高等学校教材

材料科学与工程导论

（双语）

陈克正　王　玮　刘春廷　等编

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Introduction to Materials Science and Engineering

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·北京·

本教材是材料科学与工程导论的双语教材，以现行“材料科学与工程导论”课程标准为依据，结合中文教材，以国外原版教材做参考并根据国内的教学情况及材料科学研究的最新进展对教材内容进行适度的整合。全书共分9章，具体内容包括：绪论，固体材料的结构，常用工程材料（高分子材料、金属材料、陶瓷材料和复合材料）的结构、力学性能、成分、加工工艺以及应用前景，常用工程材料的化学性能（耐腐蚀性能）和物理性能（电、磁、热和光学性能）以及新型材料（生物材料、纳米材料和智能材料）的介绍等内容。

本教材可供大专院校材料科学与工程及相关专业师生使用，也可供从事材料科学与工程研究、开发及管理的人员参考。

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前言

进入21世纪，新材料、信息和生物技术已成为科学研究和新兴战略产业发展的最重要领域。为了适应材料科学与技术的发展，培养学生跟踪国际材料科学与技术发展前沿的能力，使学生成为材料科学领域的创新型人才，国内很多高校都面向大学本科学生开设了“材料科学与工程导论”双语课程作为材料学科的基础课。

“材料科学与工程导论”双语课程是我校为材料类宽专业本科学生开设的专业课程，也是我校最早开设的双语课程，自2002年起，每年有五百余人修读本课程。2008年该课程成为山东省双语教学示范课程，2009年获得国家双语教学示范课程建设项目的资助。在“材料科学与工程导论”双语课程的建设中，教材建设是该课程建设的重中之重，也是双语教学必需解决的难题之一。“材料科学与工程导论”双语教材的编写是适应高等教育国际化进程、培养具有国际竞争力的材料领域高素质人才的重要一环。

目前，国外现有的原版英文教材不能全面满足我国材料类各专业大学本科阶段学生“材料科学与工程导论”专业基础课程双语教学的需要，也不能适应宽口径材料专业人才培养模式的需要。现阶段本科生不具备使用多本英文原版教材进行课程学习的基础和条件。因此，我们结合我校材料类专业设置特点（设高分子材料科学与工程、材料物理、材料化学、无机非金属材料、金属材料五个专业）、课程定位（专业基础必修课程）和学生学业和职业发展的需要，以现行“材料科学与工程导论”课程标准为依据，结合中文教材，以国外原版教材做参考并根据国内的实际教学情况及材料科学研究的最新进展对教材内容进行适度的整合，力图编写出适合我国大学本科生的“材料科学与工程导论”双语教材。

全书共分9章，具体内容包括：绪论，固体材料的结构，常用工程材料（高分子材料、金属材料、陶瓷材料和复合材料）的结构、力学性能、成分、加工工艺以及应用前景，常用工程材料的化学性能（耐腐蚀性能）和物理性能（电、磁、热和光学性能）以及新型材料（生物材料、纳米材料和智能材料）的介绍等内容。

本书的编写者为青岛科技大学陈克正教授（第9章），青岛科技大学王玮副教授（第2、3、6章），青岛科技大学刘春廷老师（第4、5、7章），青岛科技大学徐磊老师（第1、8章）。全书由陈克正教授任主编。

本书的编写得到了国家双语教学示范课程建设项目、青岛科技大学双语教学示范课程建设项目的资助。青岛科技大学各级领导对本书的编写和出版十分关心和支持，编者再次一并表示衷心的感谢。

由于编者水平有限，经验不足，书中难免有不足之处，恳请专家和广大读者批评指正。

编者
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Chapter 1 Introduction

Learning Objectives

After careful study of this chapter you should be able to do the following:

1. *List six different property classifications of materials that determine their applicability.*
2. *Cite the four components that are involved in the design, production, and utilization of materials, and briefly describe the interrelationships between these components.*
3. *Cite three criteria that are important in the materials selection process.*
4. *(a) List the three primary classifications of solid materials, and then cite the distinctive chemical feature of each.*
   (b) Note the two types of advanced materials and, for each, its distinctive feature (s).

