# Using Materials Science

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*Summary.* The science of the solid state has joined nuclear science and molecular biology as a field of major importance in the latter half of the 20th century. It took particular shape during the genesis of solid-state electronics and the post-transistor era of integrated circuits for telecommunications, computers, and digital signal machines. However, these developments were soon joined by techniques from the ancient fields of metallurgy and ceramics and contributions from the more current fields of synthetic polymers, rubbers, plastics, and modified bioorganic substances. This vast realm was characterized by a National Academy of Sciences study of the 1970's as "materials science and engineering." The public, as well as the scientific and engineering community, are currently concerned about the uses of research and development and the applications of knowledge for national progress. Consideration is given here to how well we are using the science of materials for industrial strength and such governmental objectives as national security and energy economy.

It is two decades since discussions in the President's Science Advisory Committee led to a national materials science and engineering policy. This enabled designation of the Advanced Research Projects Agency of the Department of Defense, working through the Federal Council for Science and Technology, as sponsor of the Interdisciplinary Laboratories in several versatile American research universities. Accordingly, new discoveries and talented people have been worked into the system of materials makers and users (*1*).

This action was concurrent with the evolution of materials science and engineering as vital industrial elements of the oncoming era of communications, computers, and information technology, now assuming its greatest growth. Similarly, the basis for electronics and photographics in solid-state systems forms part of the essence of the space and rocket epochs. And these, in addition, have demanded extraordinary thermal and physical endurance in yet other structures.

Thus, when the National Academy of Sciences' Committee on the Survey of Materials Science and Engineering (COSMAT) submitted its report a half-decade ago, in September 1975, it was found that the science and technology of materials had developed into a major industrial and, to a lesser but growing degree, academic mission. And in 1978 a successor group to the original committee in the Federal Council for Science and Technology, called the Committee on Materials (COMAT) of the Federal Interagency Coordinating Committee, in cooperation with Battelle Institute and the Industrial Research Institute, reported that U.S. industry devoted about $4.3 billion a year to materials life-cycle research and development. Further, the National Commission on Materials Policy, in its final report published in 1974 (*2*), indicated that the application of nonenergy materials and their processing represented 6 to 7 percent of the gross national product of the United States. The interaction of materials with energy usage has, of course, become increasingly important and illustrates the significance of advanced materials science and engineering for overall national progress (*3*).

## Role of Basic Science

In materials research, modern physical science has been integrated with age-old techniques applied to metals, ceramics, glasses, cellulose and rubber derivatives, fibers, and composites. But new paths have also been found toward achieving properties of matter unknown or even unimagined before. These mechanical, chemical, and electromagnetic properties may determine the future of great industries such as the automobile, housing, and aerospace industries. Certainly they are crucial to national security capabilities.

Even more stirring is the evidence that solid-state and materials science is becoming organized and structured so that it joins more traditional science as an intellectual entity. As such, it challenges curiosity and understanding; it provides orderly pedagogy; it thus offers ways to involve new generations of talented people in an especially close and kinetic interaction between basic knowledge and its highly practical applications.

As might be expected from the rapid changes and growth both in materials science and engineering and in the world economy, the *record* of such new work has been complicated by identity with other dominant features of solid-state science and derived technologies. Thus, electronics, communications, and computers have heavily exploited new materials. This is also true of space and missile as well as aircraft engineering, and of increasing elements of biomedicine (*4*). Similarly, more established fields, such as metallurgy, plastics, fibers, food, lumber, containers, petroleum, stone, clay and glass, and motor vehicles, have participated strongly in other aspects of the new knowledge of matter. So a great deal of current work is associated with these combinations of *makers* of materials and the often quite different *users* of materials, with the result that common elements of materials progress are often somewhat obscured.

There is another inevitable quality of such a rapidly enlarging domain of science and engineering, which is the sheer burst in volume of published material of all kinds. Thus, since 1950 we find that there have appeared no fewer than 1380 different books on polymers, the basic substances of plastics, rubbers, fibers, coatings, and adhesives. These books are likely to be categorized somewhat in terms of properties, but without general reference to the common features of atoms and molecules, of structure and order, which are expected to govern all materials.

The question then is, How well have we applied the new basic understanding of matter across this growing frontier? Correspondingly, how well have we cross-connected the findings of both technology and science that the hosts of workers in each of the special fields of use of materials are steadily generating?

