COMPLEXITY AND MATERIALS RESEARCH

In physics, simplicity has always been equated with beauty. Today in physics related to research in materials, however, a single broad trend is clear: The degree of complexity is increasing. This is evident not only in the structure of the materials but also in the techniques used for their characterization, in their synthesis and in their properties, which frequently need to satisfy diverse requirements. Our traditional metaphor, it appears, may need to be complemented with another observation: Complexity is seductive.

I cannot adequately present here the many examples that come to mind to illustrate the growing complexity of materials research. However, I shall take the canonical number, three, to suggest the many more:

▷ Recently discovered materials such as the quasicrystals, the high-temperature superconductors and the fullerenes are a subset of the notable examples of complex structures. The quasicrystals fill three-dimensional space with a symmetry totally unexpected a decade ago; the high-temperature superconductors, although made of simple layers, rely on complex bonding and charge transfer for their stability and their intriguing properties; and the newly unraveled structures of the fullerenes present yet another example of the surprising ways atoms can fill space and of the resulting unexpected behavior.

▷ Materials scientists are now deliberately producing complex structures or composites that have unique properties or whose uniqueness lies in possessing properties that simultaneously satisfy very diverse requirements. The length scale over which we are exercising control of material varies from the atomic level—as in understanding and using quantum phenomena in superlattices—to the micrometer level—for example, in producing a computer chip or the wing of a Stealth fighter. The practice of combining materials at all length scales to form composites is, of course, old hat to Nature—witness the tree or, for that matter, ourselves. To those of us in science, it is relatively new.

▷ My third example of complexity in materials research comes from the making or processing of materials, as in the manufacture of optical glass fibers or the "intelligent" processing of steel. The former will surely lead to remarkable new modes of communication and entertainment, and the latter is but one example of sensor- and computer-based processing of materials.

Materials research is unabashedly related to applications. This assertion does not apply to the fruits of research of any one individual investigator but does apply to the aggregate of our community. The twin themes of complexity and applications run through all five articles in this special issue.

In the first article, on page 24, James Langer touches on policy issues in materials research as well as, in his typically eloquent fashion, the strong and increasingly necessary interplay between science and engineering of materials. He uses pattern formation in metallurgy as an example. Dendrites are a commonly observed microstructural element in the growth of solids from vapor (snowflakes, for example) or from solution (as in the casting of metal). After decades of observation we still lack a full understanding of how the detailed microstructure, or pattern of crystal growth, of a dendrite develops. With the drive to develop more efficient processing of materials, however, it has become increasingly essential and even urgent to understand the parameters that control the microstructure. Jim's article also explicitly brings out the role of multidisciplinary research in solving problems related to materials, an aspect of materials research present implicitly in all of the articles.

The article on page 36, by Leroy Chang and Leo Esaki, is the first of two that describe artificially, or deliberately, structured materials. Esaki and his colleagues did not discover the properties of semiconductor superlattices accidentally. They anticipated many of the properties; the challenge was to build the materials. Using atom-by-atom deposition techniques they succeeded in growing multilayers with periods ranging from a few to tens of atom diameters. Their work was followed by that of many other groups, and as Chang and Esaki document, semiconductor superlattices, quantum lines and quantum dots are now the dominant field of research in semiconductor physics. Their article traces the inception of this field, the difficult materials issues, the fascinating phenomena and the potential for application.

Within the last decade or so, the field of superlattices has broadened from semiconductors to metals, insulators, polymers and their mixtures. Leo Falicov summarizes the properties of metallic magnetic superlattices in the article on page 46. As Leo notes, the superlattices have opened up an entirely new vista in quantum magnetism in solids and have exhibited a surprisingly large number of rich new phenomena with potential for application in a multibillion-dollar industry. For example, the coupling between magnetic layers separated by a nonmagnetic layer oscillates between ferro- and antiferromagnetic as the thickness of the nonmagnetic layer varies, and the period depends crucially on the roughness of the interfaces. These structures also show giant magnetoresistive effects and hence are potentially useful for magnetic storage applications, such as sensor heads. Leo's article touches as well on the essential interplay between advances in instrumentation and in equipment and progress in science.

