
Fifth Edition

**Elements of
Materials Science
and Engineering**

LAWRENCE H. VAN VLACK

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Preface

As ably described by Professor Cohen in the Foreword, the central theme of *Materials Science and Engineering* is the concept that the properties and behavior of a material are closely related to the internal structure of that material. As a result, in order to modify properties, appropriate changes must be made in the internal structures. Also, if processing or service conditions alter the structure, the characteristics of the material are altered.

This new edition of *Elements of Materials Science and Engineering*, like the four previous editions, develops that structure \Leftrightarrow properties \Leftrightarrow performance relationship. It builds on basic college chemistry and physics courses, utilizing their principles and drawing upon those backgrounds to develop additional principles as required. Liberal use is made of engineering applications to illustrate the above relationships.

This edition has changes calculated to serve the student better. (1) The text is divided into three parts to meet academic needs. (2) There has been a modest increase in attention to polymeric, ceramic, electronic, and composite materials, as encouraged by many of those 180 schools who participated in the "Survey of the Introductory Materials Course" (*Journ. Materials Education*, Vol. 5, No. 3, 1983). (3) The review and study sections at the ends of the chapters have been enlarged as an aid to instruction.

This edition contains three parts. The first part addresses the phases of materials—their structure, properties, and performance. This part (through Chapter 9) is generally applicable to all engineering disciplines. Chapters include atomic order and disorder; metals, polymers, and ceramics; and semiconductors and nonconducting materials. Part I may constitute the introductory course if there are time restrictions. Part II considers multiphase materials with attention to phase relationships, heat treatments, composites, and service performance. It will have specific interest in those disciplines that emphasize design. Part III introduces the widely used materials of cast irons (cheapest metal), concrete (greatest tonnage), and wood (greatest volume) on an optional

basis. None of these three materials is simple; but all can be approached on the structure-property basis.

Chapter 6 (polymeric materials) has been rewritten with an added section on processing. Chapter 9 (magnetic, dielectric, and optional materials) is new, as is Chapter 12 (composites). Fracture toughness has been added as a section in Chapter 13 (service performance) because of its importance to product reliability.

Study aids that were also present in the fourth edition include the chapter Previews, approximately 200 Example problems at the end of sections, a Summary at the end of each chapter, and more than 500 Study Problems. Added to the fifth edition are Quiz Samples (and answers), and a glossary of Terms and Concepts at the end of each chapter.

The study problems are separated into two categories. The first is a trial category (unshaded). These study problems parallel example problems closely, or relate directly to equations. Their purpose is to allow the students to "get their feet wet" before proceeding to the problems (shaded) that require more analysis and/or greater integration with previous topics.

As in previous editions, some sections and topics may be deleted by the instructor in deference to time or to sequel courses. These sections are marked with a bullet (•), and are not prerequisite to subsequent unmarked sections.

Unfortunately, individual acknowledgements are impossible for the hundreds of students at The University of Michigan, and to the dozens of instructors at other schools, each of whom have contributed in their way to this new edition. All comments have been seriously considered, and most have been used.

I would be remiss, however, if I did not acknowledge Professor Bigelow for his critical comments on the previous edition, and thank Professor M. Cohen (MIT) for his encouragement and numerous suggestions for this fifth edition. Likewise, the feedback of classroom responses by Professors Filisko, Hosford, Hucke, Leslie, and Tien was valued most highly. Behind the scenes of the revision, and always cooperative, were Mrs. Ardis Vukas in my office, and Marion Howe and Dick Morton of Addison-Wesley. It has indeed been a pleasure to work with them again. They made the work go smoothly. Fran's encouragement and patience have been generous and indispensable.

*Ann Arbor, Michigan
September 1984*

L.H.VV.

