Materials Education for the New Century

M.C. Flemings and S. Suresh

> Genius without education is like silver in the mine.
> —Benjamin Franklin, 1700s

Introduction

Practitioners of materials science and engineering receive their education in a wide range of academic departments and programs. At the undergraduate level, it is taught in schools of engineering, in departments with purely materials titles (e.g., "Materials Science and Engineering [MSE]," "Metallurgy and Materials Science," and "Ceramics"), and in departments in which materials is combined with another discipline (e.g., "Materials and Chemical Engineering"). Also included are materials programs and divisions housed in departments of other disciplines (e.g., "Mechanical Engineering"). At the graduate level, materials science and engineering is taught in the materials departments as just listed. It also comprises a part of the graduate program of most engineering departments, physics, chemistry, and now biology.

We concern ourselves in this article primarily with those materials departments which have a broad materials focus and an undergraduate as well as graduate academic program leading to the doctorate. We outline something of the historical development of these departments and describe the evolution of two subfields of materials, as specific examples, to better illustrate the development over time of the MSE paradigm (i.e., structure, processing, properties, performance, and their interrelationships). We present our views on how the curricula and character of these departments will evolve in light of technological, industrial, and social trends, and on how the rapidly evolving distance-education technologies will affect them. This article amplifies and extends three previously published related articles.[1–3]

From Metallurgy to MSE in U.S. Universities

Modern MSE departments initially evolved in the United States, mostly from older metallurgy departments, many of which had evolved in turn from mining departments. The materials departments at the University of Idaho and, until recently, of the University of California—Berkeley show this heritage with the retention of the words "mining" and "mineral engineering," respectively, in their titles. In the 1860s, precious metal and other nonferrous metal ore lodes were found in the Colorado and Utah Rocky Mountain region. By the 1880s, major iron ore deposits were being worked in Missouri and in the Lake Superior region. Extensive coal mining operations were under way in Pennsylvania. Additional major ore deposits continued to be discovered, and new mining companies formed, through the latter half of the 19th century. The demand for trained engineers to extract these ores and enrich them at or near the mine site was great.[4]

When the first engineering schools were formed, steelmaking was a fledgling industry, with less than 20,000 tons being produced annually in the United States. The Bessemer process was introduced to the United States in 1864, and then the open-hearth process in 1880, enabling vastly increased steel production. By the end of the century this production rate was to grow a thousandfold, to 22 million tons, to meet the needs of the burgeoning railroads and other rapidly growing industries.[5]

During this second half of the 19th century, markets were rapidly expanding for the steel being produced, and so driving the growth of the industry. Replacing brittle cast iron by steel for locomotive and rail applications helped make the "railroad mania" of this period possible. The first steel rails made in the United States were produced in Pennsylvania in 1867.[6] Design and construction of the Brooklyn Bridge began in 1867, ushering in the era of the suspension bridge. The construction of buildings with a steel skeleton frame began about 1890. With such applications came the need for improved properties and reliability, and so began the structure–processing–property–performance studies that form the basic paradigm of our field today.

The first practical electric generator was produced in Europe in 1860 and Thomas Edison invented his carbon filament electric light bulb in 1879. The ensuing growth of the electric industry provided new markets for metals, especially copper. Alexander Graham Bell's invention of the telephone was in 1876 and by 1888 there were 140,000 subscribers in the United States. Electrical energy, produced cheaply and in quantity, made possible new methods for metal refining, making possible the economic production of aluminum beginning in 1888 and of magnesium a few years later. By 1889, the teaching of "electrometallurgy" had entered the curriculum.

Ceramics seem to have received scant attention in these years from metallurgy/materials departments, and then only as a concomitant to metal processing. Glass and abrasives, where included, seem to have been treated as a product of interest to metallurgists. Of course, the markets for these materials were small compared to those for steel and other metals, and professsional opportunities abounded in the metals field.