Although human beings have only recently begun to grow superlattices, their existence in nature and concomitant anisotropic properties have been known for decades, even centuries. Mica is an example. About five years ago superconductivity was discovered in layered cuprates. The layering, or two-dimensionality, of these materials is believed to be essential for their superconductivity. Bernard Raveau, in the article on page 53, focuses not on the perfection of the layers but rather on the defects that are believed to be essential in controlling the transition temperature and the critical current density, two quantities of great interest to science and technology. Bernard's article reminds us rather forcefully of the important role defects in solids can play.

Scanning electron micrograph of a crack in an electron-beam weld of the single-crystal alloy PWA-1480, used for turbine blades, reveals dendrite growth along the preferred [100] direction. Weld solidification studies have important implications for the prediction of weld microstructures and the understanding of basic solidification phenomena.

The fifth and final article, by Eric Baer, Anne Hiltner and Roger Morgan, on page 60, takes us from inorganic to organic materials. Baer and associates show how Nature designs hierarchical structures to satisfy complex requirements in biological systems. Using these as a standard, they show how man-made composites are still primitive by comparison. They also discuss one of the outstanding problems limiting widespread commercial applications of polymer composites: the challenge of developing economical processing techniques that do not sacrifice the performance of materials.

These five articles barely touch the full spectrum of materials science and engineering activities. More can be found in the report of the National Research Council survey of the field, entitled "Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials" (1989), or in the summary of the regional follow-up meetings, entitled "A National Agenda in Materials Science and Engineering: Implementing the MS&E Report" and published by the Materials Research Society (1991). The NRC survey played an important role in defining this field to its practitioners and in delineating its importance to policymakers.

The significance of materials science and engineering to society is clear to Allan Bromley, the special assistant to the President on science and technology. Allan initiated and maintained a keen interest in the survey of this field that was carried out by many Federal agencies. This survey resulted in the Presidential Initiative on Advanced Materials and Processing announced early this year; it calls for roughly $160 million of additional support in fiscal year 1993. This Presidential initiative, like others before it, is a multiyear program, and we anticipate, but have no guarantee, that more money will be provided in subsequent years.

Two important policy issues concerning this field are worth raising:

▷ Knowledge migrates to and fro between the United States and the rest of the world, and within the United States between universities, government laboratories and industry. Most researchers in the US work, consciously or otherwise, on the premise that the bulk of knowledge is generated in this country and eventually diffuses to the rest of the world. This assertion was certainly true in the decades following World War II, but it is increasingly less valid today. No one country, the United States included, can explore and exploit the almost infinite number of possible ways of combining atoms to form structures with novel and desirable properties. Worldwide spending on materials research and, more significantly, publications in the research journals clearly show that our colleagues overseas are our equals. It is reasonable to assume that research abroad will continue to increase. From the standpoint of science this is only positive.

How should we respond to this changing environment? Asking for more money may be one answer. Using our money more effectively may be another. In particular, given the present computer and fax communication capabilities, it may make sense to seek international collaborations to, in effect, multiply the available resources. However, such collaboration will succeed only if the standards of research in US university and industrial laboratories are maintained at the highest level. Thus we must continally nurture these standards.

▷ The second policy issue relates to research at corporate laboratories. Many observers are concerned that with the decline of research and development funding in industry, US manufacturing is headed for trouble. One cannot debate this notion, for certainly at some point the mismatch between the expertise of the greater scientific community and the skills available within a single company can become so large that transfer of knowledge from the former to the latter is problematic. Are we at that stage? I do not believe so, but that does not mean we should wait until we get there. Most corporations have research laboratories to give them a competitive edge. If, however, knowledge is widely available, as it increasingly is, the notion of "captive" knowledge is increasingly obsolete, and along with it the assumptions on which the traditional corporate research laboratory operates.

How should we evolve? I do not know, but I do feel that we are in the midst of a paradigm shift, and we need to recognize this before we can change in a constructive manner. Changes in materials research, which is deeply concerned with both the generation and the use of knowledge, may well be a harbinger of the roles that university, industrial and government laboratories will play in the years to come.

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