Foreword

Materials and Society

Morris Cohen

Materials are all about us; they are engrained in our culture and thinking as well as in our very existence. In fact, materials have been so intimately related to the emergence of civilizations that they have given names to the Stone, Bronze, and Iron Ages. Both naturally occurring and manufactured materials have become such an integral part of our lives that we often take them for granted, and yet materials rank with food, living space, energy, and information as basic resources of the human race. Materials are indeed the working substance of our society; they play a crucial role not only in our way of life but also in the well-being and security of nations.

But what are materials? How do we understand, manipulate, and use them? Materials are, of course, a part of the matter in the universe, but more specifically *they are substances whose properties make them useful in structures, machines, devices, or products*. For example, these categories include metals, ceramics, semiconductors, superconductors, polymers (plastics), glasses, dielectrics, fibers, wood, sand, stone, and many composites. The production and processing of these materials into finished goods account for about one fifth of the jobs and gross national product in the United States.

Since the human body might be regarded as a structure or machine or device, we could also embrace foods, drugs, biomatter, fertilizers, etc., among the classes of materials, but it is presently customary to leave these materials to the life and agricultural sciences. For similar reasons, even though fossil fuels, water, and air likewise fall within the broad definition of materials, they are usually dealt with in other fields.

The materials of the world's population can be visualized to flow in a vast *materials cycle*—a global cradle-to-grave system. Raw materials are taken from the earth by mining, drilling, excavating, or harvesting; then converted into bulk materials like metal ingots, crushed stone, petrochemicals, and lumber; and subsequently fabricated into engineering materials, like electric wire, structure steel, concrete, plastics, and plywood, for meeting end-product requirements in society. Eventually, after due performance in the service of humanity,

these materials find their way back to earth as scrap, or preferably re-enter the cycle for reprocessing and further use before their ultimate disposal. In this huge international activity, almost one third of the world's raw materials are processed or consumed in the United States.

An important aspect of the materials-cycle concept is that it reveals many strong interactions among materials, energy, and the environment, and that all three must be taken into account in national planning and technological assessment. These considerations are becoming especially critical because of mounting shortages in energy and materials just at a time when the inhabitants of this planet are manifesting deeper concern for the quality of their living space. As a case in point, if scrap aluminum can be effectively recycled, it will require only about one twentieth the energy needed for an equivalent tonnage of primary aluminum from the ore, and the earth would be that much less scarred by the associated removal operations.

Consequently, the materials cycle is a system that intertwines natural resources and human needs. In an all-embracing way, materials form a global connective web that ties nations and economies not only to one another on this planet but also to the very substance of nature.

Clearly, then, in the development of human knowledge, one is not surprised to find a *science and engineering of materials* taking its place among all the other bodies of inquiry and endeavor that extend the reach of the human race. Simply stated, *materials science and engineering* (MSE) is concerned with the generation and application of knowledge relating the composition, structure, and processing of materials to their properties and uses. As suggested in Fig. 1, there is a linkage that interrelates the structure, properties, processing, function, and performance of materials. MSE operates as a knowledge-conduction band that stretches from basic science and fundamental research (on the left) to societal needs and experience (on the right). The countercurrent flow of scientific understanding in one direction and empirical information in the other direction intermix very synergistically in MSE.

If we wish to highlight the *materials science* part of this spectrum, we focus on understanding the nature of materials, leading to theories or descriptions that explain how structure relates to composition, properties, and behavior. On

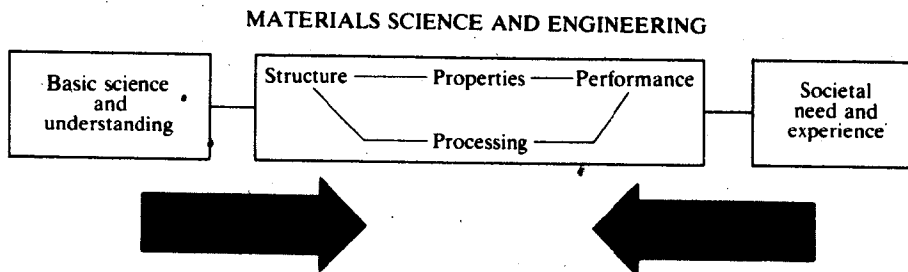


Figure 1 A representation of the central elements of MSE, in relation to the countercurrent flows of scientific and empirical knowledge.