During the first part of the 20th century, until at least 1929, new processes and exploding civilian markets resulted in continued rapid growth of metal-based industries. The age of the automobile arrived. Fifteen million model T automobiles were produced between 1908 and 1927. The invention and availability of the small electric motor at about the turn of the century made possible the many household appliances we now take for granted, such as the vacuum cleaner, the electric iron, the washing machine, and the refrigerator. The annual U.S. production of these small motors increased from zero at the turn of the century to five million by 1929. By 1929, refrigerators were being produced at the rate of a million per year. Aircraft production grew rapidly with the introduction of the Douglas DC3 in 1935. All of these products required large quantities of high-quality metals. Steel production increased from 22 million tons at the turn of the century to 62 million tons in 1929; copper production tripled in the same period, reaching one million tons, and aluminum production increased nearly 40 times, from 3000 tons in 1900 to 114,000 tons in 1929.[7]

The growth in markets for metals provided ample challenges and opportunities for metallurgy/mining departments. But the markets were not simply looking for volume at lowest cost, but strength, reliability, and other quality measures specific to the application as well. To better meet these needs, the science base of metallurgy now began to develop, with academic departments introducing subjects including thermodynamics, kinetics, structure, and structure–property relations. At the

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Massachusetts Institute of Technology (MIT), for example, four faculty members transferred into the department in the late 1920s and early 1930s from the School of Science, bringing with them fundamental approaches to microstructure, heat treatment, and x-ray-diffraction analysis. New challenges evolved from this more fundamental approach ranging, for example, from understanding and developing age hardening, following its discovery in aluminum-copper alloy in 1906, to dislocation studies, following their first observation in the electron microscope in the 1950s. Curriculum revisions resulted in new approaches to materials research and education, and in condensation and elimination of previously taught subject matter, and the dropping of research areas no longer relevant to the advanced industrial base of the day. There was no longer to be "nonferrous metallurgy" and "ferrous metallurgy" titles for major divisions or departments, but only "metallurgy." Mining had all but disappeared from the curriculum, and mineral beneficiation was soon to see its demise.

During the early 1900s, polymers were slowly making their debut. Celluloid and Bakelite had been available and employed since 1870 and 1907, respectively. By the 1930s many of the plastics now familiar to us were in production, including poly (vinyl chloride), poly(vinyl acetate), and polystyrene. By the end of the 1930s, U.S. annual production of plastic molding and extrusion materials had reached 118 million pounds.[8] Metallurgy departments did not incorporate these polymers into their teaching and research. The science underlying polymers seemed too different from that of metals. Analytical tools for the study of polymers were different. The markets for polymers were still small compared with those for metals, and professional and technical challenges and opportunities remained large in the metals field. The concept of materials science and engineering was not yet born.

The Second World War brought with it an explosion of interest in new metals and processes. Titanium, uranium, plutonium, and beryllium reached commercial production and occupied the attention of many metallurgists during this period. The years immediately after the war and well into the Cold War brought demand for high-performance aerospace materials including superalloys, titanium, aluminum, and magnesium. Vacuum melting, invented in 1947, increased rapidly. Steel production soared, as did aluminum production for building and packaging. Jobs for metallurgists were plentiful and high paying. Research opportunities were many.

> [We will see] the broadening coverage of materials science and engineering from classical processing–structure–properties–performance relationships in solid materials used in large volume to include such hitherto disconnected topics as biology, information technology, and systems engineering for materials used in small-volume applications.

There was still little incentive for metallurgy departments to look beyond their chosen arena of teaching and research.

Nonetheless, metals were not the only materials experiencing growth. By 1950, the annual production of plastic molding and extrusion materials had increased to 800 million pounds, nearly sevenfold from its pre-war maximum. New polymeric materials were coming on stream with regularity, such as Teflon in 1950, polycarbonate in 1953, and high-density polyethylene in 1955.[9] The invention of the transistor in 1948, the integrated circuit in 1958, and a plethora of other developments were to change the face of the world we live in and the professional and research opportunities in the materials field. A group of far-seeing scientists and engineers recognized in the early post-Second World War years what lay ahead and understood that many disciplines would contribute to this new materials age. A seminal step in the process was the establishment by the Advanced Research Projects Agency (ARPA) of the Department of Defense in 1959 of interdisciplinary research centers in materials. In these centers, metallurgists began to work collaboratively with engineers and scientists of other disciplines and in the process began to broaden their perceptions of what their own field could comprise.

Metallurgy departments, recognizing the new opportunities presented by the broader field of materials, and generally suffering from low undergraduate enrollments, began to change their names to incorporate materials in the title and to revise their curriculum to incorporate materials broadly. Northwestern University, the first to incorporate such a name change, did so in 1958. In 1959, a graduate degree program was established at The Pennsylvania State University in Solid State Technology, with the precept that "a new intellectual center of gravity was forming around the preparation, characterization and properties of matter."[10] Metallurgy departments from throughout the United States began to follow suit.