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Now it might be asked why these questions are so compelling, since science will tend to generalize the fundamental properties of matter on the atomic and molecular scale anyway. Further, it might be said that the uses of materials by industries and government are so specialized nowadays that one has to have a self-contained technology for each of them, and cross-linkages do not help much. I believe that these views are invalid. This conclusion is based on several decades of intimate participation in the progress of materials science and engineering, especially electronic materials, polymers, and materials for space and rocket systems.

Instead, the needs for new understanding and ideas about the behavior of materials under demanding conditions are such that transfer of knowledge across what have conventionally been impermeable barriers is the best way to advance. This involves especially combining techniques of materials engineering and of design. It offers vast new opportunities for economic gains and help with productivity in industries such as automobiles, other machinery, and energy conversion. But it demands detailed understanding of such solid-state effects as relaxation under stress, creep, fatigue, and many other mechanical and chemical behaviors, which are much affected by design and shapes, thermal and other fabricating dependencies on design, and the like (*3, 5*).

## Polymers

Strikingly, the atomic and molecular exchangeability among large areas of materials systems (and functions) once typified by basic compositional differences is spreading rapidly. Thus, polyesters govern a variety of both plastics and fibers; increasing numbers of polyolefins, like polyethylene and polypropylene, similarly constitute textiles, sheets, and moldings. Styrene's interaction in synthetic rubbers as well as rigid plastics has become a classic example. While the polyamides and glass remain rather differentiated as principal fiber and sheet materials, respectively, their roles are also being inverted, as glass fibers become reinforcing agents for polymers and nylon becomes a major molded structural element. This interchangeability occurs in many other cases—for example, W. G. Pfann and F. L. Vogel's discovery of atom dislocations in single-crystal germanium and the transfer of that finding to modifying the strength and processing qualities of a whole range of metals, from aluminum to zirconium.

The sheer quantities involved are indeed symptomatic of the need for unifying principles of science and engineering in creating and assuring the eventual properties of these classes of matter. For instance, in the 1970's, use of polyamides as rigid thermoplastics grew in the United States from 92,000,000 to 327,000,000 pounds (1969 through 1979), while their use in fibers, including the aromatic polyamides or aramides, went from 1,411,000,000 to 2,720,000,000 pounds. Likewise, the use of olefins in fibers grew from 269,000,000 to 759,000,000 pounds, while their use as plastics grew from 6,580,000,000 to 16,643,000,000 pounds in the same decade. A similar path could be traced for polyesters, which, although they vary in structure, are still basically dominated by the interaction of ester linkages, as shown long ago following W. Carothers' epochal discovery (*6*).

Overall, in the field of synthetic organic solids and composites, knowledge about basic qualities such as primary valence bonding, interchain dispersion, and dipolar forces between chains has guided new development. It is essential for understanding intra- and interphase as well as intercomposition or composite systems. This scope of precepts about matter calls for models of polymer solids comprising larger volumes than the intergroup or "average chain" configurations of earlier models. This is further supported by the growing interest in macromolecular systems qualified by additions of small molecules—an approach that has been used in plasticizing for decades and is now used in the induction of electrical and photosensitive behavior. This is also related to the borderline between the classic use of carbon in conducting rubber, dominated by interparticle contacts in a dielectric continuum, and intrinsic chain conductivities induced by polar and ionic properties, as in polyamides (*7*).

Indeed, a remarkable aspect of materials research, in its span from metals to nonmetals and from adhesives to glasses, is the consistency of concepts and experimental observations, even when rigorous analytical treatment is unavailable. The dual behavior of many solids, including the synthetic organics, as insulators and semiconductors or conductors, depending on detailed compositional variations, was noted in the early experiments of Pohl and co-workers (*8*), while a series of modern findings affirm the concepts of polyene conductivity advanced by Garrett (*9*).