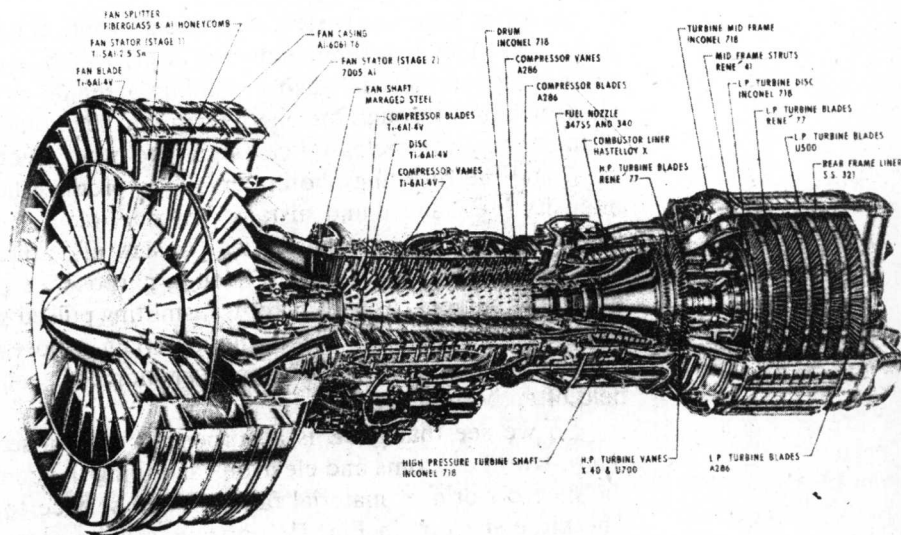


Figure II Materials in a jet engine. The jet engine is a complex system designed for converting fuel energy into motion. Here a major goal is to improve the ratio of thrust to weight. Each of the designated materials is selected and processed to serve an assigned function in harmony with all the other operating materials. (Taken from "Materials and Man's Needs," Committee on the Survey of Materials Science and Engineering, National Academy of Sciences, Washington, DC, 1974; courtesy of the General Electric Company.)

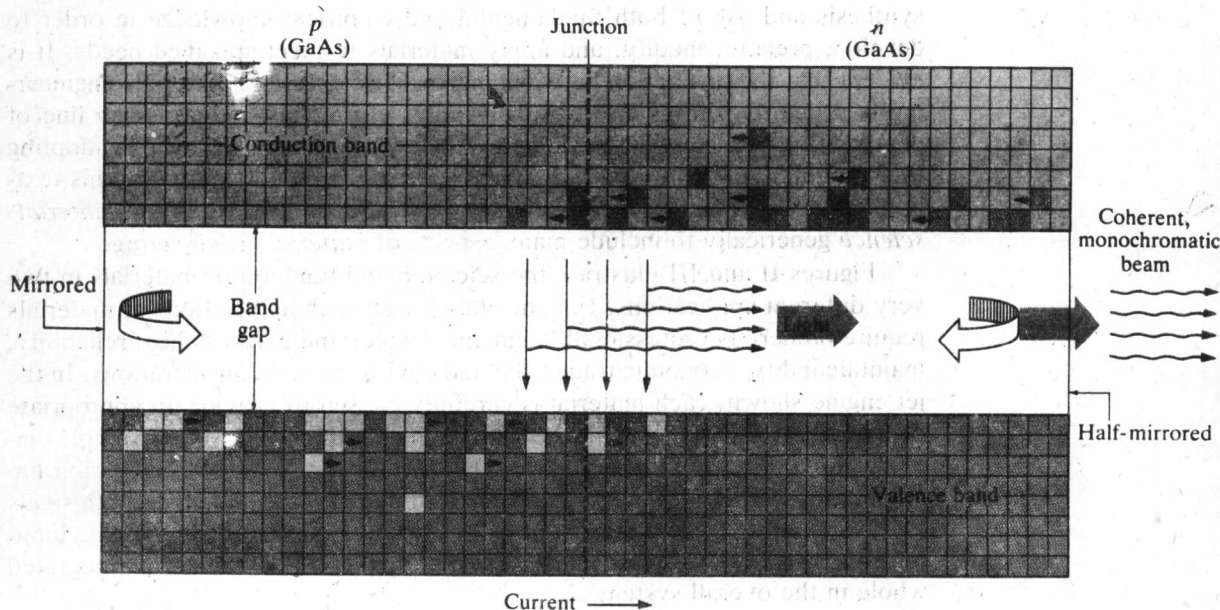
the other hand, the *materials engineering* part of the spectrum deals with the synthesis and use of both fundamental and empirical knowledge in order to develop, prepare, modify, and apply materials to meet specified needs. It is evident that the distinction between materials science and materials engineering is primarily one of viewpoint or center of emphasis; there is no line of demarcation between the two domains, and we find increasing logic in adopting the combined name of *materials science and engineering*. Actually, this textbook joins the two, both in its title and coverage, by using the term *materials science* generically to include many aspects of *materials engineering*.