1.1 Historical Perspective

The designation of successive historical epochs as the Stone, Copper, Bronze, and Iron Ages reflects the importance of materials to mankind. Human destiny and materials resources have been inextricably intertwined since the dawn of history; however, the association of a given material with the age or era that it defines is not only limited to antiquity. The present nuclear and information ages owe their existences to the exploitation of two remarkable elements, uranium and silicon, respectively. Even though modern materials ages are extremely time compressed relative to the ancient metal ages they share a number of common attributes. For one thing, these ages tended to define sharply the material limits of human existence. Stone, copper, bronze, and iron meant successively higher standards of living through new or improved agricultural tools, food vessels, and weapons. Passage from one age to another was (and is) frequently accompanied by revolutionary, rather than evolutionary, changes in technological endeavors.

It is instructive to appreciate some additional characteristics and implications of these materials ages. For example, imagine that time is frozen at 1500 BC and we focus on the Middle East, perhaps the world's most intensively excavated region with respect to archaeological remains. In Asia Minor (Turkey) the ancient Hittites were already experimenting with iron, while close by to the east in Mesopotamia (Iraq), the Bronze Age was in flower. To the immediate north in Europe, the south in Palestine, and the west in Egypt, peoples were enjoying the benefits of the Copper and Early Bronze Ages. Halfway around the world to the east, the Chinese had already melted iron and demonstrated a remarkable genius for bronze, a copper—tin alloy that is stronger and easier to cast than pure copper. Further to the west on the Iberian Peninsula (Spain and Portugal), the Chalcolithic period, an overlapping Stone and Copper Age held sway, and in North Africa survivals of the Late Stone

Age were in evidence. Across the Atlantic Ocean the peoples of the Americas had not yet discovered bronze, but like others around the globe, they fashioned beautiful work in gold, silver, and copper, which were found in nature in the free state (i. e. , not combined in oxide, sulfide, or other ores).

Why materials resources and the skills to work them were so inequitably distributed cannot be addressed here. Clearly, very little technological information diffused or was shared among peoples. Actually, it could not have been otherwise because the working of metals (as well as ceramics) was very much an art that was limited not only by availability of resources, but also by cultural forces. It was indeed a tragedy for the Native Americans, still in the Stone Age three millennia later, when the white man arrived from Europe armed with steel (a hard, strong iron-carbon alloy) guns. These were too much of a match for the inferior stone, wood, and copper weapons arrayed against them. Conquest, colonization, and settlement were inevitable. And similar events have occurred elsewhere, at other times, throughout the world. Political expansion, commerce, and wars were frequently driven by the desire to control and exploit materials resources, and these continue unabated to the present day.

When the 20th century dawned the number of different materials controllably exploited had, surprisingly, not grown much beyond what was available 2000 years earlier. A notable exception was steel, which ushered in the Machine Age and revolutionized many facets of life. But then a period ensued in which there was an explosive increase in our understanding of the fundamental nature of materials. The result was the emergence of polymeric (plastic), nuclear, and electronic materials, new roles for metals and ceramics, and the development of reliable ways to process and manufacture useful products from them. Collectively, this modern Age of Materials has permeated the entire world and dwarfed the impact of previous ages.

Only two representative examples of a greater number scattered throughout the book will underscore the magnitude of advances made in materials within a historical context. In Figure 1. 1 the progress made in increasing the strength-to-density (or weight) ratio of materials is charted. Two implications of these advances have been improved aircraft design and energy savings in transportation systems. Less visible but no less significant improvements made in abrasive and cutting tool materials are shown in Figure 1. 2. The 100-fold tool cutting speed increase in this century has resulted in efficient machining and manufacturing processes that enable an abundance of goods to be produced at low cost. Together with the dramatic political and social changes in Asia and Europe and the emergence of interconnected global economies, the prospects are excellent that more people will enjoy the fruits of the earth's materials resources than at any other time in history.

1. 2 What is Materials Science and Engineering?

