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MICRO- and MACROMECHANICAL PROPERTIES of MATERIALS

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Foreword

Macro- and micromechanical properties of materials is an important area in materials science because mechanical problems related to structural and functional materials during production, processing, and application still occur. Properties, such as efficient, safe, environmental-friendly and low-powered, and the efficient use of materials and their lifetime prediction are all based on the systematic analysis of their mechanical properties. The ability to analyze the macro- and micromechanical properties of materials is one of the basic skills for all materials science undergraduate and postgraduate students. Yichun Zhou and his colleagues at Xiangtan University, the authors of *Micro- and Macromechanical Properties of Materials*, have written a comprehensive textbook for both students and research scientists.

This book systematically covers macro- and micromechanical properties of metallic and nonmetallic structural materials, and various functional materials, as well as the macro- and microfailure mechanisms under various loading conditions. During the preparation of this book, the authors were committed to introduce structure and function, macroscopic and microscopic scales, scientific theories, and engineering applications. Some cutting-edge research has also been integrated into this book, such as strain gradient theory, scale effects, cross-scale numerical simulation, microfracture mechanics, mechanical properties of smart materials, thin films, and coatings.

This book has three significant features. First, it is an integration between scientific methods and theories. The development of modern materials science has changed rapidly, and it is more useful to learn the fundamentals of scientific methods rather than to learn by rote. This book covers the fundamentals of this discipline and the main theories of the subject while also serving as an introduction to research methods. By combining these two individual areas, the book increases the attractiveness of its contents and also helps to stimulate and innovate the research activities of students.

Second, it is a combination of educational reform and scientific research. Over the last decade, valuable experience has been gained on the subject of mechanical properties of materials by this teaching and research group through undergraduate teaching. Some achievements gained during teaching were also implemented through fostering the materials science talent. Moreover, many research findings conducted by this research group on mechanical properties were incorporated into this book. Introducing some of the latest research techniques and achievements on materials and mechanics has also raised the academic quality of this book.

Third, it is a combination of theories and engineering applications. Materials science is a subject that involves engineering practices and practical applications. This book focuses on the links between scientific theories and engineering applications from various perspectives, from the macro- to the microscale, from theoretical calculation to practical implications, and from materials production to property analysis. Integrating fundamental theories with research findings has enriched the content of this book and has also enabled students to develop their creativity and practical ability.

The authors of this book have long devoted themselves to teaching and research in mechanics and materials science. Editorial director Professor Yichun Zhou, who was the winner of the National Outstanding Youth Science Foundation Award and the National Distinguished Teachers Award, currently serves as the director of the Key Laboratory of Low Dimensional Materials & Application Technology of the Ministry of Education at Xiangtan University. The editorial board's deputy director, Professor Xuejun Zheng, was the winner of the National Outstanding Youth Science Foundation Award. The course entitled "Micro- and Macro-Mechanical Properties of Materials" taught by the authors at the University of Xiangtan was given the National Excellent Course Award in 2005, and their teaching materials were designated the Eleventh Five-Year Project national planning materials for general higher education. The authors then became the backbone of their teaching and research group, Materials and Devices, and in 2007 won the title for being the first national-level teaching/research group.

I believe that the publication of this book will encourage cross-links between mechanics and materials science and will also play a role in nurturing new materials scientists. Therefore, I am delighted to have written the foreword and to recommend this book to readers.

Boyun Huang
Academician of the Chinese Academy of Engineering
Vice-Chairman of the China Association for Science and Technology
President of Central South University

Foreword to the English Language Edition

Micro- and Macromechanical Properties of Materials is a unique textbook, providing a complete and rigorous overview in the research areas of mechanics and materials sciences from the viewpoint of length scales. It combines reviews of both theoretical and applied research, as well as reviews of the most recent studies in the field.

Professor Zhou is a prestigious scientist. He has won research awards from the Chinese Academy of Sciences and the Hunan provincial government in China. He was also granted the Functional Materials Scientist Award by the committee of International Conference on Advances in Functional Materials.