The transition from metallurgy to materials was not to prove an easy one for our field. It has been difficult to develop courses that teach underlying principles of materials broadly, as opposed to those relating to a particular materials class. Extending our structure–processing–property–performance paradigm to ceramics has been much easier for us than extending it to polymers. Our faculties have traditionally focused on structural materials, and the transition to functional materials has been difficult for many departments. Nonetheless, these departments have been doing what their forebears had also to do, that is, change to employ the advancing science and technology of the time, and to meet the industrial and societal needs of the time.

The early 1970s marked what was to prove a watershed for the materials field, with the development of integrated circuits containing in excess of 10,000 components per chip, the invention of optical fibers suitable for communication, and the explosion of electronic devices that would follow. Demand for materials-trained engineers by the electronic materials industry was already high and would increase over the ensuing decades, with development of an increasing array of "functional" materials. Meanwhile in the 1970s, developments in the structural field continued apace. Experimental applications for metal-matrix composites began. Kevlar™ fiber was introduced. Steel production and consumption entered a long period of decline. By 1979, the volume production of plastics exceeded that of steel.

The decades of the 1980s and 1990s brought new challenges to materials departments, familiar to many of us still practicing in the field. Important among them were the end of the Cold War and the resulting greater focus on civilian industry, the global economy, and questions of competitiveness, ecological issues including recycling and global warming, and developments in biomaterials. There is, in addition, the continuing rise of the information age, now including the Internet, with the implications this new age has for all aspects of materials science and engineering.

At the beginning of the 1970s, less than 50% of the metallurgy/mining departments in the United States had changed

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their names to contain materials in the title, and the vast majority of faculty members remained focused on metals. Two decades later, in 1990, 80% of the departments had done so, but of the roughly 1000 faculty members in such departments, 70% still had metallurgy as their primary research focus. Of the remaining 30%, 12% specialized in ceramics; 9% in polymers; and 9% in semiconducting, magnetic, or optical materials.[9] Today, nearly all of these departments have materials in their title, with the percentage of faculty members engaged primarily in research on metals continuing to decline. As has been discussed at length by Flemings and Cahn,[2] what these departments now do, after some 30 years of gestation, is appropriately considered a new academic discipline.

In Europe, the number and evolution of distinct materials departments is difficult to assess. In some European countries, academia is organized by institute rather than full departments, and several institutes may constitute what U.S. universities define as an MSE Department. Figure 1 illustrates materials-related institutes in German universities. In the United Kingdom, information is available on the number of research and non-research scientific degrees granted. Table I shows the number of degrees given in 1996/1997 in materials-related disciplines.

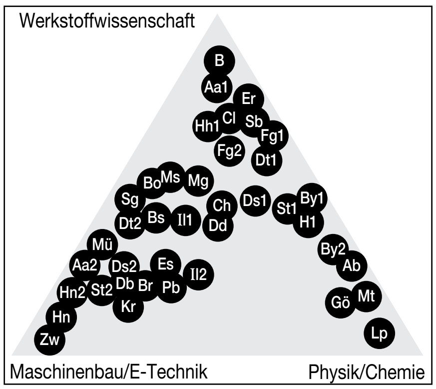

Figure 1. Diagram of materials-related institutes in German universities: Werkstoffwissenschaft *(materials science),* Maschinenbau/E-Technik *(mechanical and electrical engineering), and* Physik/Chemie *(physics and chemistry). The abbreviations inside the diagram represent the individual universities. Reproduced with permission from Deutsche Gesellschaft für Materialkunde, DGM-Aktuell, Oberursel, Germany, 1992.)*

An Evolutionary Example: The Development of Solidification Teaching and Research

Metal smelting, casting, and ingot making have their roots in the earliest days of metallurgy. Bronzes were being cast by at least the third millennium B.C. in Mesopotamia. A fully developed cast iron industry existed in China by the first millennium B.C., arriving in the West by A.D. 1400. In these times, and until the development of modern engineering universities in the mid-19th century, the processing of these cast materials was largely an art, kept as closely guarded secrets by guilds and later by companies.

