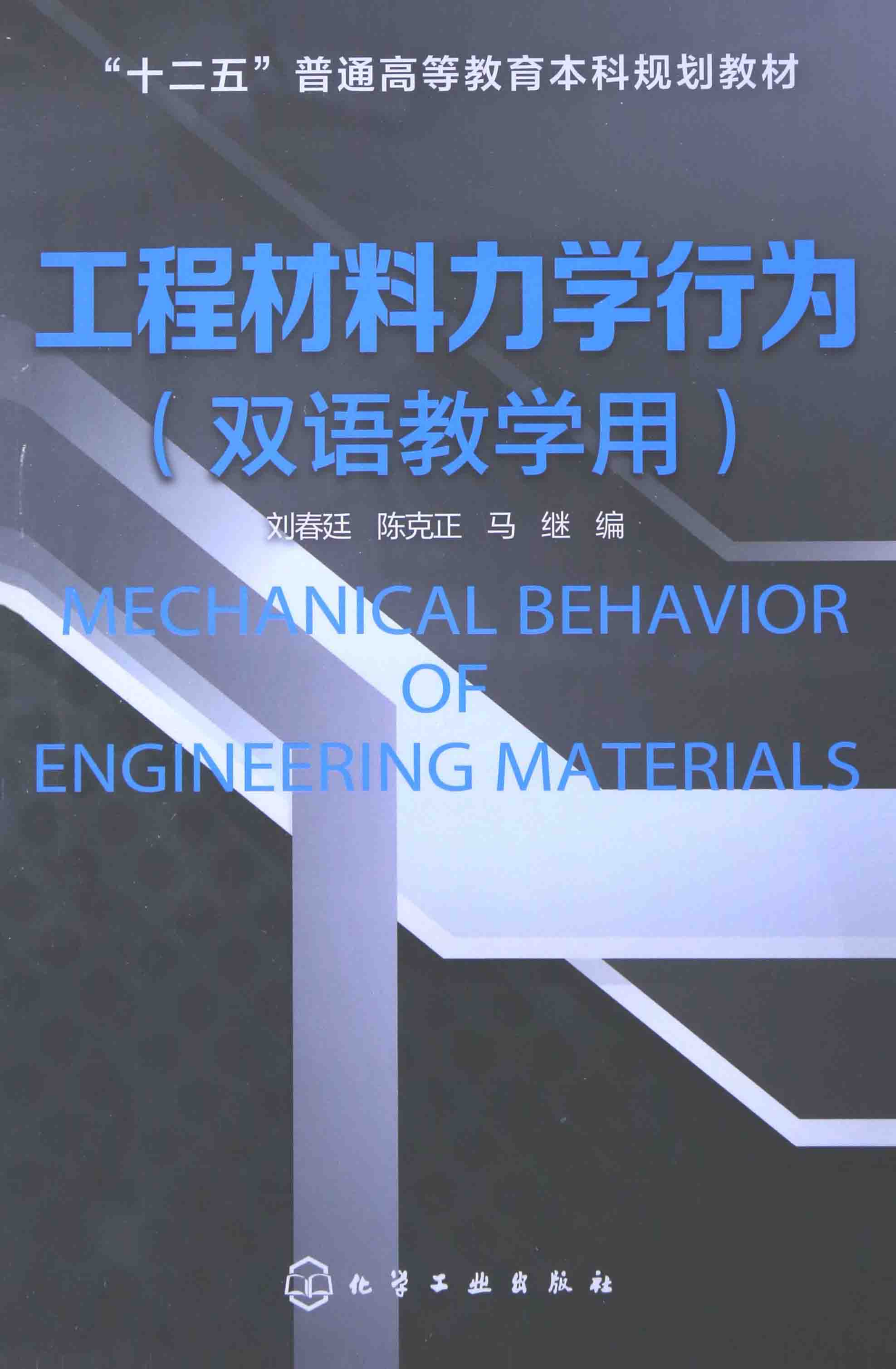

“十二五”普通高等教育本科规划教材

工程材料力学行为

（双语教学用）

刘春廷　陈克正　马　继　编

MECHANICAL BEHAVIOR OF ENGINEERING MATERIALS

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本书以“材料力学性能的基本概念-物理性质-性能指标的测试-影响因素-指标的工程意义与评价及应用”为主线贯穿始终，使学生对材料性能知识有着较完整的了解，以便达到举一反三、触类旁通的效果。本书内容共分十一章，第一至七章为金属材料的力学性能，介绍材料在静载下的力学性能（包括弹性、塑性、强度、硬度、断裂等）、冲击韧性、断裂韧性、疲劳性能及高温蠕变性能等。第八至十章的论述以金属材料为主，兼顾陶瓷、高分子和复合材料的力学行为。第十一章介绍环境对工程材料如金属、高分子和复合材料的影响。为配合学习，各章末附有英文专业术语的中文翻译，并带有参考文献和习题，便于读者个性发展和深入研究学习。

本书涉及知识面宽，信息量大，基础性、科学性、实用性强，在叙述方面，深入浅出，清晰易懂，内容新颖，引入新材料、新技术、新成果和新进展，有利于培养学生的创新意识，拓宽读者专业知识面，便于读者了解当前国内外工程材料力学行为的研究现状和发展趋势。

本书作为材料类和机械类专业基础课程材料科学导论的教学用书，适用教学时数为48～64学时，主要面向材料类和材料加工类以及机械类本科学生，也可供近材料类专业选用和有关工程技术人员学习参考，可根据具体情况进行删减或补充。

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前 言