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Preface

The development of science, technology, and the national economy generates increasing demands for a vast variety of materials with higher quality and higher performance in more severe operating conditions. Materials efficiency and the service lifetime of materials under certain operating conditions are the most important factors in evaluating material performance. Efficiency, safety, low energy consumption, and environmental friendliness are the ultimate pursuits in new materials development and applied research. According to the statistics of some industrialized countries, losses due to materials failures and the consequent structural failures account for 8%–12% of their national GDP. Moreover, casualties caused by accidents linked directly to these failures are immeasurable. At present, the situation in China is far worse than in the developed Western countries. On the other hand, there is great potential for the development of new materials. Due to the complexity of factors affecting materials performance—the inherent properties of materials, their design, processing status, and operating environment and conditions—it is impossible to design the perfect material at once. Therefore, the recognition of these problems had to rely on countless failures and the gradual accumulation of experience.

In our new economical and harmonious society, we must design and create materials that are efficient, safe, have low power consumption, and are environmental friendly. In order to have a relatively clear prediction of their efficiency and service lifetime, we must have a clear understanding of their mechanical behavior and failure mechanisms during production, processing, and service.

To assist undergraduate students of materials science and engineering in their understanding of the fundamental principles of mechanics, and to subsequently apply their knowledge to research and development of high-performance new materials that are harmonious to our society and environment as well as to improve traditional teaching materials, I have been teaching undergraduate courses on the mechanics of materials since 1996. An appropriate Chinese textbook on the topic is essential in order to teach this course. Initially, we had chosen topics that had the largest impact on the subject from domestic references. As our teaching progressed, we found that the majority of the topics concerned structural materials and their properties on a macroscopic scale. This conformed to the historical development of the subject of materials science in our country, which began with metal materials and their heat treatment, welding, molding, and high-molecular-weight materials. But, in fact, the subject of "materials science and engineering" is a twofold subject.

From a scientific perspective, the relationship between materials structure and their properties involves the exploration of the laws of nature, which is fundamental science. From an engineering perspective, materials were developed to fulfill engineering purposes and to serve economic growth, which is applied science. The main purpose of materials research and development is application, and an appropriate production and processing route is essential to yield materials with the desired properties. Therefore, "materials science and engineering" is a subject that consists of studies of the structure of materials, the production process, and material properties and performance, as well as the relationships between them, and it requires combined knowledge from both scientific and engineering backgrounds.

Materials science has three important features. First, it is a multidisciplinary subject. It involves physics, mechanics, chemistry, metallurgy, and computational science, and these subjects are interlinked. Second, it is a discipline closely linked with practical applications. The aim of materials science is to develop new materials that have improved performance and properties, to have better utilization of materials, and to reduce cost and pollution during their production. Third, materials science is a growing discipline. Unlike physics, chemistry, and mechanics, which are very mature systems, materials science enriches and perfects itself through the development of other disciplines.

In recent years, materials science and technology has been the fastest growing discipline, and it has not only created a large number of new high-performance materials and unprecedented processing methods but has also significantly changed the production of traditional materials. Since the 1990s, materials science and technology has undergone a revolutionary transformation. The trend can be summarized as follows: (1) materials science and engineering has rapidly become a unified discipline and places more emphasis on practical applications; (2) research has focused on the microlevel in order to discover new substances and develop new materials; (3) composite materials have become an important direction of development; (4) research methods have become oriented in the direction of theory–computer simulation–experiment; (5) the trend for innovation in modern materials science and technology has become cheaper and faster, providing better results from a technological innovation perspective; and (6) the trend has been to integrate materials research, development, production, and application.

Based on these characteristics and the attribution and developing trends of the materials science and engineering disciplines, we believe that current teaching materials for structural materials and their macroscopic properties is insufficient. Beginning in 1998, we began to experimentally implement the topics of macro- and micromechanical properties into our course; the course subsequently won the National Excellent Courses Award in 2005. A year later, this book was recognized as the national planning textbook for general higher education in the Eleventh Five-Year project. The backbone of this book is a combination of materials science and mechanics, with three distinct integrated features: the combination of science (fundamental principles) and engineering (applications), across the macroscopic and the microscopic levels, and from structural to functional materials. This book is also a combined effort of all the associated teaching and research staff from the Department of Material and Photoelectronic Physics and the Low Dimension Materials and Application Technology Laboratory (the National Key Laboratory of the Ministry of Education) of Xiangtan University.