Figures II and III illustrate the selection and function of materials in two very different applications. For societal use, all such applications of materials require numerous professional judgments concerning performance, reliability, maintainability, economic trade-offs, and environmental considerations. In the jet engine shown, each material is carefully chosen to provide an appropriate combination of properties that will serve the intended function. Examples include superalloys for turbine blades, heat-resistant alloys for combustion liners, fatigue-resistant titanium alloys for compressor vanes, high-strength steels for gears and shafts, wear-resistant alloys for bearings, and light-weight aluminum alloys for casings. And all of these materials must operate as an integrated whole in the overall system.

Another materials system is the electro-optical device shown schematically in Fig. III. This is a semiconductor laser, which is essentially composed of a suitably doped material such as gallium arsenide or indium phosphide. When electrons drop through the energy gap into the holes in the valence band, part of the energy thus released can stimulate other electrons to undergo this process, and the resulting photon emissions produce laser light. The laser-beam intensity is enhanced and sustained by multiple reflections from mirrors at the left and right faces of the device. Lasers of various types are now widely employed for intense localized heating purposes, e.g., welding, surface treatment, and surgery, as well as for transmitting pulsed signals along optical fibers in telecommunications. Electronic materials, whose useful properties depend on electrical, optical, and magnetic phenomena, constitute a rapidly growing field of activity in MSE.

So we see that MSE is a purposeful enterprise, reaching down into the micro-world of atoms and electrons and tying the condensed state of matter to the macro-world of material function and service to meet societal problems. The circular chart in Fig. IV portrays a large section of human knowledge, extending from basic sciences at the core, through applied sciences in the middle ring, to various engineering fields in the outer rim. In the center, we show physics and chemistry flanked by mathematics and mechanics; and on

Figure III. Semiconductor laser (schematic). Photons of light are emitted when electrons combine with electron holes at the p - n junction of properly doped gallium arsenide or comparable semiconductors. The emitted light is reflected at the two ends, returning to stimulate the combination of additional electron-hole pairs. These build up an intense coherent beam that exits into an optical train for a variety of sophisticated applications.