By the beginning of the 20th century, simple heat flow theory was beginning to be used to help foundrymen understand better how to "riser" their castings to eliminate shrinkage porosity. With the invention of the microscope, some attention began to be given by researchers to cast microstructures. Macrostructure was, however, of greater early practical interest, especially with the finding in the early 1900s that steel structural failures were occurring as a result of ingot macrosegregation. By the 1930s, radiography was beginning to be employed in commercial production of highest quality castings, shedding new light on macroscopic aspects of castings and their solidification behavior.

The war years and immediate postwar years brought renewed interest to microstructural aspects of solidification. The emergence of aerospace as a major industry brought with it a great need for stronger, more reliable airframe structural materials, and for improved high-temperature engine alloys. Microstructural understanding and microstructural control were correctly seen as keys to achieving these goals.

During the 1960s, vacuum casting and pouring of reactive alloys became a growth enterprise, and by the late 1960s continuous casting was entering industrial consciousness, soon to largely replace conventional steel ingot casting. So, research and teaching began to incorporate these new processes. Modern transport phenomena (heat flow, fluid flow, mass-transport analyses) were brought to bear on the casting process to understand and better control microscopic and macroscopic processes.

Another industry was developing rapidly in the 1960s and 1970s that involved solidification from a melt—that of semiconductor single-crystal growing. At first, the chasm between "plane front" crystal growth of a semiconductor melt and dendritic solidification of a metal seemed large indeed. However, it soon became apparent that at a sufficiently fundamental level, the processes were closely similar, and the engineering prac-

Table I: Number of Degrees Granted in the United Kingdom, 1996/1997.*

Courses	Doctorate Degree Mainly by Research	Master's Degree Mainly by Research	Master's Degree not Mainly by Research	Postgraduate Diploma or Certificate	Postgraduate Diploma or Certificate, Mainly by Research	First Degree (Bachelor's)
Minerals technology	21	7	83	4	0	128
Metallurgy	110	10	21	1	34	69
Ceramics and glasses	10	1	13	0	0	34
Polymers and textiles	23	3	97	13	0	839
Other materials technology	74	32	69	156	0	369

*Extracted from Table 2 in Reference 2; data were originally supplied by the Society for Research into Higher Education, London, by agreement with the Higher Education Statistics Agency, UK.

tice of one could benefit greatly by the understanding of the other. Now well-understood phenomena including constitutional supercooling, melt convection, grain multiplication, and dendritic growth mechanisms were beginning to be studied both by those from the point of view of the crystal grower and that of the metal caster.

In later years we were to see the applicability of solidification fundamentals to other materials and other industries. The casting of ceramic bricks, and of ceramic abrasive materials are examples. Glass fiber drawing and glass molding are another. Polymer crystallization and polymer casting, which we still see as a little removed, are gradually becoming a part of the domain we solidifiers like to consider our own, at least with respect to its structure–processing–property–performance aspects.

Today the focus of solidification research continues its shift. Computer modeling of microscopic and macroscopic processes occupies a vitally important role, both for process control and for our fundamental understanding. New materials provide new challenges for solidification researchers: high-temperature superconductors and bulk glassy metals, to mention two. New instruments let us make experimental measurements on time scales and size scales not dreamed possible only a few years ago. New processes provide not only new challenges, but also new windows on solidification. These new processes include strip casting, atomization, and solidification of nanostructures.

Thus, over the past 50 years the foundry and ingot casting industries have changed dramatically, with much growth and excellent employment opportunities in segments of the industries. Meanwhile other industries, with new processes, and often wholly different materials, have sprung up that have at their core many of the same materials fundamentals as does the foundry industry.

How should those of us in materials departments prepare our students for such industries? And for similar industries yet to be born? How should we decide what sort of research we should do to contribute to such industries? The chemical engineer might answer, by concentrating on our core expertise of transport properties, kinetics, and systems. The mechanical engineer might answer, by concentrating on design, manufacturing, and systems. As materials scientists and engineers, our answer today is by focusing on structure–processing–property–performance, and the system that comprises their interrelationship, one with each of the others.

> With the large-scale retirement of scientists and engineers trained in such disciplines as plutonium and beryllium metallurgy, there is a dearth of new and young talent available for future leadership roles in many areas of nuclear and environmental safety, which critically depend on classical metallurgy and materials science/engineering training.