工程材料力学行为是高等院校机械类、材料类和近机械类、近材料类学生的一门重要的专业基础课。随着经济、科技和教育的国际化发展，中国在走向世界，世界也在向中国走来，而双语教学是今后中国教育改革的趋势和发展的方向。本书在参考大量外文文献和外文教材的同时，依照中国人撰写教材和著作的逻辑思维以及分析问题和解决问题的方式方法，编写符合中国人自己思路的英文形式的教材，为双语教学的进一步实施提供物质基础。

工程材料力学性能属于材料科学与工程一级学科主干专业课程，其任务是使学生在学完“材料科学导论”、“材料科学基础”等相关课程后，通过学习“材料力学性能”，并与材料工程理论及实践相结合，进一步掌握材料各种主要性能的基本概念、物理性质、变化规律和性能指标的工程意义，了解影响材料性能的主要因素及材料性能与其化学成分、组织结构之间的关系，基本掌握改善或提高材料性能指标、充分发挥材料性能潜力的主要途径，以及材料或机件失效的基本分析方法，培养学生具有合理选材用材、开发新型材料的必要的基础知识和基本技能。

全书共分十一章，以“材料力学性能的基本概念-物理性质-性能指标的测试-影响因素-指标的工程意义与评价及应用”为主线，前七章详细阐述金属材料在静载荷、冲击载荷和交变载荷作用下的力学性能，并从断裂力学的角度出发，重点阐述工程材料的抗断裂性能等。紧跟着后三章分别阐述高分子材料、陶瓷材料和复合材料的力学行为，最后一章主要介绍工程材料在环境介质（高温和腐蚀条件）作用下的力学行为。本书以阐述宏观规律为主，将宏观规律与微观机理相结合，同时强调理论与实际相联系。

在本书的编写过程中，美国加州大学（University of California，San Diego）Marc André Meyers 教授在提供原版英文教材等方面，给予很大的帮助，在此谨表深切的谢意！同时本书在编写过程中参考了已出版的各种文献和教材（见每章末后附的参考文献），并注意吸收各院校、研究所和企业的教学改革经验及科研成果，对此，谨向上述涉及的单位和个人表示衷心的感谢。

