高等学校教材

材料力学性能

Mechanical Properties of Materials

刘春廷　马继　主编

Editor: Chunting Liu, Ji Ma

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·北京·

本书是根据教育部最新颁布的课程教学基本要求和课程改革的精神编写的，以英文为表达形式，在内容和形式上有较大的更新，为材料性能学课程开展双语教学提供适用教材。

全书共十章，以工程材料的强度—硬度—塑性—韧性力学性能为主线，前七章详细阐述金属材料的力学性能，后三章分别阐述高分子材料、陶瓷材料和复合材料的力学性能，重点阐述工程材料在静载荷、冲击载荷和交变载荷及在环境介质（高温和腐蚀条件）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。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。

本书作为机械类和材料类学生的专业基础课程材料性能学的教学用书，适用于48~64学时教学，主要面向机械类和材料类专本科学生，也可供近机类和近材料类专业选用，还可供有关工程技术人员学习参考。

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前　言

材料力学性能是高等院校机械类、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，中国走向世界的同时，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。

全书共十章，以工程材料的强度—硬度—塑性—韧性力学性能为主线，前七章详细阐述金属材料的力学性能，后三章分别阐述高分子材料、陶瓷材料和复合材料的力学性能，阐述工程材料在静载荷、冲击载荷和交变载荷及在环境介质（高温和腐蚀条件）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。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。

为配合学习，各章前提出学习目的，各章末附有本章小结、重要词汇、参考文献和思考题与习题，便于读者深入学习研究。本书力求语言简洁，信息量大，科学性、实用性强，内容新颖，引入新成果和新进展，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材料力学性能研究动态和发展趋势。

在本书的编写过程中，美国加州大学（University of California, San Diego）Marc Andr´e Meyers 教授在提供原版英文教材等方面给予了很大的帮助，在此谨表深切的谢意！同时中国科学院金属研究所的胡壮麒院士、管恒荣研究员和孙晓峰研究员对本书提出了许多宝贵的意见, 在此表示由衷的感谢！

同时本书在编写过程中参考了已出版的各种文献和教材（见各章末的参考文献），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，书中若有不足之处，恳请广大读者和师生批评指正。

编　者
2009 年 6 月

Preface

Courses in the mechanical properties of materials are standard in both mechanical engineering and materials science/engineering curricula. These courses are taught, usually, at the junior or senior level. This book provides an introductory treatment of the mechanical properties of materials with a balanced mechanics—materials approach, which makes it suitable for both mechanical and materials engineering students.

The book covers mechanical properties of metals, polymers, ceramics, and composites and contains more than sufficient information for a one-semester course. It therefore enables the instructor to choose the path most appropriate to the class level (junior- or senior-level undergraduate) and background (mechanical or materials engineering). The book is organized into 10 chapters. Chapter 1 contains introductory information on materials that students with a previous course in the properties of materials should be familiar with. In addition, it enables those students unfamiliar with materials to "get up to speed." Chapter 2 through 7, on mechanical properties of metals, contains strength, hardness, toughness and ductility. Chapters 3 and 4, respectively, deal with fracture from a microstructural viewpoint (microfracure) and a macroscopic (primarily mechanical), and a broad treatment of plastic deformation and flow and fracture criteria are presented in Chapter 4. A detailed treatment of the fundamental mechanisms responsible for fatigue and creep, respectively, is presented in chapters 5 and 6. This is supplemented by a description of the principal testing and data analysis methods for these two phenomena. Chapters 7, on stress corrosion cracking (SCC) and hydrogen damage in metals, is essential to the understanding of environmentally assisted fracture in materials. Ceramics, polymers, composites, and intermetallics are nowadays important structural materials for advanced applications and are comprehensively covered in this book. In Chapters 8, 9 and 10, mechanical properties of nonmetals, including ceramics, polymers and composite materials are presented, respectively.

The objective is to include features in the book that will expedite the learning process. These learning aids include:

- Learning objectives;
- Numerous illustrations, now presented in the book, and photographs to help visualize what is being presented;
- End-of-chapter summary;
- Key terms and descriptions of key equations;
- Each chapter contains, at the end, a list of suggested reference; readers should consult these sources if they need to expand a specific point or if they want to broaden their knowledge in an area.
- All chapters contain solved examples and extensive lists of homework problems.These should be valuable tools in helping the student to grasp the concepts presented.