An Evolutionary Example: Teaching and Research in the Area of Mechanical Behavior of Materials

The need to design against the failure of metallic materials used in such applications as hoist chains in the mining industry, rolling stock axles, rails and iron bridges in railway systems, and wire ropes and propeller shafts in the marine industry served as a major catalyst for probing into the mechanical properties of materials as far back as the mid-1800s.[11] During that time, the primary practitioners of this branch of study were mechanical, mining, and civil engineers, as the concepts of material microstructures and their effects on mechanical properties had not been fully developed. In fact, it was believed, as noted from a study commissioned in 1849 by the British Institution of Mechanical Engineers, that the repeated application of stresses led to the "crystallization" of a metal which, in turn, was postulated to be a precursor to cracking. This so-called "crystallization theory" of damage under repeated stresses was disproved convincingly in the very early 1900s by Alfred Ewing and co-workers. These British metallurgists documented the evolution of slip bands in many grains of a polycrystalline specimen of Swedish iron which was subjected to repeated loads; these slip bands served as the precursors to dominant cracks (see reference 11 for details). Mechanical properties of materials were not primary topics of coverage, although subjects dealing with the mechanics and mechanical integrity of structures were taught in civil and mechanical engineering curricula.

Interest in the study of mechanical properties of materials, in general, and research specifically into the effects of microscopic deformation mechanisms on the overall mechanical response began to surge precipitously in the early decades of the 20th century because of many major developments. By the first decade of the 20th century, elasticity theory of dislocations was a well-developed topic studied by solid mechanicians and applied mathematicians. The notion that the true strength of a material could be substantially smaller than its theoretical strength as a natural consequence of the existence of dislocations led to considerable research into defect theory. Concomitant with this viewpoint, there emerged numerous theoretical and experimental studies aimed at increasing the strength of materials by obstructing the motion of dislocations during mechanical deformation, through control of the underlying microstructure. The strategy here was to manipulate such factors as composition, heat treatment, grain size and texture, and precipitate and particle dispersion and reinforcements for optimizing strength and ductility. Associated with these developments there emerged a closer link between the "schools of science" and "schools of engineering." Advances in x-ray diffraction also led to developments in the characterization of the structure and internal stresses in materials.

The invention of the transmission electron microscope in the 1950s and the ensuing capabilities to directly observe dislocations and other defects in thin foils made from deformed materials provided experimental confirmation of many previously developed mechanistic models and theories. These new tools for probing the microstructure-mechanical property connection also led to a rapid rise in fundamental research into the micromechanisms of deformation during the post-Second World War years. The ready availability of hardness testers provided a useful tool for the "local" mechanical characterization of structural metals.

The chief focus of such fundamental research in mechanical metallurgy primarily centered around ferrous microstructures, in response to the rapid growth in the automotive industry and steel industry, which was spurred by the expansion of the highway infrastructure. The introduction of long-distance commercial jet travel beginning in the 1950s also led to the realization that mechanical integrity of the airframe structures was vital to the success of this increasingly popular mode of transportation. This realization was an outcome of several disastrous accidents involving the first commercial jet aircraft, The Comet. Consequently, the mechanical metallurgy of nonferrous metals, particularly aluminum and nickel-base superalloys, for airframe and engine applications, respectively, became topics of research efforts. This period also saw the onset of substantial interest in nonmetallic structural materials, such as engineering plastics and ceramics. Although primarily focused on metallurgy, many materials teaching programs comprised faculty members whose main research efforts were aimed at nonmetallic materials.

The 1960s produced major advances in the means by which mechanical properties were investigated, due to the emergence of three powerful "characterization" tools: the finite element method, the field of fracture mechanics, and the scanning electron microscope. The finite element method provided the flexibility to simulate deformation and failure processes in real structures with complex geometries and stress states, with a flexibility that was hitherto impossible to achieve through analytical means alone. The widespread availability of mainframe computers in the early 1970s dramatically broadened the scope of the finite element method to include studies of the micromechanics of materials. The implementation of fracture-mechanics methodologies for damage-tolerant design of structures in such safety-critical applications as commercial aircraft and nuclear reactors also introduced sophisticated mathematical concepts in the design and maintenance of "inherently flawed," real engineering structures. The advent of the scanning electron microscope facilitated the study, at high magnifications, of the micromechanisms of deformation, damage, and failure in bulk metallic and nonmetallic materials.