Materials science and engineering (MSE) is an interdisciplinary field concerned with inventing new materials and improving previously known materials by developing a deeper understanding of microstructure—composition—synthesis— processing relationships. The term

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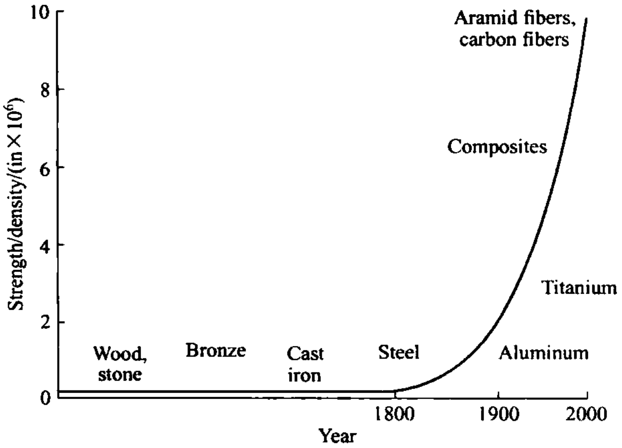

Figure 1. 1 Chronological advances in the strength-to-density ratio of materials. Optimum safe load-bearing capacities of structures depend on the strength-to- density ratio. The emergence of aluminum and titanium alloys and, importantly, composites is responsible for the dramatic increase in the 20th century

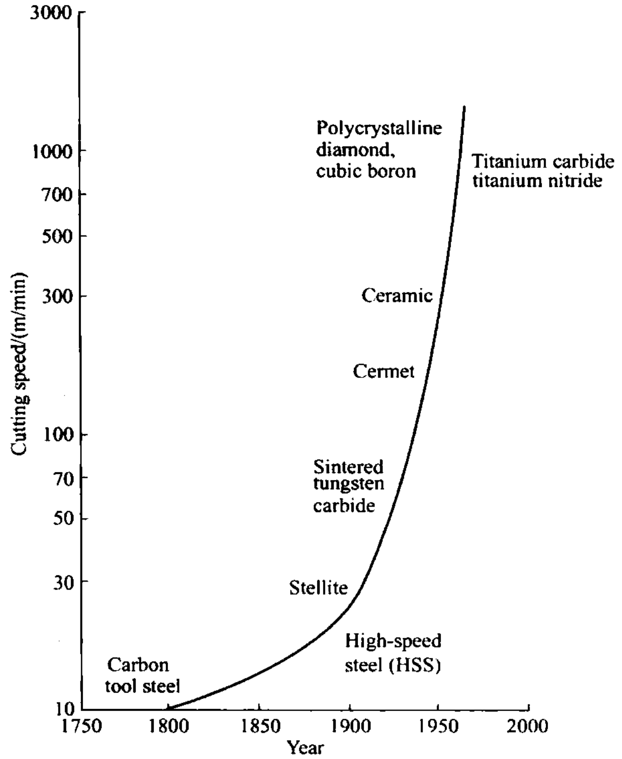

Figure 1. 2 Increase in machining speed with the development over time of the indicated cutting tool materials

composition means the chemical make-up of a material. The term structure is at this point a nebulous term that deserves some explanation, as seen at different levels of detail. The structure of a material usually relates to the arrangement of its internal components. Subatomic structure involves electrons within the individual atoms and interactions with their nuclei. On an atomic level, structure encompasses the organization of atoms or molecules relative to one another. The next larger structural realm, which contains large groups of atoms that are normally agglomerated together, is termed "microscopic", meaning that which is subject to direct observation using some type of microscope. Finally, structural elements that may be viewed with the naked eye are termed "macroscopic." Materials science and engineering not only deal with the development of materials, but also with the synthesis and processing of materials and manufacturing processes related to the production of components. The term synthesis refers to how materials are made from naturally occurring or man-made chemicals. The term processing means how materials are shaped into useful components to cause changes in the properties of different materials. One of the most important functions of materials scientists and engineers is to establish the relationships between a material or a device's properties and performance and the microstructure of that material, its composition, and the way the material or the device was synthesized and processed. In materials science, the emphasis is on the underlying relationships between the synthesis and processing, structure and properties of materials. In materials engineering, the focus is on how to translate or transform materials into a useful device or structure.

One of the most fascinating aspects of materials science involves the investigation of a material's structure. The structure of materials has a profound influence on many properties of materials, even if the overall composition does not change! For example, if you take a pure copper wire and bend it repeatedly, the wire not only becomes harder but also become increasingly brittle! Eventually, the pure copper wire becomes so harder and brittle that it will break! The electrical resistivity of wire will also increase as we bend it repeatedly. In this simple example, take note that we did not change the material's composition (i. e., its chemical make up). The changes in the material's properties are due to a change in its internal structure. If you look at the wire after bending, it will look the same as before; however, its structure has been changed at a very small or microscopic scale. The structure at this microscopic scale is known as microstructure. If we can understand what has changed microscopically, we can begin to discover ways to control the material's properties.