由于编者水平有限，加之时间仓促，书中还存在不少不足之处，恳请广大读者和师生批评指正。

编者

2014 年 6 月

Contents

Chapter 1 Introduction

The successful utilization of materials requires that they satisfy a set of properties. These properties can be classified into thermal, optical, mechanical, physical, chemical, and nuclear, and they are intimately connected to the structure of materials. The structure, in its turn, is the result of synthesis and processing. A schematic framework that explains the complex relationships in the field of the mechanical behavior of materials, shown in Figure 1. 1, is Thomas's iterative tetrahedron, which contains four principal elements: mechanical properties, characterization, theory, and processing. These elements are related, and changes in one are inseparably linked to changes in the others. For example, changes may be introduced by the synthesis and processing of, for instance, steel. The most common metal, steel has a wide range of strengths and ductilities (*mechanical properties*), which makes it the material of choice for numerous applications. While low carbon steel is used as reinforcing bars in concrete and in the body of automobiles, quenched and tempered high-carbon steel is used in more critical applications such as axles and gears. Cast iron, much more brittle, is used in a variety of applications, including automobile engine blocks. These different applications require, obviously, different mechanical properties of the material. The different properties of the three materials, resulting in differences in performance, are due to differences in the internal structure of the materials. The understanding of the structure comes from *theory*. The determination of the many aspects of the micro-, meso-, and macrostructure of materials is obtained by *characterization*. Low-carbon steel has a primarily ferritic structure, with some interspersed pearlite (a ferrite-cementite mixture). The high hardness of the quenched and tempered high-carbon steel is due to its martensitic structure (body-centered tetragonal). The relatively brittle cast iron has a structure resulting directly from solidification, without subsequent mechanical working such as hot rolling. How does one obtain low-carbon steel, quenched and tempered high-carbon steel, and cast iron? By different *synthesis* and *processing* routes. The low carbon steel is processed from the melt by a sequence of mechanical working operations. The high-carbon steel is synthesized with a greater concentration of carbon ($>0.5\%$) than the low-carbon steel is (0.1%). Additionally, after mechanical processing, the high-carbon steel is rapidly cooled from a temperature of approximately 1,000 ℃ by throwing it into water or oil; it is then reheated to an intermediate temperature (tempering). The cast iron is synthesized with even higher carbon contents ($\sim 2\%$). It is poured directly into the molds and allowed to solidify in them. Thus, no mechanical working, except for some minor machining, is needed. These interrelationships among structure, properties, and performance, and their modification by synthesis and processing, constitute the central theme of materials science and engineering. The tetrahedron of Figure 1.1 lists the principal processing methods, the most important theoretical approaches, and the most used characterization techniques in materials science today.

The selection, processing, and utilization of materials have been part of human culture since its beginnings. Anthropologists refer to humans as "the toolmakers," and this is indeed a very realistic description of a key aspect of human beings responsible for their ascent and domination over other animals. It is the ability of humans to manufacture and use tools, and the ability to produce manufactured goods, that has allowed technological, cultural, and artistic progress and that has led to civilization and its development. Materials were as important to a Neolithic tribe in the year 10,000 B.C. as they are to us today. The only difference is that today more complex synthetic materials are available in our society, while Neolithics had only natural materials at their disposal: wood, minerals, bones, hides, and fibers from plants and animals. Although these naturally occurring materials are still used today, they are vastly inferior in properties to synthetic materials.