## Organization of Living Matter

These widely concordant experimental observations of the electromagnetic and mechanical behavior of materials, under highly divergent conditions of use, encourage us to venture into new dimensions of the science and technology of aggregates. One reason for this is that the supramolecular organizing principles of nature in living matter so vastly exceed the best of our efforts. Thus, in all of our ingenious composites, mixtures, and even molecular combinations, nothing achieved so far comes near the biomorphology that is routine in growing plants and animals. Thousands of researchers over the centuries have marveled at the way bones balance mineral and organic phases. Skins assemble collagen plastics with hydrated rubbers, and feathers incorporate just the right amounts of silica and polypeptides in exquisite combinations. Only recently have we begun to see any path toward comparable processes in making and applying artificial materials. Microfibrils and microtubules are being recognized as widespread units in biomorphology, and modern polymer techniques produce something like the right dimensions of fibrils, but so far we have little idea of how the motility of microtubules arises.

There is good reason to believe that we must now begin to understand ways of generating specified motion—motion such as we have depended on purely thermal agitation to generate on a micro scale (and crude rheology, or at best solution and dissolution, on a larger scale). We really have not joined the phenomenon of Brownian motion in charged and relatively visible colloids with our new understanding of macromolecular qualities, including internal charges and internal discharging by conduction.

Polypeptides and the cellulose-lignin matrices that are so fabulously effective in plant growth probably exploit these factors widely. The path to get us started on this new mission of controlled micromorphology brings us back to the comments about simulation of polymer structure under dynamic circumstances, over volumes larger than segments. A vision of how this could be for the system polyethylene is being worked out by Weber (*10*) and Helfand *et al.* (*11*). Also, we should pursue simple boundary controls in the synthesis of macromolecules as another approach to understanding the structure that nature produces with such facility. Thus, in latex polymerization, molecular weight was long ago controlled by the size of the latex particle in the production of microgels (*12*). This method is now widely applied in modifying the structure and properties of natural rubber latices.

We are increasingly recognizing that information transfer and recognition of states is a promising approach to the biomorphology puzzle. Various conferences are emphasizing this with respect to cell composition and function (*13*). It is encouraging that there has been some primitive microtubule assembly in vitro (*14*). Ongoing studies of the recognition and coding potentials for natural and model systems will eventually tie in with these other efforts. Also, in connection with metallo-organic polymers and particular electronic components of large molecules, researchers such as R. P. Blakemore and A. J. Kalmijn several years ago found magnetotactic bacteria whose direction of motion in water is apparently governed by the interaction of the earth's magnetic field with about 20 tiny magnetite crystals forming single magnetic domains, held in a chain 1 or 2 micrometers long within their bodies. These are again indicative of capabilities for modifying and influencing the assembly of matter as represented in life systems.

### Structural Analysis and Control

Probably, these new kinds of capabilities would first be useful technologically in composites and other high surface functions such as adhesives. Once more, the new science of surfaces and films is strongly represented in materials science and engineering. Remarkable affirmation of such basic scientific concepts as quantum mechanics appears in this work. An example is molecular beam epitaxy, a method of synthesizing crystals by depositing one layer of atoms after another under precisely controlled conditions. These domains are so carefully arranged, with precise composition (and therefore energy shifts) controlled within 5 angstroms of an interface, that quantum well structures have modeled exactly the properties expected from a two-dimensional electron gas (*15*). The quantum mechanical particle-in-a-box, which most of us learned as an act of faith essential for wave mechanics, is now available.

This feature of fundamental science for materials gives hope for much more, but as noted in our statements about polymers, plastics, and adhesives, the questions are still vastly more numerous than the answers. Nowhere is this more apparent than in the use of solids as heterogeneous catalysts. Yet, there is extensive use of basic knowledge of structure and bonding which suggests that the new structural probes, such as extended x-ray absorption fine structure (EXAFS), electron impact spectroscopy/microscopy as pursued by D. Joy and his associates, and various electron emission and x-ray absorption schemes, will increasingly illuminate this mysterious realm of materials.

Such exact structural analysis has been essential for progress in superhard materials. In the case of diamond, nitrides, borides, and others, there is an important continuity in relating the bonding of perfect crystals to that of amorphous solids. In turn, the basic theories of P. W. Anderson and N. Mott have opened a new vision of bonding in glasses and other disordered systems. Thus, the finding of Klement *et al.* (*16*) that metals can be vitrified is a scientific as well as a technical resource.