The book was arranged in 15 parts: Introduction (written by Yichun Zhou and Shiguo Long), Chapters 1 and 2 (Yichun Zhou), Chapter 3 (Yongli Huang), Chapter 4 (Li Yang, Shiguo Long, and Yichun Zhou), Chapter 5 (Yongli Huang), Chapter 6 (Xuejun Zheng), Chapter 7 (Weiguo Mao), Chapter 8 (Li Yang), Chapter 9 (Shiguo Long and Shangda Chen), Chapter 10 (Jiangyu Li and Shuhong Xie), Chapter 11 (Xuejun Zheng and Yichun Zhou), Chapter 12 (Wenbo Luo), Chapter 13 (Weiguo Mao), and Chapter 14 (Shiguo Long). We would like to acknowledge some of our PhD and master's students, especially Lianghong Xiao, Xuehong Yu, Dan Wu, Sha Zhang, Zhaofeng Zhou, Zengsheng Ma, Jun He, Tonggang Ou, and Bo Wu, for their work in preparing teaching materials and drawings, printing texts, searching the literature, guiding experiments, and helping with tutorial sessions.

During the past five years, there have been detailed discussions with the authors who have written individual chapters about possible modification of equations and graphs. The majority of the content in this book came directly from monographs and papers that we have published. Our research activities have been funded by two of the outstanding youth funds of the National Natural Science Foundation of China (NSFC), two key projects from the NSFC, two projects from National 863 Project in the materials field, and 20 projects from the NSFC and youth projects, a major project of the Ministry of Education. This book is a result of ten years of our teaching experience, under the able guidance of many of our senior professors in the field of mechanics and materials science, including Sirs Changxu Shi, Zhemin Zheng, Jiluan Pan, Hengde Li, and Kezhi Huang; Academicians Yilong Bai, Boyun Huang, and Wei Yang; and Professors Tingqing Yang, Zhuping Duan, Tongyi Zhang, Yonggang Huang, Daining Fang, and Qibin Yang. Many of the chapters are from their earlier publications and theses. A special thank you goes to Academician Boyun Huang for writing the foreword to this book. We would also like to acknowledge the authors whose work has been referenced in this book, the relevant departments who supported this work, and the colleagues and students who contributed to the publication of this book.

Due to various limitations, many topics in this book on macro- and micromechanics were insufficiently covered. In order to improve the content, we welcome feedback from the reader.

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We would also like to thank Allison Shatkin, senior acquisitions editor at Taylor & Francis Group, for her help and encouragement and the Chinese publishers of the original work, China Higher Education Press, for their help in the publication of this book.

We would like to acknowledge some of our PhD and master's students—Lianghong Xiao, Xuehong Yu, Dan Wu, Sha Zhang, Zhaofeng Zhou, Zengsheng Ma, Jun He, Tonggang Ou, and Bo Wu—for their work in preparing teaching materials and drawings, printing texts, searching the literature, guiding experiments, and helping with tutorial sessions.

Introduction

Materials are those substances used in the manufacture of goods, devices, components, machinery, or other products and are the basis for mankind's survival and development. The introduction of new materials and applications plays an important role in the progress of human civilization.

Materials, information, and energy are the three pillars of modern civilization. Because of the diversity of materials, there are no uniform standards for classification. However, materials can be grouped into two major areas: (1) structural and functional materials and (2) traditional and new materials.

Structural materials are based on their mechanical properties and are used to make bearing carrier. Structural materials have certain unique physical or chemical properties, such as gloss, thermal conductivity, radiation resistance, corrosion resistance, and antioxidation. Functional materials are also classified mainly by their unique physical and chemical properties, or their biological function. In many cases, a material—such as iron, copper, or aluminum—is both structural and functional. Traditional materials such as steel, cement, and plastics are those that have matured and have been used in mass production and in industrial applications. These materials are known as fundamental materials because of their high value and wide range of use as well as their underlying importance for many pillar industries. New materials (advanced materials) are those that are under development and that have the potential for improved performance. There is no clear boundary between new materials and traditional materials. Traditional materials can become new materials through the use of new technology to improve their technical characteristics and enhance their performance, which substantially brings in added value. New materials can also become traditional materials after long-term production and application. Traditional materials are the foundation for the development of new materials and advanced technologies, and new materials often promote further development of conventional materials.