Until the 1970s, the principal focus of research on mechanical properties centered around structural materials. With the enormous growth of the microelectronics industry commencing in the 1970s, conventional concepts emerging from classical mechanical metallurgy were immediately transferred into functional applications. The characterization of stresses in thin films by monitoring the changes in the substrate curvature (where the analysis most widely used in the semiconductor industry even today is one predicated upon the mechanics model of G.G. Stoney in 1909) is an example of conventional concepts of structural mechanics applied to functional materials. The means of controlling defects, such as dislocations, and their consequences on optical and electronic properties are topics of major concern in the fabrication and characterization of layered and graded materials used in optoelectronic devices. In this situation, analyses predicated upon on conventional dislocation theories, appropriately modified to account for the strained-layer epitaxial systems, provide the foundation for scientific enquiry and practical design. In the study of reliability of metal interconnects in microelectronics circuitry, classical mechanical metallurgy concepts involving such phenomena as grain growth, texture, and stress voiding play a central role. Mechanical properties of materials and mechanics of defects in materials contribute coursework and research topics in essentially every engineering department and division, including bioengineering.

Technological Trends

The jobs in which MSE graduates find themselves depend in part on their university and region, but many, perhaps most, are taking jobs in greatly different industries than did their predecessors of a few decades ago. Many of the companies urgently needing materials technologists today did not exist 20 years ago. Companies, which were major recruiters then, are now taking on fewer materials graduates. Some companies have fallen on hard times. Others, for example, primary and secondary metal producers, have found that they need fewer individuals with a classical metallurgy or materials education, but more individuals skilled in advanced technologies including modeling, sensing and control, and information technologies. A survey of where graduates of MSE departments find employment would be of much interest to curriculum planners.

On the basis of the foregoing discussions, it is possible to identify some distinct trends that are likely to have a major impact on education and research in materials science and engineering in the decades to come. Perhaps most importantly, the rapidly growing importance of the information technologies is resulting in a shift of emphasis in materials education and research from structural materials and properties to functional materials and properties. The shift is clearly evident in student interest, enrollment statistics, government funding, and the founding or closing of new journals. A result is the broadening coverage of materials science and engineering from classical processing–structure–properties–performance relationships in solid materials used in large volume to include such hitherto disconnected topics as biology, information technology, and systems engineering for materials used in small-volume applications. This shift has precipitated a rapid "realignment of knowledge" in materials education and research, whose pace is likely to accelerate in the years to come.[12]

The integration among seemingly distant disciplines, where materials technologies play a critical role, is likely to accelerate. Examples include (1) materials development for drug delivery devices; (2) tissue engineering; (3) *in situ* monitoring and control of defects and cracks in such structural applications as highways, bridges, airport runways, ship hulls, or wings of aircraft; (4) more efficient access to materials data for the purpose of online quality control in production lines or by designers through the use of web-based materials data banks with live feedback and updates; and (5) the development of new materials based on classical metallurgy principles for use in novel and hitherto unforeseen applications.

Advances in computer hardware and software and the broad availability of inexpensive and powerful computers are expected to accelerate the role of computational materials science and engineering in education and research. These advances are also expected to facilitate systematic studies of processing, properties, and performance, spanning the atomistic, microstructural, and continuum size scales with a flexibility and precision that cannot be achieved through experiments alone. (Of course, the development of such computational tools inevitably requires systematic experiments for calibration and verification.)

Recent advances in distance education technologies have generated unprecedented opportunities for global collaboration and live interactions in materials education and research. This trend is expected to accelerate in the decades to come. A desirable by-product of this technology is the possibility that students who take up industry or government positions would, as a routine part of their professional development, be able to periodically upgrade their skills through participation in virtual classrooms.

Despite the seemingly rapid move away from structural materials, it is also apparent that the scientific and technological impact of classical metallurgy and materials science, rooted in the study of structural metals and alloys, is likely to continue in the decades to come on various accounts. The fundamental concepts rooted in classical metallurgy and materials science, such as equilibrium thermodynamics, kinetics, phase transformations, transport theory, micromechanics of deformation and failure, and defect theory, also have significant importance in many materials employed in a broad array of functional applications. Just a few of many examples include (1) grain growth in thin films;

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(2) the role of threading/misfit dislocations in influencing the performance of quantum wells and optoelectronic properties in strained-layer, graded heteroepitaxial structures; (3) micromechanical and nanomechanical studies of thin-film and small-volume properties by such methods as microindentation and nanoindentation; (4) studies of processing, characterization, and phase stability of functional coatings in microelectronics, optical devices, solid-oxide fuel cells, and magnetic storage media; (5) the characterization of stresses in multilayered thin films and flat-panel displays by recourse to x-ray diffraction, substrate curvature measurements, and indentation; and (6) processing of nanostructures and devices. These functional applications inevitably require a solid foundation for students and researchers in the traditional concepts of metallurgy and materials science, in addition to an awareness of the fundamentals in related disciplines, such as physics and chemistry.