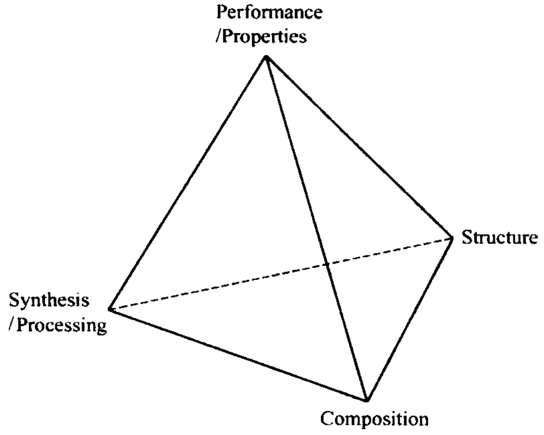

Figure 1. 3 Scope of materials science and engineering

Let's examine an example using the materials science and engineering tetrahedron presented on the Figure 1. 3. Steels, as you may know, have been used in manufacturing for more than a hundred years, but they probably existed in a crude form during the Iron Age, thousand of years ago. In the manufacture of automobile chassis, a material is needed that possessed extremely high strength but is easily formed into aerodynamic contours. Another consideration is fuel-efficiency, so the sheet steel must also be thin and lightweight. The sheet steels should also be able to absorb significant amounts of energy in the event of a crash, thereby increasing vehicle safety. These are somewhat contradictory requirements.

Thus, in this case, materials scientists are concerned with the sheet steel's①composition; ②strength; ③weight; ④energy absorption properties; and⑤malleability (formability).

Materials scientists would examine steel at a microscopic level to determine if its properties can be altered to meet all of these requirements. They also would have to consider the cost of processing this steel along with other considerations. How can we shape such steel into a car chassis in a cost-effective way? Will the shaping process itself affect the mechanical properties of the steel? What kind of coatings can be developed to make the steel corrosion resistant? In some applications, we need to know if these steels could be welded easily. From this discussion, you can see that many issues need to be considered during the design and materials selection for any product.

1.3 Why Study Materials Science and Engineering?

Why do we study materials? Many an applied scientist or engineer, whether mechanical, civil, chemical, or electrical, will at one time or another be exposed to a design problem involving materials. Examples might include a transmission gear, the superstructure for a building, an oil refinery component, or an integrated circuit chip. Of course, materials scientists and engineers are specialists who are totally involved in the investigation and design of materials.

Many times, a materials problem is one of selecting the right material from the many thousands that are available. There are several criteria on which the final decision is normally based. First of all, the in-service conditions must be characterized, for these will dictate the properties required of the material. On only rare occasions does a material possess the maximum or ideal combination of properties. Thus, it may be necessary to trade off one characteristic for another. The classic example involves strength and ductility; normally, a material having a high strength will have only a limited ductility. In such cases a reasonable compromise between two or more properties may be necessary.

A second selection consideration is any deterioration of material properties that may occur during service operation. For example, significant reductions in mechanical strength may result from exposure to elevated temperatures or corrosive environments.

Finally, probably the overriding consideration is that of economics: What will the finished product cost? A material may be found that has the ideal set of properties but is prohibitively expensive. Here again, some compromise is inevitable. The cost of a finished piece also includes any expense incurred during fabrication to produce the desired shape. The more familiar an engineer or scientist is with the various characteristics and structure — property relationships, as well as processing techniques of materials, the more proficient and confident he or she will be to make judicious materials choices based on these criteria.

1.4 Classification of Materials

Solid materials have been conveniently grouped into three basic classifications: polymers, ceramics, and metals. 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 characteristics is offered next. Another classification is advanced materials—those used in high-technology applications—viz. semiconductors and biomaterials materials; these are discussed in Section 1. 5.

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 (O, N, and Si). Furthermore, they have very large molecular structures, often chain-like in nature, which 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. 4), 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 (Figures 1. 5 and Figure 1. 6). 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 (Figure 1. 8) and are nonmagnetic. Chapter 3 is devoted to discussions of the structures, properties, applications, and processing of polymeric materials.