The origin of mechanics is closely related to human activity. As soon as humans became productive, mechanics inevitably emerged. If a stone could not be moved by hand, for example, a stick could be used as a lever to pry it out. The development of mechanics has gone through several stages. Before the seventeenth century, mechanics was at an early stage of development, concerned mainly with the practical aspects of living. In the period between the seventeenth and nineteenth centuries, mechanics in the classical mechanics stage were represented by Newtonian mechanics. Modern mechanics began after the mid-twentieth century and includes solid mechanics, fluid mechanics, and general mechanics.

Solid mechanics is concerned with the law of displacement, movement, stress, strain, and destruction generated by the internal particles of a deformable solid under the action of external factors such as load, temperature, and humidity.

Mechanical properties of materials refer to the mechanical behavior of materials under external loads. The most common mechanical properties are (1) elastic modulus, which describes the relationship between stress and strain; (2) yield strength, which refers to the minimum stress necessary for the plastic deformation of materials; and (3) hardness, which, not surprisingly, describes a material's softness or hardness. Mechanical properties were the earliest material properties that humans learned to use. In the Stone Age, for example, humans learned how to test the strength and hardness of stone.

The systematic study of the mechanical properties of materials began in the mid-1800s, when metalloscope were used to study the microstructure of materials. Mechanical properties are primarily determined by studying the material's composition and the material's microstructure [4]. With the development of device miniaturization and integration, knowledge of the mechanical properties of structural materials has become increasingly important. At the same time, structural materials and functional materials are being combined, which requires us to know their function and structural strength.

The best way to improve the mechanical properties of structural materials and functional materials is to enhance their micromechanical properties. In addition, materials design is very important in the development of new materials, and to do that, we must also understand the microscopic properties of materials. Therefore, the macro- and micromechanical properties of materials are an important meeting point of materials and mechanics.

MATERIALS SCIENCE AND ENGINEERING AND ITS DEVELOPMENTAL HISTORY AND TRENDS

It can be said that human history is the history of materials development. The continuous development and use of new materials are fundamental for modern human civilization.

The use of materials has undergone seven eras in human history (see Table 1) [3].

From the ancient Stone Age to the Iron Age, the use of metals marked the development of social productivity and the beginning of civilized human society. In the eighteenth century, the advent of the Steel Age caused a global industrial revolution, resulting in a number of economically well-developed powers. The Silicon Age began in 1950, creating the era of information technology that has sparked a revolution with profound impact on the modern world.

The era of steel and silicon led to an understanding of the influence of materials science on social development and progress. Today, scientists specializing in materials research, economists, bankers, business leaders, and leading economic policy makers at the national level are paying close attention to the development of materials research in order to grasp opportunities and to make the right judgments and decisions.

The mistakes Great Britain has made in its technology policies is an example that illustrates this issue. At the advent of the Steel Age, Britain's early development of its steel industry contributed to its dominant position in worldwide steel production and also brought tremendous vitality to its economic development. After World War II, Japan's industrial development required the production of its own low-cost and high-quality steel. In 1952, Japan's annual steel production was only 7 million tons, while Britain annually produced 17 million tons of steel. By 1962, only ten years later, Japan's annual steel output jumped to 27.5 million tons, while Britain's steel production was 20.8 million tons. By 1972, Japan was far ahead, producing 96.9 million tons of steel, compared to

TABLE 1
The Seven Eras of Human Materials Usage

Beginning of Era	Era
ca. 100000 BCE	Stone Age
ca. 3000 BCE	Bronze Age
ca. 1000 BCE	Iron Age
ca. 1 CE	Cement Age
ca. 1800 CE	Steel Age
ca. 1950 CE	Silicon Age
ca. 1990 CE	New Materials Age

Source: Briggs, A., *The Science of New Materials*, Blackwell, Oxford, U.K., 1992.

Britain's 25 million tons. Britain's technology policy promoted the growth of Japan's auto industry, as well as the rapid development of its other major industries that used steel products.

After 1970, the Japanese began to recognize the world's entry into the Silicon Age. In addition to maintaining its dominant position in steel production, Japan also targeted silicon materials and developed its semiconductor industries, which resulted in its worldwide leadership role in the production of household appliances. In contrast, Great Britain ignored the arrival of the silicon era. Because of the absence of corresponding technology policies and strategic vision, nearly 2000 British silicon research scientists flowed into the U.S. Silicon Valley. Consequently, in 1988, the United Kingdom's trade deficit with Japan reached £2.2 billion in information technology products alone, which did not even include products like the silicon-controlled autofocus camera. The result has been, as the British have complained, that "Britain has no semiconductor industry, and the United Kingdom has degraded from a first-rate economic power to the second-tier of economically developed countries, while Japan has developed from a second-tier economically developed country to a first-rate economic power. The attitude of the United Kingdom is like a country that still remains in the Stone Age, but with no progress into the Bronze Age" [4].