With the end of the Cold War, there is a growing need to ensure that nuclear and radioactive materials used in mass-destruction weapons are properly destroyed, stored, or disposed of. With the large-scale retirement of scientists and engineers trained in such disciplines as plutonium and beryllium metallurgy, there is a dearth of new and young talent available for future leadership roles in many areas of nuclear and environmental safety, which critically depend on classical metallurgy and materials science/engineering training.

Many branches of the public infrastructure, such as national highways, commercial aircraft, and nuclear reactors (which were built during the growth period spanning the 1950s to the 1970s), have approached or exceeded their useful design lives. The continued use of this basic infrastructure, or its costly replacement or repair, will inevitably require, over the coming decades, large numbers of materials engineers trained in structural properties. In addition, in the United States, such factors as the projected increase in the population over the coming decades and the rapid rise in commercial air travel (especially over the Pacific Ocean) would inevitably generate large demands for innovation in structural materials technology, with a concomitant demand for materials engineers.

Innovations in structural materials technologies also have major implications for the large-scale production of functional devices. An example is the recent development and widespread commercialization of magnesium alloy and titanium alloy cases for lightweight laptop computers and sub-notebooks. Here, advances in the processing and mechanical performance of magnesium alloys, with such desirable properties as low density, affordable cost, amenability to large-scale manufacture, abrasion resistance, high strength, and impact resistance, have made a variety of laptop computers more portable and popular than just a few years ago. Such innovations in structural materials are expected to continue in the development of components for personal digital assistants and cellular phones, with advances in the processing and mechanical properties of polymers, ceramics, metals, and composites.

> With globalization of science, engineering, and industry, and with developing information technologies, distance collaborations in education and research become possible, and perhaps necessary for our materials departments of the future.

Miniaturization continues to offer numerous possibilities for innovations in materials science and technology in areas such as microelectronics, microelectromechanical systems (MEMS), nanoelectromechanical systems (NEMS), and biology. Consider, for example, the rapid pace of technology in microelectronics. Aluminum and copper metal interconnect lines used in integrated circuits made in the year 2001 can carry electric current densities of 8×10^5 A/cm^2 at 105°C. By comparison, electrical wiring used in residential buildings typically carry current densities of 100 A/cm^2; bulk metal wires would melt from Joule heating when made to carry current densities of 10^4 A/cm^2. The Si substrate, on which thin metal lines are patterned into current-carrying lines in an integrated circuit, serves as a good heatsink. By the year 2008, the total length of interconnect lines per computer chip is expected to rise to 9 km, and the feature size is expected to diminish down to 70 nm, with a concomitant increase in the current density carried by the metal interconnect lines to values as high as 2.1×10^6 A/cm^2 at 105°C. Miniaturization also facilitates faster computing speeds. The Pentium IV microprocessor fabricated in the year 2001 has 42 million transistors and is capable of executing 17 billion instructions per second. Intel Corp. announced recently[13] that it has successfully fabricated, on an experimental scale, Si transistors as small as 25 nm in width and 1 nm in thickness, using novel processing methods that employ the same materials used in existing microprocessors and memory chips. If this technology becomes amenable to mass production, ultra-tiny devices capable of switching on and off some 1.5 trillion times a second and microprocessors with speeds as high as 20 GHz with one billion transistors could be synthesized. These advances also offer new challenges in understanding and predicting mechanical phenomena such as stress evolution and nanomechanics of deformation and failure at critical locations of microelectronic devices and packages, and coupled electrical-mechanical effects such as electromigration (which is the current-induced biased self-diffusion of metal atoms that can lead to circuit failure by material extrusion or void formation).

Educational Opportunities in the Decades Ahead

With globalization of science, engineering, and industry, and with developing information technologies, distance collaborations in education and research become possible, and perhaps necessary for our materials departments of the future. Advances in computer hardware and software, the widespread availability of powerful and inexpensive computers, and the growing worldwide use of the Internet have facilitated unprecedented opportunities for global interactions in research and education in materials science and engineering. Many academic institutions, particularly those in the Western world, have for many years made use of distance teaching by employing traditional videoconferencing capabilities involving live and taped lectures. In the materials science and engineering field, examples include classes taught to students from industry who are enrolled in the University of Maryland and Stanford University, and the alliances MIT has established with overseas universities including the National University of Singapore, the Nanyang Technological University of Singapore, and Cambridge University in the United Kingdom.