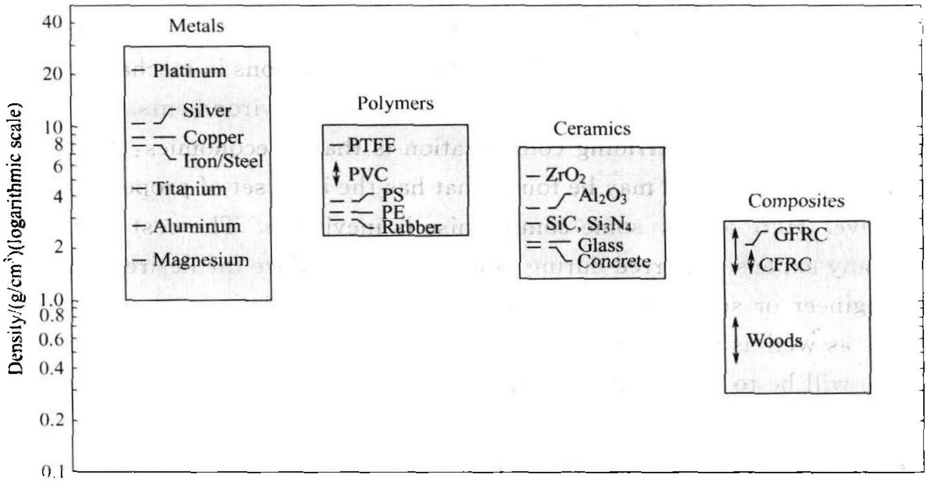

Figure 1. 4 Bar-chart of room temperature density values for various metals, ceramics, polymers, and composite materials

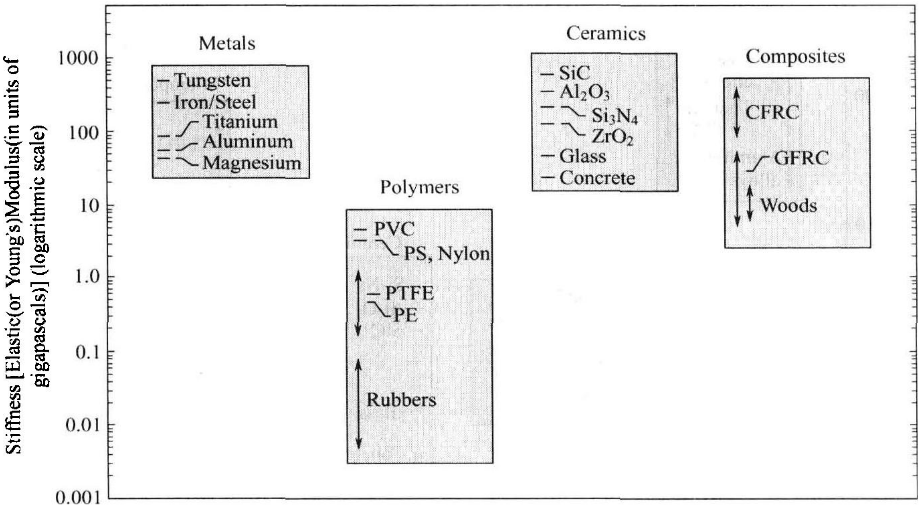

Figure 1.5 Bar-chart of room temperature stiffness (i. e. , elastic modulus) values for various metals, ceramics, polymers, and composite materials

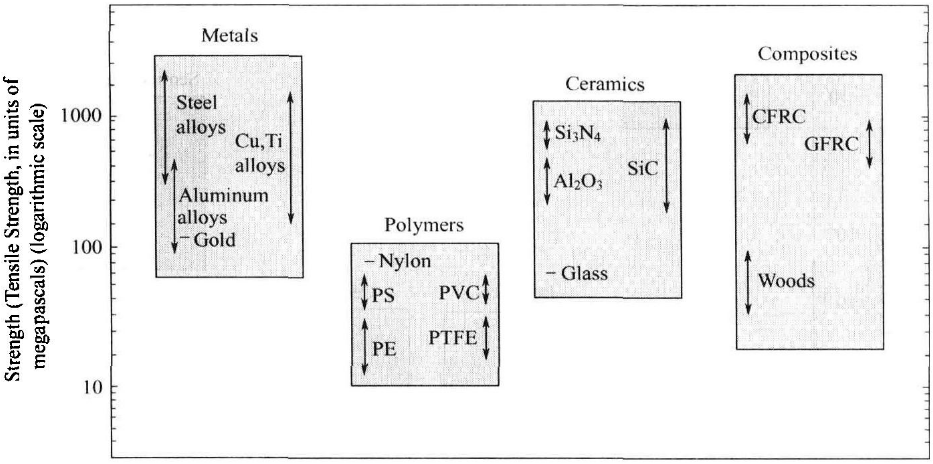

Figure 1.6 Bar-chart of room temperature strength (i. e. , tensile strength) values for various metals, ceramics, polymers, and composite materials