It is now recognized that materials development has been a milestone in the history of human evolution, and an important pillar of modern civilization. Further development of science and technology leads to enhancement in the quality of life. Moreover, a rapid increase in world population, the accelerated depletion of resources, and the deteriorating environment have demanded higher levels of sophistication in materials science and technology.

The field of materials science and engineering is now entering into an unprecedented period of innovation and development. New materials are the precursor for high-technology development. New materials research and the scale of industrialization have become important indicators for measuring a country's regional economic development, technological advancement, and national defense capabilities.

"Material" is a term that existed long ago, but the emergence of "materials science" only began in the early 1960s. The Cold War was at its height when the USSR successfully launched Sputnik, the world's first satellite, on October 4, 1957. The U.S. government and the general public were shocked by U.S.S.R's achievement and realized that they were lagging behind in their research into advanced materials. Therefore, in order to catch up, the Americans engaged in an in-depth study of materials and established more than ten material research centers in their universities, achieving significant results through the use of advanced scientific theories and experimental methods. Since then, the term "materials science" has become popular [1].

Materials science is often understood as the study of the relationship between the organization, structure, and the nature of materials, and the exploration of their natural laws. In fact, materials science is an applied science, and the purpose of materials research and development is to practically apply its results to daily life and to promote economic development. A material with practical value must be prepared through rational technological processes and must be mass produced in order to be classified as an engineering material. Therefore, soon after the term "materials science" emerged, "materials science and engineering" was proposed. Materials engineering refers to the study of technologies and the technical problems involved in the process of preparing materials for practical use. Therefore, "materials science and engineering" is a discipline that studies the composition and structure, the synthesis and processing, and the properties and performance of materials, as well as the relationships between them. The image of a tetrahedron on the cover of *Acta Materialia*, a well-known material research journal, best describes the four basic elements of materials science and engineering: composition and structure, synthesis and processing, properties, and performance.

The four-element model of materials science and engineering has two main features [1].

First, there is a special relationship between the properties and the performance of materials, in which the performance of materials represents the behavior of its properties under conditions of use. Environmental conditions such as stress state, ambience, media, and temperature have a great impact on the properties of materials. Some materials perform well under normal circumstances, but when they are placed in a corrosive environmental media, their performance declines significantly. Other materials have excellent performance when their surfaces are smooth, but their performance diminishes greatly when their surfaces have gaps. This behavior is especially prominent for certain high-strength materials: whenever there is a scratch, it may cause catastrophic damage. Therefore, the introduction of environmental factors is very important for engineering materials.

Second, the theory and design of materials has its proper position at the center of the tetrahedron. Because each of these four elements (or a combination of several related elements) has its own corresponding theory, a model can be built based on the theory. Through this model, materials design and technological design are used to enhance the properties and performance of materials, thereby conserving resources, reducing pollution, and cutting down costs. This is the ultimate goal of materials science and engineering.

Materials science has three important attributes [1]:

Interdisciplinary science: Materials science is the result of the integration and interaction between physics, mechanics, chemistry, metallurgy, and computer science.

Practical application: The purpose of materials science is to develop new materials, improve their performance and quality, and rationally use materials, while reducing cost and pollution.

Ongoing development: Unlike physics, chemistry, and mechanics, which are mature sciences, materials science can be enriched and improved through the development of relevant disciplines.

Materials science and technology is one of the fastest growing scientific and technological fields in recent years. It has created many new high-performance materials and unprecedented processing methods but has also dramatically changed the production of traditional materials. Since the 1990s, materials science and technology has undergone revolutionary changes. These developmental trends can be summarized as follows [5]:

- The discovery and development of new substances and new materials at an in-depth and microlevel
- The development of composite materials
- The growing importance of thin film and coating science and technology [6]
- The integration of theory, computer simulation, and experimentation in the development of new materials [7]
- The impact of modern technology and innovation leading to cheaper, faster, and better performance of materials
- The integration of research, development, production, and application in the emergence of new materials
- The integration of materials science and engineering into a unified discipline, with a focus on practical application and development

INTERDEVELOPMENT OF MATERIALS SCIENCE AND SOLID MECHANICS

Mechanics is one of the seven fundamental natural sciences and is closely related to the eight major applied sciences. Solid mechanics studies the deformation, flow, and destruction of a solid material and the structure (components) bearing the force. It is an important branch of mechanics [8].