Today, new technological developments are permitting more ambitious undertakings. These include developments in video streaming; data compression; broad-band transmission; web-based chat rooms; instant electronic display whiteboards; and high-speed, noncommercial communication channels (i.e., Internet II). With the rapid advances in

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communication technology, it is likely that students and researchers participating in distant learning will be able to collaborate in joint research projects whereby control and monitoring of experiments (such as imaging in the transmission electron microscope or the nanoindentation of a thin film on a substrate) are achieved in real time from a distant location. It is anticipated that such collaborations among international and national organizations, as well as between academia and industry, would increase substantially as high-speed, broad-band communication technologies become common and affordable in the next several years.

The lessons of the past, the present status, and the research opportunities outlined in this article mark a clear path for future curriculum development in materials departments. We cannot predict what will be the best professional opportunities for our students in the future, nor can we predict for certain which industries will provide the best potential for them. We cannot predict which materials class will provide the important new products of the future, nor do we wish to. It is no longer necessary to do so, with the disciplinary base we now have.

We can, however, be confident that the central paradigm of our discipline, structure–processing–properties–performance (Figure 2) will provide students with the foundation for a productive career in a changing environment. With that paradigm, we can find our own unique way of contributing to newly evolving fields, such as that of biotechnology, that looms so large in front of us. The paradigm covers the spectrum from the basic science to the industrial application and so allows for ample leeway for students to pursue their own bent, and for the field to evolve with the times. It covers the range of "structural" to "functional" materials, and so allows the emphasis of the curriculum to shift with the times, as has been necessary through the entire history of materials/metallurgy departments. Recognizing that the "performance" aspect of the paradigm includes economic and social cost, the paradigm encompasses design, manufacturing, and environmental issues. The interrelationships of the four aspects of the paradigm encompass the systems engineering of our field.

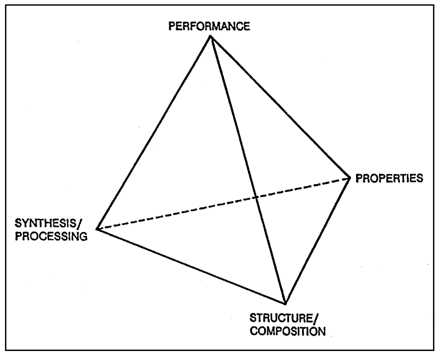

Figure 2. The four elements of materials science and engineering.[9]

Some will say that such a curriculum as proposed is too abstract, too removed from industrial practice. They see a real danger. It is one to be countered by employing industrial practice as examples of applications of the broad principles taught, as well as by exposing students directly to industrial practice. Some may also feel that a curriculum designed this way neglects the traditional industries that have heretofore been the backbone of our field. To the contrary, our departments will attract a larger, stronger body of students, better able to serve the traditional as well as the emerging industries. To put the matter more starkly, the survival at all of many departments will depend on their degree of broadening within the MSE paradigm.

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***Merton C. Flemings** is Toyota Professor Emeritus of Materials Processing and the director of the Lemelson-MIT Program at the Massachusetts Institute of Technology (MIT). His research group focuses on the broad field of solidification and solidification processing, including casting, composite materials, crystal growing, ingot solidification, rapid solidification, continuous casting, and semi-solid processing. Flemings received his ScD degree from MIT in 1954 where he later joined the faculty and headed the Department of Materials Science and Engineering from 1982 to 1995. He co-chaired the National Materials Study for the National Academy of Sciences in the late 1980s. Among his numerous honors and awards is the Materials Research Society 1997 David Turnbull Lectureship for outstanding contributions to understanding materials phenomena and properties through research, writing, and lecturing.*

***Subra Suresh**, R.P. Simmons Professor of Materials Science and Engineering, heads the Department of Materials Science and Engineering at the Massachusetts Institute of Technology. His research addresses theoretical and experimental studies of the mechanical properties of materials. He received his ScD degree at MIT, then, prior to joining the faculty, he was an assistant research engineer at the University of California—Berkeley and a professor of engineering at Brown University.*

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