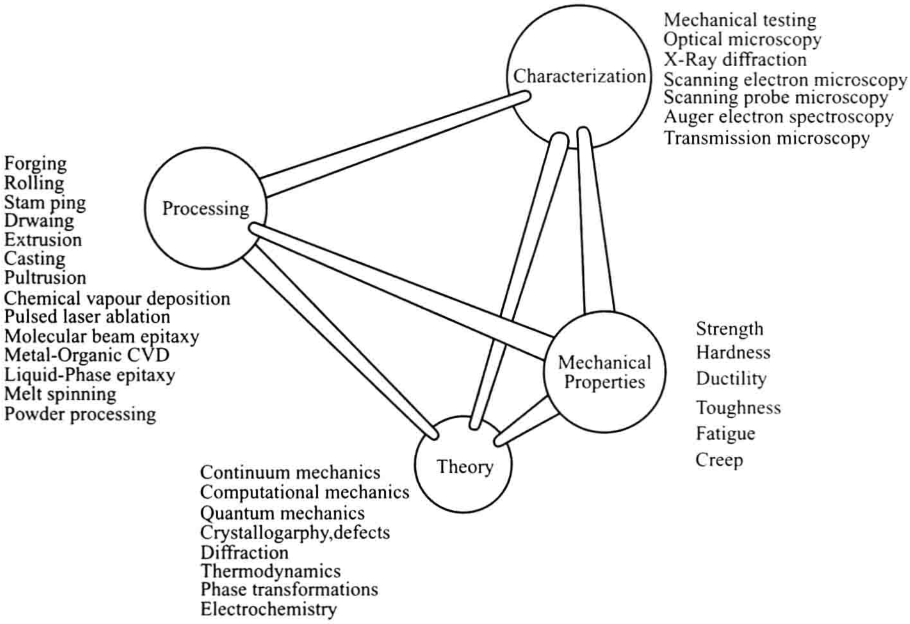

Figure 1.1 Iterative materials tetrahedron applied to mechanical behavior of materials.

Solid materials have been conveniently grouped into three basic classifications: metals, ceramics, and polymers. This scheme is based primarily on chemical makeup and atomic structure, and most materials fall into one distinct grouping or another, although there are some intermediates. In addition, there are the composites, combinations of two or more of the above three basic material classes. A brief explanation of these material types and representative properties is offered next.

Metals

Materials in this group are composed of one or more metallic elements (such as iron, aluminum, copper, titanium, gold, and nickel), and often also nonmetallic elements (for example, carbon, nitrogen, and oxygen) in relatively small amounts. Atoms in metals and their alloys are arranged in a very orderly manner (as discussed in Chapter 3), and in comparison to the ceramics and polymers, are relatively dense (Figure 1. 2). With regard to mechanical characteristics, these materials are relatively stiff (Figure 1. 3) and strong (Figure 1. 4), yet are ductile (i. e. , capable of large amounts of deformation without fracture), and are resistant to fracture (Figure 1. 5), which accounts for their widespread use in structural applications. Metallic materials have large numbers of nonlocalized electrons; that is, these electrons are not bound to particular atoms. Many properties of metals are directly attributable to these electrons. For example, metals are extremely good conductors of electricity and heat, and are not transparent to visible light; a polished metal surface has a lustrous appearance. In addition, some of the metals (viz. , Fe, Co, and Ni) have desirable magnetic properties.

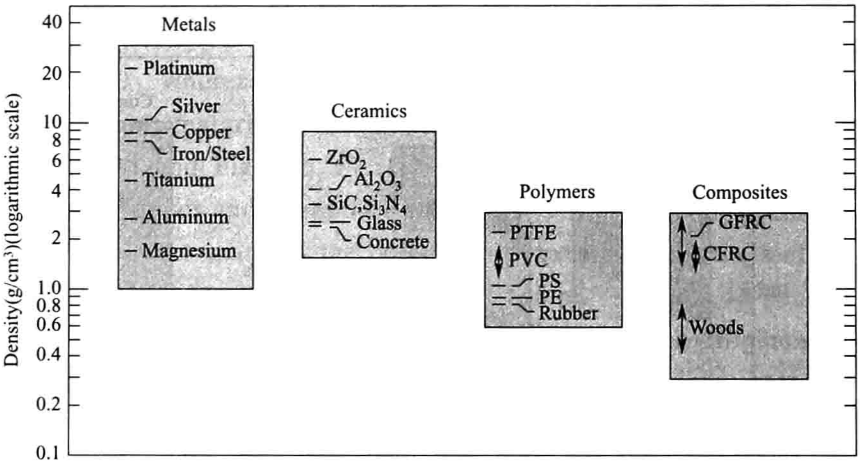

Figure 1. 2 Bar-chart of room temperature density values for various metals, ceramics, polymers, and composite materials.