The infancy of solid mechanics can be traced back to 2000 BC when the Chinese and other ancient civilizations began to construct buildings and design simple travel and hunting tools with embedded mechanical principles. The Zhaozhou stone arch bridge, built in China during the mid-Kaihuang (AD 591–605) of the Sui Dynasty, employed the basic ideas of a modern bar, plate, and shell design. The accumulation of practical experience and the achievements of seventeenth-century physics led to the development of the theory of solid mechanics. The eighteenth century was the developmental period of solid mechanics. Social needs—such as the manufacture of big machines and the construction of large bridges and plants—became the driving force for the advancement of solid mechanics.

Modern solid mechanics refers to the period after World War II. During this period, there were two developments: (1) the finite element method and the computer were widely used and (2) fracture mechanics and composite mechanics emerged as new branches of solid mechanics. After Turner proposed the concept of the finite element method in 1956, a large number of applications in solid mechanics were developed that have solved many complicated problems.

Cracks always exist in the structure of a material, which has motivated the exploration of the crack-tip stress-and-strain fields and the pattern of crack propagation. As early as the 1920s, Griffith first proposed an important concept: the actual strength of glass depends on the crack propagation stress. In 1957, G. R. Irwin introduced the stress intensity factor and its critical values to determine crack propagation. As a result, modern fracture mechanics was born and has grown rapidly since the late 1950s.

Material mechanics is the first developed branch of solid mechanics. It studies the mechanical properties, deformation states, and fracture patterns of a material under external forces. It also provides the basis for the selection of materials, and the sizes of components, in the process of engineering design.

Fracture mechanics, also known as fracture theory, is the latest developed branch in solid mechanics. It studies the crack-tip stress-and-strain fields in engineering structures and analyzes the conditions and patterns of crack propagation.

Solids usually contain cracks. Even without macroscopic cracks, microdefects within the solid (such as pores, grain boundaries, dislocations, and inclusions) develop into macroscopic cracks under the effects of loads and corrosive media, and especially under alternating loading conditions. Therefore, it can be said that fracture theory is crack theory. The fracture toughness and crack propagation rate proposed by fracture theory are important indicators used to predict critical cracking size and component life-span estimation, which have been widely used in the engineering structure. In general, the purpose of fracture mechanics includes the study of crack propagation patterns, the establishment of fracture criteria, and the control and prevention of fracture failure.

Composite material mechanics is the study of the mechanical properties of components in modern composite materials—primarily fiber-reinforced composite materials—and their deformation patterns and design criteria under a variety of different support conditions and external forces. Composite material mechanics is concerned with material design, structural design, and design optimization. It is a new branch of solid mechanics developed in the 1950s.

If elastic mechanics were mainly confined to the nineteenth century, then in the twentieth century, solid mechanics has been greatly developed and substantially expanded, resulting in the emergence of many new branches in the field. Both solid mechanics and materials science play an important role in modern industry. With the development of science and technology, the interrelationship between solid mechanics and materials science has become increasingly evident. Over the years, solid mechanics has established a series of important concepts and methods, such as continuous media, stress, strain, bifurcation, fracture toughness, and the finite element method. These brilliant achievements led to the development of modern civil and construction industry, the machinery manufacturing industry, and the aerospace industry, but also provided the theoretical basis—along with the use of partial differential equations—for a wide range of natural sciences such solid-earth geophysics, nonlinear science, materials science and engineering.