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 2), and in comparison to the ceramics and polymers, are relatively dense (Figure 1.4). With regard to mechanical characteristics, these materials are relatively stiff (Figure 1.5) and strong (Figure 1.6), yet are ductile (i. e. , capable of large amounts of deformation without fracture), and are resistant to fracture (Figure 1.7), 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 electric-

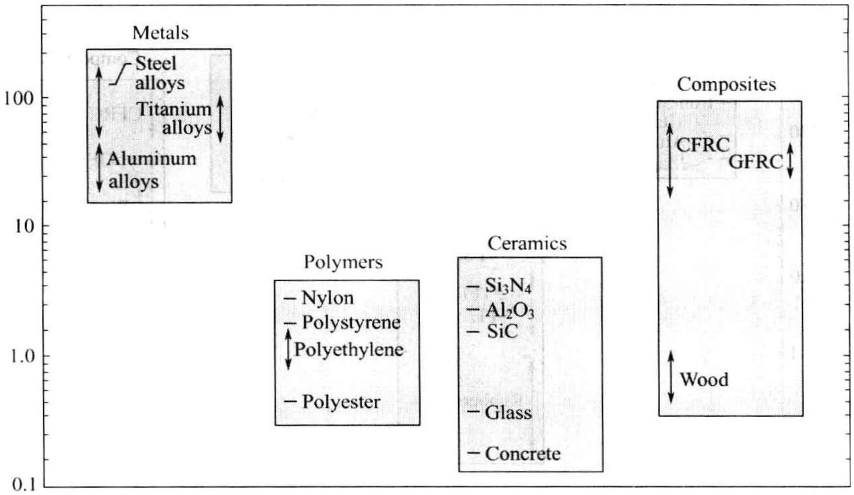

Figure 1.7 Bar-chart of room-temperature resistance to fracture (i. e. , fracture toughness) for various metals, ceramics, polymers, and composite materials

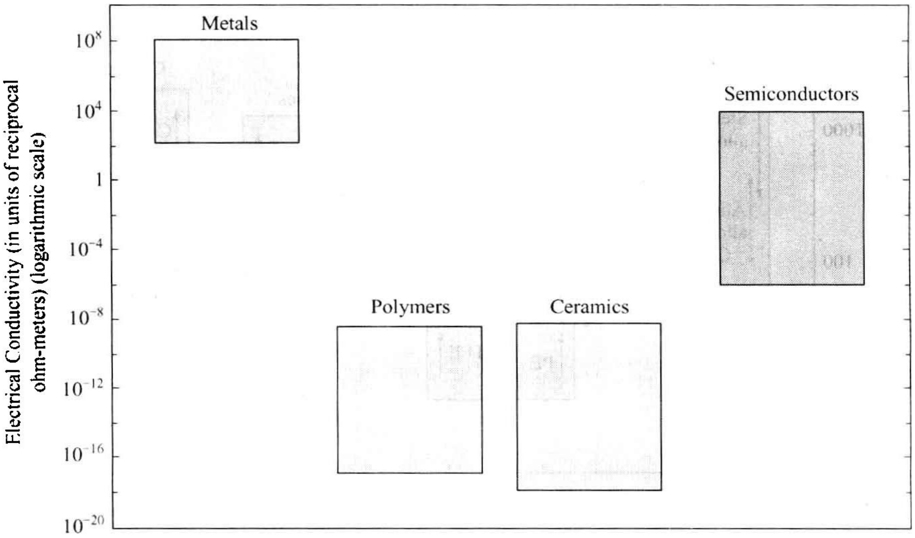

Figure 1.8 Bar-chart of room temperature electrical conductivity ranges for metals, ceramics, polymers, and semiconducting materials

ity (Figure 1. 8) 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. Furthermore, the types and applications of metals and their alloys are discussed in Chapter 4.

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

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