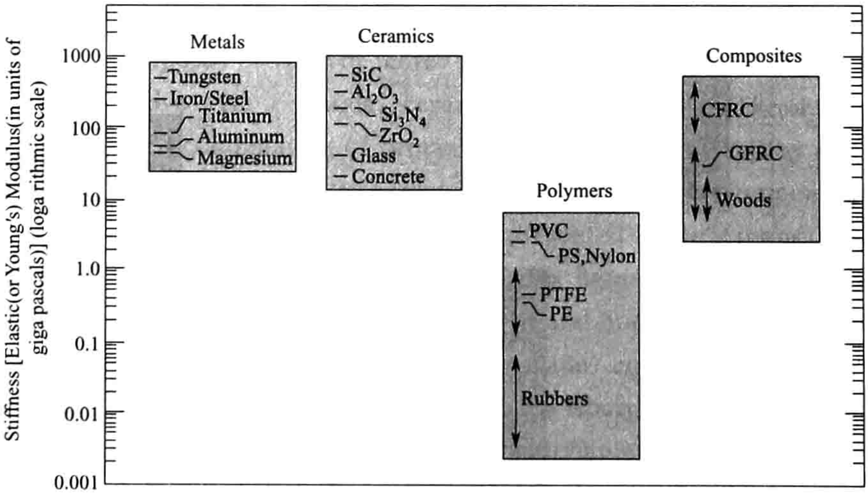

Figure 1. 3 Bar-chart of room temperature stiffness (i. e. , elastic modulus) values for various metals, ceramics, polymers, and composite materials.

In this book, the types and mechanical properties of metals and their alloys are discussed from Chapter 2 to Chapter 6.

Ceramics

Ceramics are compounds between metallic and nonmetallic elements; they are most frequently oxides, nitrides, and carbides. For example, some of the common ceramic materials include aluminum oxide (or alumina, Al_2O_3), silicon dioxide (or silica, SiO_2), silicon carbide (SiC), silicon nitride (Si_3N_4), and, in addition, what some refer to as the traditional ceramics—those composed of clay minerals (i. e., porcelain), as well as cement, and glass. With regard to mechanical behavior, ceramic materials are relatively stiff and strong—stiffnesses and strengths are comparable to those of the metals (Figure 1.3 and Figure 1.4). In addition, ceramics are typically very hard. On the other hand, they are extremely brittle (lack ductility), and are highly susceptible to fracture (Figure 1.5). These

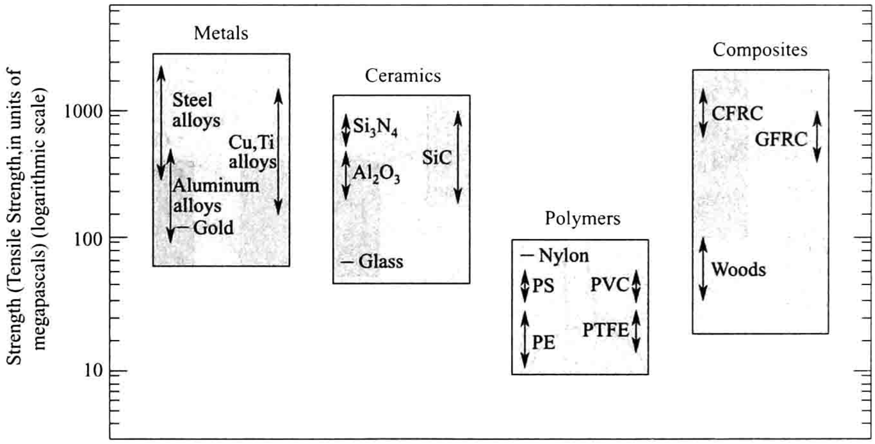

Figure 1.4 Bar-chart of room temperature strength (i. e., tensile strength) values for various metals, ceramics, polymers, and composite materials.