Due to the complexity of the objects involved, modern solid mechanics raises a series of challenging issues that are at the forefront of science. The mechanical properties of materials and the study of the fracture of materials have become the current focus of problems in solid mechanics. In May 2005, the 96th "Young Scientist Forum" was organized by the China Association for Science and Technology (CAST) at Xiangtan, Hunan. The theme of this event was "The challenges posed by the rapid development of materials science on solid mechanics." The forum conducted in-depth discussions on the challenges and opportunities faced by the following two major trends: (1) the development of solid mechanics under the conditions of low-dimensional nanomaterials, smart materials, and multifield coupling and (2) the development of the solid mechanics of materials [9]. The Materials Science and Engineering Committee of the U.S. Department of Energy organized a symposium and invited 19 leading scholars from 7 renowned universities and research institutions for discussions on the future direction of the development of material mechanics. Its research report was published in the prestigious journal *Mechanics of Materials* in 2005 [10]. These discussions show that low-dimensional nanomaterials bring new opportunities for development in the research of solid mechanics.

Theoretical Research

Since the early 1980s, modern manufacturing technology has enabled the manufacture of a variety of new low-dimensional materials with optimum performance, such as zero-dimensional quantum dots, atomic cluster, nanopowders, one-dimensional quantum wires, nanowires, nanotubes, nano-superlattices, quantum two-dimensional arrays, thin films, coatings, and one- or two-dimensional quasicrystals. Most of these materials demonstrate complex structural forms and excellent physical properties. The study of the relationships among their growth patterns, physical properties, and structural forms has attracted scholars from many fields in materials, physics, mechanics, mathematics, and biology. Because of the size effect and the properties of low-dimensional materials—which are very different from corresponding bulk materials and substrate materials—the existing theoretical basis and the experimental methods for research into low-dimensional materials may not be appropriate. The development of low-dimensional materials has brought mechanics scholars into a new realm of nontraditional macro- and microresearch. Therefore, searching for the theories and methods appropriate for the design and prediction of the mechanical properties of low-dimensional materials raises a number of current research challenges: What is the scope of research for the mechanics of low-dimensional materials and nanomaterials? How can researchers propose a new theory that is neither traditional macro-Newtonian mechanics nor traditional microscopic quantum mechanics?

Cross-Scale Numerical Simulations

Research and experience have shown that material properties are not statically dependent on the chemical composition of materials but, to a large extent, dependent on the microstructure of materials. Microstructure refers to the collection and spatial distribution of all lattice defects of nonequilibrium thermodynamics. Its space scales can vary from a few tenths of a nanometer to several meters, and its corresponding temporal scales can range from a few picoseconds to several years. A major goal in the research of materials science has been to understand the quantitative relationship between the macroscopic properties of materials and their microstructure. It is well known that numerical simulation is a powerful tool for materials design and the prediction of material properties. However, it is clearly not feasible, using a single micro- or macroapproach, to study problems of microstructure evolution where there are differences in spatial and temporal scales over several orders of magnitude. For these cross-scale problems, researchers encounter serious issues in mathematics and physics.

Experimental Representations

The challenge of experimental mechanics posed by low-dimensional materials—a new object of research—is how to develop new experimental methods and study new testing technologies that can measure micro- and nanostructures and the mechanical properties of materials. Structural research should emphasize the following: (1) loading methods and deformation measurements of micro- and nanostructures, (2) testing methods for the ultra-high-frequency features of micro- and nanostructures, (3) macroloading environmental control technologies on the microevolution of microzones, (4) the experimental methods and simulation techniques of low-dimensional structures, and (5) measuring methods of microloading and microsensing of microspecimens.

Challenges and Opportunities of Smart Materials, Device Mechanics, and Multifield Coupling Mechanics

Smart devices are extensively used in the rapid development of information technologies and integrated microoptoelectromechanical systems (MOEMS). Smart devices raise scientific issues such as multifield coupling and the structural mechanics of subtle information. When stress, strain, or thermal activity intensively interact with electromagnetic behavior, the laws of mechanics for smart materials, their information technology, and their structural design becomes extremely important. Therefore, solid mechanics faces new challenges in the determination of the constitutive relation of anisotropic smart materials, the analysis of the field under multifield coupling, and the determination of basic physical mechanics parameters.