The notion of supramolecular assemblies arises once more in connection with new qualities provided by polyphase ceramics and metals. Improved methods of microassembly may involve temperatures of 2000°C instead of 20°C, but will nonetheless deal with predesigned morphology. In the development of materials such as high-strength, low-alloy steels the age-old art of distribution of particles is being linked with the science of imperfections, found in the totally different arena of semiconductor single crystals. The still more distant realm where nature in living forms distributes the tiny domains and phases we have noted before, and which are the essence of living materials performance, beckons for exploration.

Many years ago, J. D. Fowlkes calculated the positions of veins in plant leaves and showed that nature had distributed the reinforcing members to ensure the greatest photoexposure for a given size and shape. The mystical exercise of living growth and form remains for other science to explain. But the new findings about composites, combinations of both organic and inorganic substance, impel us to keep seeking new ways of producing dispersion and aggregation. These should be more like nature's and less like those of the conventional milling machine, extruder, or blender.

It is likely that some distribution of charges and their changes underlie these dynamics in growth and form, just as they underlie solid-state electronics and electromagnetism. The modern emphasis on this area is an accurate reflection of the major technical as well as scientific advances based on the study of solids, as well as a reflection of the vast industrial and technological role of communications and computers, which depend on these materials. Discoveries of the properties of the hard superconductors have practically reorganized parts of the periodic table. Magnets of the rare earth–transition metal compounds, systems which amazed me when they were discovered, have intrinsic coercivities of 3 million amperes per meter and can eventually advance the development of electric motors and magnetic control systems. Similarly, the other vital technologies of photovoltaic cells, display devices, and magnetic memories in bubble systems, and the now conventional junction device semiconductors, have been based on knowledge and control of the pure crystalline state. But it is purity and perfection outside all our experience with matter. The behavior achieved may require particular impurities of less than $10^{12}$ atoms per cubic centimeter—levels hardly known in any other scientific studies. However, thanks to improved methods of preparation and analysis, in the future we would expect such purities to be widely achieved and employed (*17*). That organic systems as well as the classical inorganic ones are sensitive to impurity levels of this sort is indicated in the study of prostaglandins, whose action on cells, perhaps through membrane effects, is a dramatic reminder of the sensitivity possible in condensed systems.

### Implications of Precise Materials Processing

What should concern us now is not so much the influence of the transistor and its integrated-circuit and thin-film derivatives on our lives and economics, for that chronicle is well known, but rather the wider potential of precise materials processing. It is now possible to form exact materials structures that approximate the dimensions and controls about which I speculated earlier, in discussing the challenge of making material aggregates with efficiencies related to that of living tissues. Experimental thin-film circuits are being achieved with a line width of 2 μm or less in the elements of the circuit. And 1.25-μm dimensions are a reasonable objective for the next few years. Although this is still a long way from the atomic or molecular etchings so deftly employed by nature, which would represent a limit of film control of 3 to 5 nanometers, the interesting point is that the micrometer dimensions will eventually be achieved in manufacturing processes.

Further, an interesting principle of morphology dominates this field. That is, the aim is not so much a very small size for circuit elements such as diodes or transistors; instead, it is downsizing their configuration and interconnection dimensions. The conductors joining them cost about one-hundredth of what they would cost on a printed circuit board of conventional small dimensions. And a modern silicon chip with 150,000 components must contain about 500,000 conductors. Here we are reminded that aggregation of the elements is the basis of efficiency, just as aggregation of various mechanical or chemical elements may turn out to be in materials composites for the future, about which we have speculated. The role of basic science, and particularly of materials research and development, in this extraordinary chapter of electronics progress has been expertly reviewed by Linvill and Hogan (*18*). They show how the capabilities and styles of civilization have been influenced by the evolution of electronics derived from these materials properties. Earlier, Sir John Cockcroft noted in his address to the British Association for the Advancement of Science that without them, the exploration of outer space and the deployment of missile defenses would have been inconceivable. Thus, as in the chronicle of material ages in the past—the Bronze, and Iron, and the Steel ages—other opportunities for dramatic advances will be provided through substances and structures.