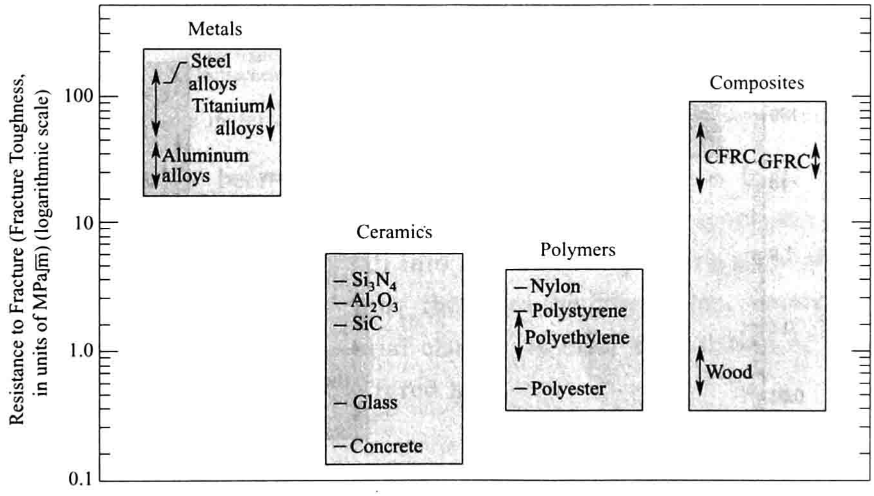

Figure 1.5 Bar-chart of room-temperature resistance to fracture (i. e., fracture toughness) for various metals, ceramics, polymers, and composite materials.

materials are typically insulative to the passage of heat and electricity (i. e., have low electrical conductivities), and are more resistant to high temperatures and harsh environments than metals and polymers. With regard to optical characteristics, ceramics may be transparent, translucent, or opaque (Figure 1. 2), and some of the oxide ceramics (e. g., Fe_3O_4) exhibit magnetic behavior. Chapters 8 are devoted to discussions of the mechanical properties of these materials.

Polymers

Polymers include the familiar plastic and rubber materials. Many of them are organic compounds that are chemically based on carbon, hydrogen, and other nonmetallic elements (viz. O, N, and Si). Furthermore, they have very large molecular structures, often chain-like in nature that have a backbone of carbon atoms. Some of the common and familiar polymers are polyethylene (PE), nylon, poly (vinyl chloride) (PVC), polycarbonate (PC), polystyrene (PS), and silicone rubber. These materials typically have low densities (Figure 1. 2), whereas their mechanical characteristics are generally dissimilar to the metallic and ceramic materials—they are not as stiff nor as strong as these other material types (Figure 1. 3 and Figure 1. 4). However, on the basis of their low densities, many times their stiffnesses and strengths on a per mass basis are comparable to the metals and ceramics. In addition, many of the polymers are extremely ductile and pliable (i. e., plastic), which means they are easily formed into complex shapes. In general, they are relatively inert chemically and unreactive in a large number of environments. One major drawback to the polymers is their tendency to soften and/or decompose at modest temperatures, which, in some instances, limits their use. Furthermore, they have low electrical conductivities and are nonmagnetic.

Chapters 8 are devoted to discussions of the mechanical properties of polymeric materials.

Composites

A composite is composed of two (or more) individual materials, which come from the categories discussed above—viz., metals, ceramics, and polymers. The design goal of a composite is to achieve a combination of properties that is not displayed by any single material, and also to incorporate the best characteristics of each of the component materials. A large number of composite types exist that are represented by different combinations of metals, ceramics, and polymers. Furthermore, some naturally-occurring materials are also considered to be composites—for example, wood and bone. However, most of those we consider in our discussions are synthetic (or man-made) composites.

One of the most common and familiar composites is fiberglass, in which small glass fibers are embedded within a polymeric material (normally an epoxy or polyester). The glass fibers are relatively strong and stiff (but also brittle), whereas the polymer is ductile (but also weak and flexible). Thus, the resulting fiberglass is relatively stiff, strong, (Figure 1. 3 and Figure 1. 4) flexible, and ductile. In addition, it has a low density (Figure 1. 2).

Another of these technologically important materials is the "carbon fiber reinforced polymer" (or "CFRP") composite—carbon fibers that are embedded within a polymer. These materials are stiffer and stronger than the glass fiber-reinforced materials (Figures 1. 3 and Figures 1. 4), yet they are more expensive. The CFRP composites are used in some aircraft and aerospace applications, as well as high-tech sporting equipment (e. g. , bicycles, golf clubs, tennis rackets, and skis/snowboards). Chapter 9 is devoted to a discussion of the mechanical properties of these interesting materials.