Direction of Material Solid Mechanics Is Gradually Emerging

Materials science is different from physics, chemistry, and mechanics, which have very mature systems. The system of material solid mechanics is emerging. The difference between actual material strength and current theoretical strength is one to two orders of magnitude. This contradiction has resulted in the establishment of important physical and mechanical theories, such as dislocations and cracks. However, this fundamental contradiction still exists. Today, solid mechanics is not limited to computing small strain and stress, but requires the determination of deformation localization, damage, life span, and fracture. A further problem is how to reasonably configure materials with different properties and functions together, forming composite materials. These composites must practically optimize such factors as specific gravity, stiffness, strength, toughness, and functionality, as well as price, and contribute to the science of materials design. A further step is to develop specific manufacturing and processing techniques, such as plastic forming and particle beam processing technologies, which will achieve rational mechanical understanding and optimization control. At that stage, the entire material and manufacturing industries will transform from so-called kitchen chemistry to resource conserving, energy conserving, and rational, optimized industries.

The composition of materials is important for the development of new materials and the transformation of traditional materials, which include composite materials, surface modification of materials, thin films, and coatings. It makes the material interface problem particularly prominent. The combined effect of residual stress and external load will result in the fracture of materials, because the mismatch of thermal parameters and the mechanics of materials on both sides of the interface will cause residual stress. Therefore, interface mechanics will encounter such problems as micro- and macrodeformation, the theoretical analysis of the entire process from damage to fracture, numerical simulation, and experimental measurement. In particular, the following questions must be asked: Is the concept of interface fracture toughness, and interface strength, suitable? Is it possible to find reasonable parameters representing the entire process of the interface from deformation to damage to fracture?

The Mechanics of Biological and Biomimetic Materials Is Gradually Becoming a Direction of the Discipline

Using the knowledge of solid mechanics, we have been gradually learning to design materials and devices based on inspiration from biology and biotechnology. By drawing from knowledge of biological systems, we can design new materials possessing the stress distribution of the best biological systems, their optimal structural and functional properties, and their best evolution patterns. We can also develop methods for designing hierarchical multiscale new materials by studying the microstructure and stress-and-strain fields of biological materials. We may even boldly predict that microelectromechanical systems (MEMS) or nanoelectromechanical systems (NEMS) already exist in the biological body and that highly sensitive components and new high-performance materials with real social and ecological harmony are biological materials. Therefore, continued development in this area will have a significant impact on the engineering, biological, and medical industries, as well as the materials industry and the military.

New Domains, New Directions, And New Interdisciplinary Approaches Have Pioneered A "New Frontier" of Solid Mechanics

With the rapid development of materials science, traditional solid mechanics has been greatly expanded. New domains, new directions, and new interdisciplinary approaches have pioneered a "new frontier" of solid mechanics. Research on low-dimensional materials has demonstrated that solid mechanics is not limited to the traditional thinking of continuous media but has been extended to the microscopic level of materials, pursuing the nature of the relationship between microstructure and macroscopic properties.

After encountering new materials such as carbon nanotubes and thin films, researchers began to develop new experimental methods and to study new testing techniques that could measure the micro- and nanostructure of materials, and their mechanical properties.

The study of microstructure has evolved. Spatial scales now vary widely from a few tenths of nanometers to several orders of magnitude, and temporal scales range from a few picoseconds to several years, changing the relationship between the macroscopic properties of materials and their corresponding microstructure. This cross-scale research has not only extended the research domain of solid mechanics but has also integrated such disciplines as materials science, physics, mechanics, and mathematics.

The "kitchen cooking" methods of material manufacturing have collapsed, and people are beginning to rationally design materials based on aspects of their microstructure and their micro- and macroproperties. Solid mechanics also plays a very important role in today's information technology and in the rapid development of integrated MOEMS.

INCREASINGLY CLOSE RELATIONSHIP BETWEEN MACROSCOPIC PROPERTIES AND MICROSTRUCTURE OF MATERIALS

In the field of materials science and engineering, there is no unified classification for the levels of material structure, even though there are a variety of classification methods. However, it is possible, based on the spatial scale of objects, to divide materials structure into three levels:

Engineering design level: This scale, corresponding to the macroscopic properties of materials, involves research and design into the processing and performance of bulk materials.

Continuum model scale: When the scale is in millimeters or above, the material is regarded as a continuous medium, and the behavior of single atoms or molecules of the material is not considered.

Microdesign level: When the spatial dimension is in micrometers or below, the scale is atomic- or molecular-level design.

According to a combined spatial and temporal scale, the levels of material structure could be divided into four levels:

Macrolevel: This is the main scope of daily human activity, which uses brute strength or machinery and equipment. The spatial scale of this level is roughly from meters to tens of