## Photonics

Indeed, I believe that another such era is already beginning. Functionally, it can be termed an epoch of photonics. It is primarily the descendant of the laser, which has stimulated a host of new optics and light energetics. And as lasers were made according to principles set forth by Charles Townes and Arthur Schawlow, materials science supported the various solid-state versions. Two spectacular materials developments are extending this field now. One is the glass fibers, which conduct photons thousands of times more efficiently than the clearest glass developed up to now. Thus, losses of 1 decibel or less per kilometer are ensured, commercially, at 0.8- and 1.3-$\mu$m wavelengths of the transmitted light. But the remarkable modified chemical vapor deposition synthesis of these lightguides has also resulted in superior mechanical qualities of the fibers. Single fibers with strengths of 800,000 pounds per square inch and higher are readily produced, with exceedingly uniform values for a large number of specimens. These materials properties may eventually enhance the practical use of fiber glass reinforcements in the large realm of composites. Already there is a pronounced effect on improved optics of fiber scopes for physiological, medical, and other instrumental inspection and, of course, for communications and instrumentation in aircraft, automobiles, and other vehicles, where light weight and freedom from electromagnetic interference are of special value.

Overall, the study and application of materials are in lively interaction with the other exciting frontiers of science and technology, ranging from biomedicine to nuclear structure. The challenging ways in which the many-body systems in solids can be related to the fundamentals of physics and chemistry—the fundamental principles of nature—have been elegantly expressed by Anderson (*19*). These concepts of what Anderson calls the "hierarchical structure of science" have guided much of the effort in our laboratories and others for more than four decades.

Thus we are convinced that such highly practical endeavors as materials technology will continue to be (in fact, will increasingly be) supported by strong science. Striking current advances in the basic concepts of disordered or amorphous matter provide good examples. For centuries, silica-derived glass was regarded as an indispensable but puzzling kind of witches' brew. Now, theoretical and experimental studies are being stimulated by the materials functions of glass fibers, although sheet glass has been the principal light transmitter for more than 3000 years. In other areas of amorphous structures, carbon has been curiously involved. Diamond is the quintessence of crystalline perfection. Graphite, noted for its crystalline anisotropy, is exploited in lubrication, as an electrode and resistor, as a neutron moderator, and in a host of other uses. But what lies between, in terms of somewhat cross-linked graphite or vastly disordered tetrahedral carbon, has again opened a variety of new systems. The use of graphite fiber reinforcements reflects remarkable hardness and strength. These apparently arise from nongraphitic properties characteristic of what might better be called polymer carbon, since the cross-linkage can readily be established by this macromolecular route (*20*).

These highly disordered states of matter round out our present perspective on advanced materials. Their hardness (surpassed only by that of the most refractory crystals), their corresponding high modulus of elasticity, their versatile electrical properties and response to electrical modification by doping are all symbolic of the opportunities which lead us into yet new ventures of materials synthesis and processing. High among these is our growing knowledge of surfaces, intrinsic in epitaxial processes but also applicable to a very wide range of new materials systems. Here the laser is repaying its debt to materials science and engineering by enabling a remarkable energy input. This is virtually exclusively to the electrons of an exposed surface, which then heat up the crystal or glass by electron-phonon collisions. [Yaffa (*21*) estimates that 1 electron volt of energy can go from electrons to atoms through a series of 20 electron-phonon collisions.]

Indeed, we see now, through pulsed laser energy inputs and the succeeding electronic excitation transformed to heat, ways of processing locally. This occurs especially in surfaces but also in tiny domains for a range of materials that is already producing new alloys, metastable mixtures, and extraordinary crystallite distributions. This may, indeed, turn out to be a step toward the specific internal motion control proposed earlier. In the surface of a silicon crystal, heat will appear in a region about 1 $\mu$m thick during a $10^{-8}$-second laser pulse of a typically 532-nm, frequency-doubled, Nd:YAG beam. It can be limited with pulses of 10 to 100 nanoseconds to depths of melting of 1 $\mu$m, and can then be quenched by the bulk surroundings at about $10^9$ K per second.

Work in this very active field is still at a rather early stage, with many conferences being organized internationally. But the point is that a new treatment of surfaces is adding still another process to the ever-widening frontiers of materials science and technology.

## Conclusion

In materials research, science is being related progressively to engineering, and a consistency of fundamental precepts and practical performance is emerging. Thus, with a per capita usage of about 10 tons of matter annually in the United States and with synthetic polymer production, in volume of matter, already greater than our total steel output, we can look forward to creating (with renewable materials, including biomass) extraordinary services of matter, from satellites to paperweights. The pattern of linking novel thought and useful practice as closely as they have been in the modern materials industry may itself be a major stimulus for progress in human affairs (*22*).


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