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Chapter 2 Mechanical Properties of Metals

Learning Objectives:

After studying this chapter you should be able to do the following:

1. Define engineering stress and engineering strain.
2. State Hooke's law, and note the conditions under which it is valid.
3. Define Poisson's ratio.
4. Given an engineering stress-strain diagram, determine (a) the modulus of elasticity, (b) the yield strength, and (c) the tensile strength, and (d) estimate the percent elongation.
5. For the tensile deformation of a ductile cylindrical specimen, describe changes in specimen profile to the point of fracture.
6. Compute ductility in terms of both percent elongation and percent reduction of area for a material that is loaded in tension to fracture.
7. Give brief definitions of and the units for modulus of resilience and toughness (static).
8. For a specimen being loaded in tension, given the applied load, the instantaneous cross-sectional dimensions, as well as original and instantaneous lengths, is able to compute true stress and true strain values.
9. Name the two most common hardness-testing techniques; note two differences between them.
10. (a) Name and briefly describe the two different microindentation hardness testing techniques, and (b) cite situations for which these techniques are generally used.

2.1 Introduction

Many materials, when in service, are subjected to forces or loads; examples include the aluminum alloy from which an airplane wing is constructed and the steel in an automobile axle. In such situations it is necessary to know the characteristics of the material and to design the member from which it is made such that any resulting deformation will not be excessive and fracture will not occur. The mechanical behavior of a material reflects the relationship between its response and deformation to an applied load or force. Important mechanical properties are strength, hardness, ductility, and stiffness.

The mechanical properties of materials are ascertained by performing carefully designed laboratory experiments that replicate as nearly as possible the service conditions. Factors to be considered include the nature of the applied load and its duration, as well as the environmental conditions. It is possible for the load to be tensile, compressive, or shear, and its magnitude may be constant with time, or it may fluctuate continuously. Application time may be only a fraction of a second, or it may extend over a period of many years. Service temperature may be an important factor.

Mechanical properties are of concern to a variety of parties (e. g., producers and consumers of materials, research organizations, and government agencies) that have differing interests. Consequently, it is imperative that there be some consistency in the manner in which tests are conducted, and in the interpretation of their results. This consistency is accomplished by using standardized testing techniques. Establishment and publication of these standards are often coordinated by professional societies. In the United States the most active organization is the American Society for Testing and Materials (ASTM).

The role of structural engineers is to determine stresses and stress distributions within members that are subjected to well-defined loads. This may be accomplished by experimental testing techniques or by theoretical and mathematical stress analysis. These topics are treated in traditional stress analysis and strength of materials texts.

Materials are frequently chosen for structural applications because they have desirable combinations of mechanical characteristics. The present discussion is confined primarily to the mechanical behavior of metals; polymers and ceramics are treated separately because they are, to a large degree, mechanically dissimilar to metals. This chapter discusses the stress-strain behavior of metals and the related mechanical properties, and also examines other important mechanical characteristics. Discussions of the microscopic aspects of deformation mechanisms and methods to strengthen and regulate the mechanical behavior of metals are deferred to later chapters.

2.2 Concepts of Stress and Strain

If a load is static or changes relatively slowly with time and is applied uniformly over a cross section or surface of a member, the mechanical behavior may be ascertained by a simple stress-strain test; these are most commonly conducted for metals at room temperature. There are three principal ways in which a load may be applied: namely, tension, compression, and shear [Figures 2.1(a)～(c)]. In engineering practice many loads are torsional rather than pure shear; this type of loading is illustrated in Figure 2.1(d). One of the most common mechanical stress-strain tests is performed in *tension*. As will be seen, the tension test can be used to ascertain several mechanical properties of materials that are important in design. A specimen is deformed, usually to fracture, with a gradually increasing tensile load that is applied uniaxially along the long axis of a specimen. Normally, the cross section is circular, but rectangular specimens are also used. This "dogbone" specimen configuration was chosen so that, during testing, deformation is confined to the narrow center region (which has a uniform cross section along its length), and, also, to reduce the likelihood of fracture at the ends of the specimen.