which bring significant economic effect. Ceramic can withstand much higher temperature than metal, thus burning efficiency of ceramic can be improved, and the weight of automobile engine can be decreased at the same time. Because of that, the development of ceramic material based engine is blooming all around world.

Besides, symbiotic relationships between materials, can also be mutual promotion. For example, slag is byproduct of blast furnace iron making, but slag can be raw material of cement; the byproduct of coking-artificial coal, is an important chemical material.

Concerning the further development of the material, there are two aspects to disscuss, one is the improvement of traditional materials, while the other one is the development of new materials.

1.3.1 Improvement of traditional materials

Materials which have been brought into production or used for a long term are traditional materials. The intention of improvement is to meet the requirement of consumer, which is to improve performance and reduce cost.

Improving process technology is the most effective way to improve properties of traditional material. By this way, the cost of materials can be reduced, while the productivity can be increase. The oxygen (jet) steelmaking process does not only accelerate smelting process, but also enhance the quality of molten steel (phosphorus content and gas content are reduced, but draw radius is enhanced); heightening blast temperature can enhance the process of ironmaking, which reduce energy consumption, enhance the quality of molten steel; continuous casting and rolling process, accelerates smelting process, which also reduces energy consumption.

The application of a new process can leads to the prosperity of new materials and vanishment of traditional materials. For example, Austenitic stainless steel has a high corrosion resistance, so it is widely used in chemical device manufacture. But after welding, intergranular corrosion may happen in heat affected zone, this phenomena relates to the deposition and separate intergranular carbides out. The application of extra-low-carbon stain less steel can solve this problem; but in the process of extra-low-carbon stain less steel in electric arc, the cost will rise, and the furnace life is short, so people have to substitute extra-low-carbon stain less steel with Cr18Ni9Ti. However, the application of AOD in 1970s reduces the cost of extra-low-carbon stain less steel, and improve its quality. Now it rapidly replaces Cr18Ni9Ti.

1.3.2 Development of new materials

1. Energy materials

In the past 30 years, the average operating temperature of fuel turbine blade has risen by 6.67 °C every year. If operation temperature rise to 83 °C, thrust will increase by 20%. This achievement should thank to reinforcement technique of nickel-based alloy and the application of directional solidification technique. The application of rapid solidification technique and isostatic molding technology further raise the operating temperature. The application of SiC can raise the operating temperature of blades to 1 200 °C. In addition, the iron loss all over world can reach four thousand billion kWh. If amorphous metals are introduced, one thousand billion kWh can be saved every year, 1 billion U.S. dollar can be saved in USA as well.

Nowadays, energy sharply exhausts in the same time, solar energy radiated to earth is 1 hundred thousand times the whole energy consumption of world in one year. Because of that, photoelectric conversion materials are highly valuable.

2. Information materials

The storage and transmission devices require a small size, a light weight and a swift process. The line weight of silicon chips is 30 μm in 1960, downsized to only 1 μm in 1986. Every chip can contain 1.6×10^6 bit information, which is more than 10^5 times transistors' content. The line weight of silicon chips reached 0.1 μm in 1990.

Information transferred by light is more reliable than transferred by electric wave or electron. Optical fiber was applied in telephone in 1970s; the first transatlantic submarine cable which reaches a length of 6 684 km can support forty thousand calls at one time. At present, optical signals has to convert to electrical signals to be magnified; non-linear optical materials are being developed. The magnitude of optical signals is equal to the magnitude of transistor electrical signals, it can maximize optical signal.

3. Biological materials

A variety of materials is being developed to prolong life expectancy. High polymer materials, ceramic materials and composite materials are used to produce artificial organ such as blood vessel, cardiac valve, heart, bones and skins. It used to be widely believed that artificial organ should not react with human environment; now it is widely believed that not all the chemical reactions are harmful. Some of them can be utilized to reinforce interfaces or absorb foreign matter. The amount of biomedical materials increases by 13% per year, annual profit is up to fifty billion dollars.

4. Automobile materials

In industrially developed countries, automotive industry, construction industry and farm-machinery industry are three core industries. In 1994, 49 millions automobiles were produced all over the world. The amount of steel, aluminum alloy and plastics used in automatic industry is up to 65millions tons. Take America for example, there are 164 millions automobiles in the USA travelling 2×10^{12} km per year. Suppose one gallon gas can support 20 km driving, then the total consumption is 10^{11} gallons gas. Therefore, automatic industry consumes huge numbers of energy and materials. On the premise of effective environmental conservation, every country is developing light and economical automobile materials. And automobile manufacture ability is an important symbol of high industrialization levels.

In addition, high temperature superconducting materials are applied to daily life, and film superconducting materials are already ripe; high temperature superconducting materials in bulk form have achieved a big breakthrough. The highest T_C can reach 135 K. Volumed $Bi_2Sr_2CaCu_2O_Y$ superconducting materials have been produced, yearly output value of which may reach 60-90 billion dollars.

As soft magnetic materials, amorphous metals are available to iron core of transformer, iron loss of which is only equivalent to one third of transformers made by stainless steel smelting. Amorphous metals are widely used. They are continuous production in the U.S, and production rate can reach 1t/h by one autocrimper device.

When particulate materials are as tiny as nanometer size, special properties will appear. For example, diffusion coefficient will increase 100 times; Solubility of solute atoms will increase 2 500 times; ceramic materials are converted from brittle to plastic; conductors become non-conductors and so on. It can be predicted that these materials will become the core of research and application.

1.4 Materials and mechanical engineering

1.4.1 Relationship of materials and mechanical engineering

Materials are "hand", mechanical engineering is "fist", and mechanical engineers are "boxer". Without a pair of hands, boxer can't give a fist. Similarly, without materials, there are no mechanical engineering. In order to make a qualified machine, mechanical engineer have to acquaint with the properties of materials.

1.4.2 Materials of mechanical engineering

Mechanical engineering is based on the related physical science, technical science and combined experience of production. This subject aims to research on theories and resolve problems exciting in, design, manufacture, application and maintenance. Before the industry revolution, most machines are wooden structures made by carpenter, and metals (mainly are iron and steel) are only used in the production of small accessories in, for example, instruments, clocks, locks, pumps and wood structure. The precision of metal processing relies on careful work of mechanics. With the wide application of steamer, and the development of large machinery and equipments such as metallurgical machinery, mining machine and steamboat, metal accessories which need contour machining and cutting are more and more, as metals expand from copper and iron to steel. The rapid development of mechanical working supplies the need of equipment. At the same time, with the increase of production volume and the development of the precision machining technology, a lot of production methods come out. Machine is one of the five elements (others are people, capital, energy, and material) which consists of social production and service. It plays an important role in the production of energy and materials. In the future, the aim of development is to reduce energy cost, develop environmental-friendly renewable resources and reduce the environmental pollution. This is consistent with material engineering.

Materials of mechanical engineering are applied in manufacture. In the struggle with the nature, materials change constantly to fit the need of society. Stone and wood are the oldest materials applied in tool manufacture. After that, metal materials were discovered and used. The use of metal materials in China had a long history. Although people acquainted with gold, silver,