Full acknowledgment is here to all sources of tables and illustrations. We might have inadvertently forgotten to cite some of the sources in the final text; we sincerely apologize if we have failed to do so. The patient and competent typing of the manuscript by Jennifer Natelli, drafting by Jessica Mckinnis, and editorial help with text and problems by H.C. (Bryan) Chen and Elizabeth Kristofetz are gratefully acknowledged. we would like to acknowledge research support, over the years, from the U.S. Office of Naval Research, Oak Ridge National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratories. we are also very thankful to his wife, Nivedita; son, Nikhilesh; and daughter, Kanika, for making it all worthwhile! Kanika's help in word processing is gratefully acknowledged. We acknowledge the continued support of the National Science Foundation (especially R.J. Reynik and B. Mac- Donald), the U.S. Army Research Office (especially G. Mayer, A. Crowson, K.Iyer, and E.Chen), and the Office of Naval Research. The inspiration provided by his grandfather, Jean-Pierre Meyers, and father, Henri Meyers, both metallurgists who devoted their lives to the profession, has inspired us. Professor Marc Andr'e Meyers from University of California, San Diego and Professor Krishan Kumar Chawla from University of Alabama at Birmingham generously supported the writing of the book. The help provided by Professor R.Skalak, director of the institute, is greatly appreciated. The Institute for Mechanics and Materials is supported by the National Science Foundation. The authors are grateful for the hospitality of Professor William D.Callister, Jr. from Department of Metallurgical Engineering, The University of Utah during the part of the preparation of the book.

Chunting Liu
Ji Ma
June, 2009

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 1000ºC 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 (about 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.

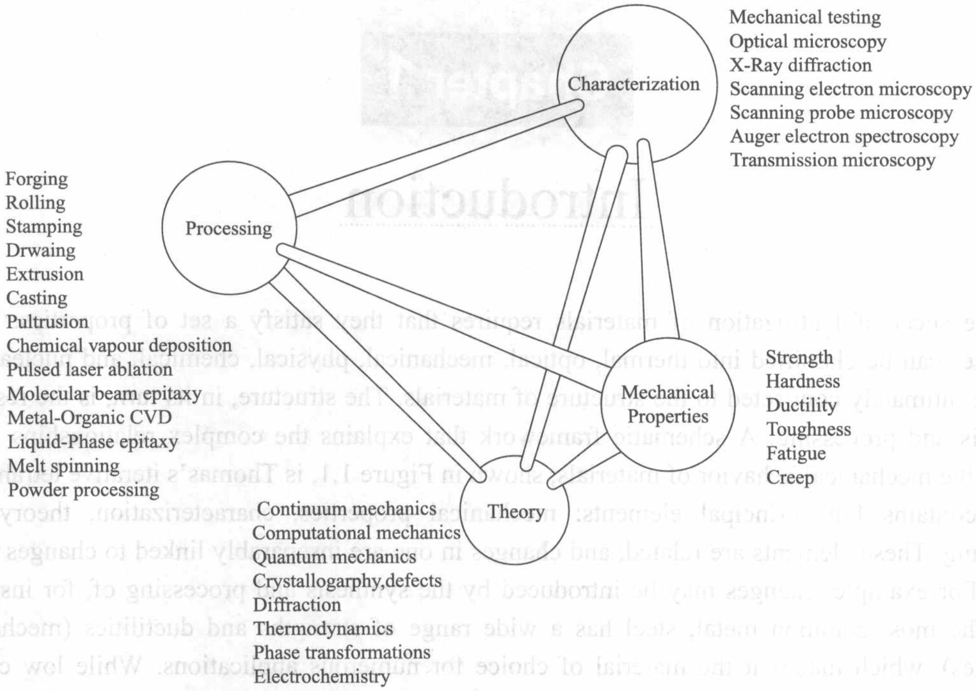

Figure 1.1 Iterative materials tetrahedron applied to mechanical behavior of materials. (After G.Thomas.)

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 10000 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.

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.

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

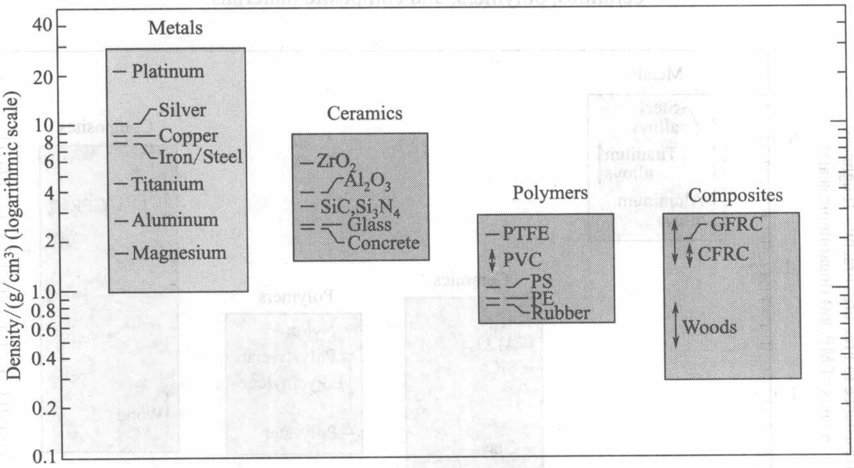

Figure 1.2 Bar-chart of room temperature density values for various metals, ceramics, polymers, and composite materials.