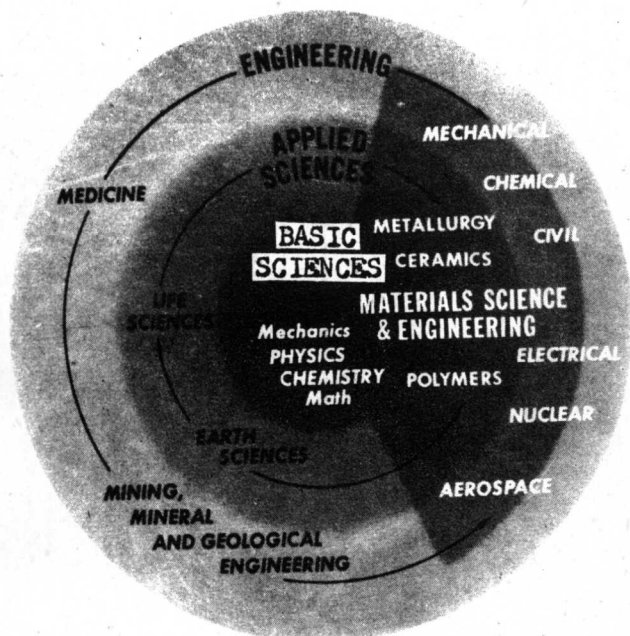


Figure IV Materials science and engineering. This text draws from introductory science principles of physics and chemistry to relate *composition and structure* of materials to the *properties and service behavior* that are important to engineers. More than one fourth of our national technical effort involves the development and technology of materials. This effort draws from the physical sciences and all branches of engineering. (Courtesy National Academy of Science.)

moving out radially, we pass through various applications-oriented disciplines. The part of this map to be visualized as materials science and engineering is the shaded sector at the right, which may be compared to other sectors designating the life sciences and the earth sciences. In its broad sense, MSE is a multidiscipline that embraces (but does not replace!) some disciplines (e.g., metallurgy and ceramics) and some subdisciplines (e.g., solid-state physics and polymer chemistry), and also overlaps several engineering disciplines.

There are, of course, many scientists and engineers who are materials specialists—metallurgists, ceramists, and polymer chemists—and who are wholly involved in materials science and engineering. Equally important, government data, when analyzed, reveal that one of every six hours of professional work done by *all other engineers* directly involves materials and their utilization. The time fractions are even higher for chemists and physicists. As a result, the equivalent of one-half million of the nearly two million scientists and engineers in this country contribute to this major segment of our national product and our national well-being.

Thus, materials science and engineering constitutes a framework in which professionals in many disciplines work creatively to probe nature's processes and, at the same time, advance knowledge in response to the pull of human needs.

Cambridge, Massachusetts
September 1984

Morris Cohen

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Chapter One

Introduction to Materials Science and Engineering

PREVIEW

Materials have always been an integral part of human culture and civilization; for example, the stone, bronze, and iron ages of the past. Likewise, today's advanced technologies involve sophisticated materials, since all of them utilize devices, products, and systems that must consist of materials. The engineer's expertise is in adapting *materials and energy for society's needs*.

The theme of this text is that *the properties of materials depend upon their internal structure*. In turn, the properties influence the *performance* of a material, both during manufacture and in ultimate service. To change the performance of a material, its internal structure must be modified. Conversely, if service conditions alter the structure, the engineer must anticipate what changes will occur in properties and performance.

The final section of this introductory chapter reviews selected properties that are associated with general physics. They will give us a basis for making our first structure \Leftrightarrow property \Leftrightarrow performance ties. For convenience, we commonly categorize materials as metals, polymers, and ceramics.

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This chapter, like all the chapters of this text, is concluded with a Review and Study section that includes (1) a *Summary*, (2) a glossary of key *Terms and Concepts*, (3) *Discussion* topics, (4) *Quiz Samples*, and (5) *Study Problems*.

STUDY OBJECTIVES

1. To become aware of the close association of materials with past cultures, and with current technological advances.
 2. To become alert to the concept that materials possess an internal structure. (The various details of structure will be the focus of later chapters.)
 3. To recognize most materials as being in one of three main categories—metals, polymers, and ceramics; and to know the basis of distinction between these.
 4. To review selected properties from general physics, so that we will have an introductory basis for the structure \Leftrightarrow property \Leftrightarrow performance ties.
 5. To become familiar with terms and concepts that relate materials and engineering.
-