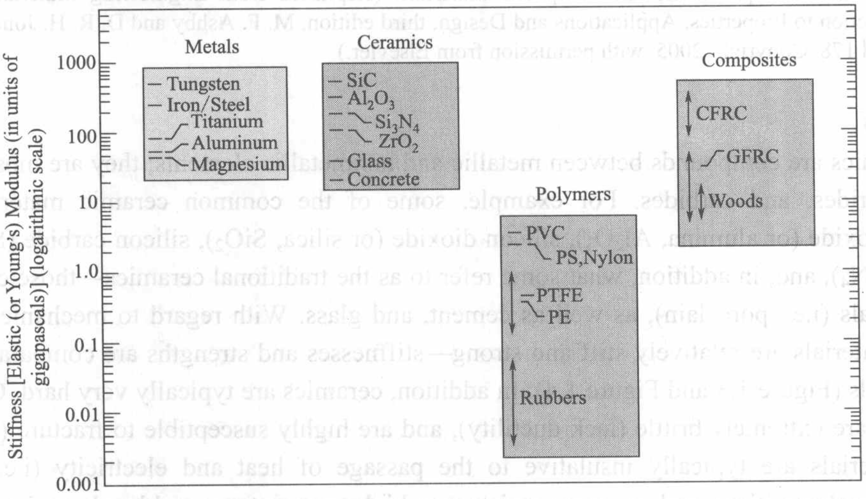

Figure 1.3 Bar-chart of room temperature stiffness (i.e., elastic modulus) values for various metals, ceramics, polymers, and composite materials.

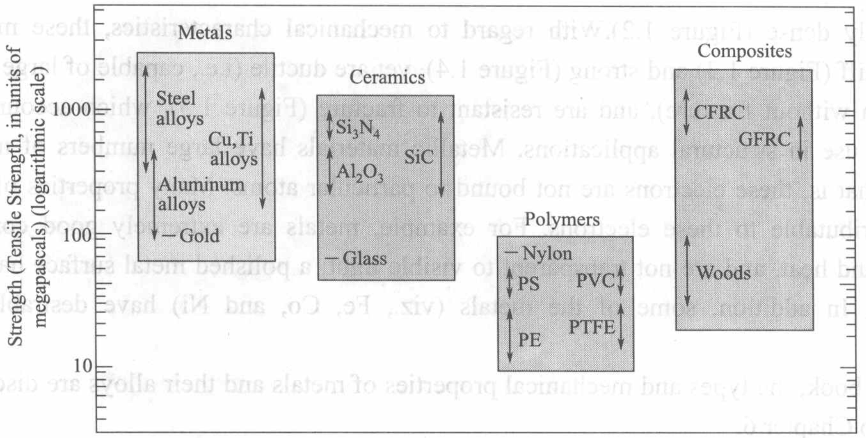

Figure 1.4 Bar-chart of room temperature strength (i.e., tensile strength) values for various metals, ceramics, polymers, and composite materials.

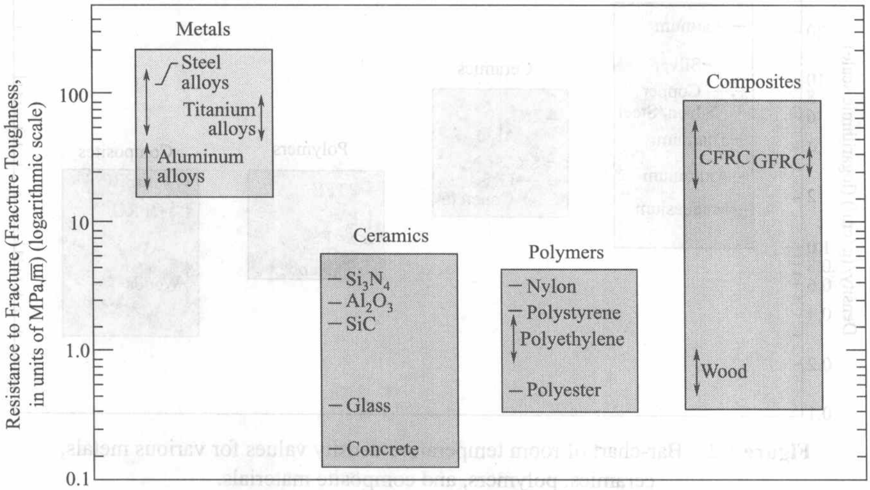

Figure 1.5 Bar-chart of room-temperature resistance to fracture (i.e., fracture toughness) for various metals, ceramics, polymers, and composite materials. (Reprinted from Engineering Materials 1: An Introduction to Properties, Applications and Design, third edition, M. F. Ashby and D. R. H. Jones, pages 177 and 178, Copyright 2005, with permission from Elsevier.)

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 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 (Figure 1.3 and Figure 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,
    c. the tensile strength,
    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,
    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