Instrumentation for materials research

Techniques such as scanning and transmission electron microscopy, Auger spectroscopy, ESCA and others help us to relate the composition and structure of a material to its performance in a desired application.

Richard S. Claassen

Materials, energy and knowledge together comprise the three basic elements of all industrial activity. Materials as a field of endeavor is not a unified discipline in the traditional sense but is, rather, interdisciplinary, involving several traditional disciplines. The science and technology of materials application have established a community of interest and common purpose for a wide variety of activities, including a significant portion of physics.

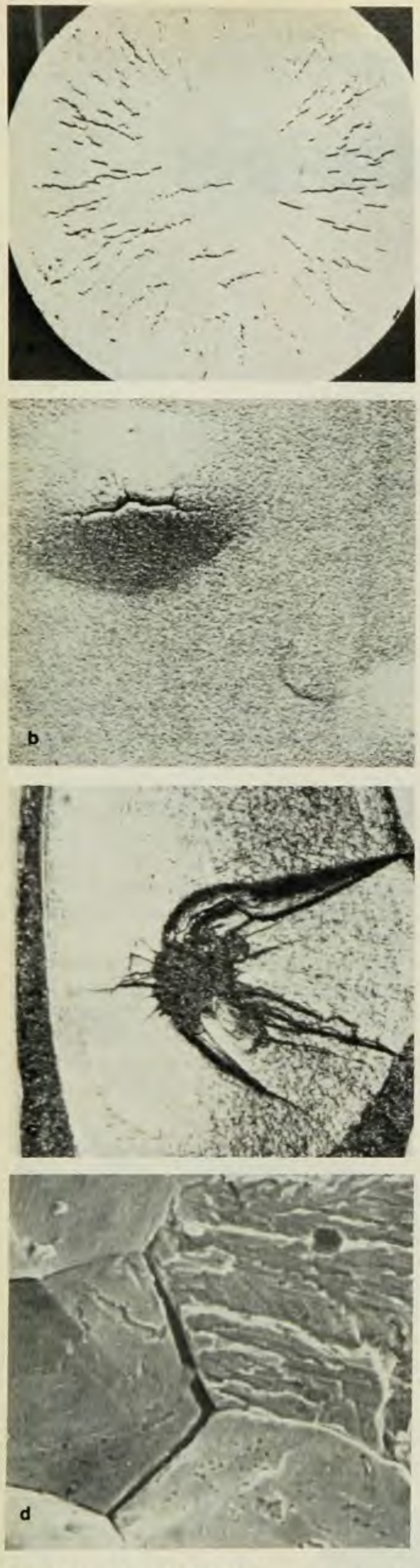
One factor in the evolution toward a materials field is the general advance in the entire field of science. Our deeper, more detailed insight into the physical phenomena that control gross behavior has provided broad unifying concepts applicable to many different materials. As a result, we are in a transition from a body of experience associated with one commodity at a time (say, ferrous metallurgy) to a knowledge of performance needs of the user (for example, specific tensile strength, or fracture toughness); to put it another way, we are moving from a supplier base (steel) to a user orientation (structure).

Physics has played a central role in this evolution, first, through new concepts of the behavior of materials at the microscopic level, and second, through the development of a variety of instruments and instrumental techniques that provide precise information at that level. The boundary between physics and materials is not sharply drawn. For the purposes of this article, a useful definition is the one developed by COSMAT (the Committee for the Survey of Materials Science and Engineering, formed under the aegis of the National Academy of Sciences). This committee's definition[1] is: "Materials are substances having properties which make them useful in machines, structures, devices, and products." My emphasis here will, therefore, be on engineering materials, or the *application* of materials for some purpose. Semiconductor materials and their application to solid-state devices, familiar to most physicists, provide a natural industrial target for the concepts and instruments of physics. Although they are less familiar to many physicists, I will be emphasizing the *commercially* important materials such as metals, glasses and polymers.

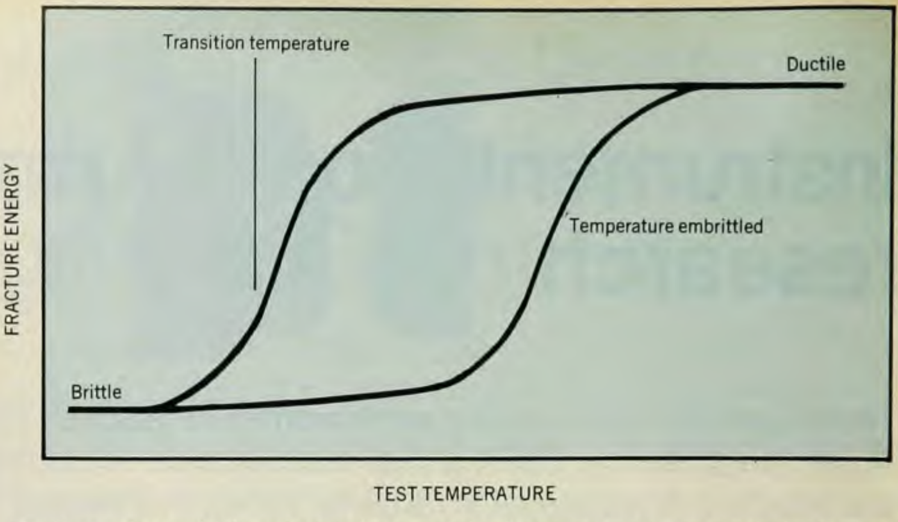
Because the application of sophisticated instruments to the study of materials is so extensive, I can describe only a small sample here. I have chosen three typical problems: fracture analysis, joining and compatibility. My intent with these examples is to show how sophisticated instrumentation techniques yield practical results in materials application.

Other articles in this issue discuss crystallography—the foundation for materials development—and ion-beam analysis—a productive combination of classical nuclear physics and practical material questions. The evolution of the

Transmission electron microscope picture of a titanate ceramic waste containing simulated fission products and actinides. The beam can easily be focussed to 0.1 micron to analyze individual crystallites for structure by electron diffraction and for composition by energy-dispersive x-ray analysis in sections less than 0.1 micron thick. Figure 1



Three failure modes in steel with a common origin. Parts a, b and c are optical photographs, approximately full size, of defects referred to as "blisters," "flakes" and "fisheyes," respectively. Part d is a scanning electron microscope picture at 3750X magnification of a hydrogen embrittlement fracture in plain carbon steel. The transverse cracks at the grain boundaries are characteristic of hydrogen embrittlement and are now known to exist in blisters, flakes and fisheyes. (Sources in reference 2.) Figure 2



Low-temperature embrittlement of steel as revealed by the fracture energy in a standardized impact test (Charpy V-notch) at various test temperatures. The left curve is representative of body-centered-cubic metals, which, below some characteristic temperature, lack thermal energy to assist plastic flow at defects. Some steel alloys, when held at temperatures of 375 to 550 deg C, experience a considerable rise in the brittle transition temperature, as illustrated by the curve on the right (labeled "Temperature embrittled"). Figure 3

instrumental capabilities of lasers to novel material processing techniques is described in the final article.

The central theme of materials development is the relationship of composition and structure to performance. This relationship can be understood only if instruments of high sensitivity, high resolution, and specific response are available to determine the key factors of composition and structure. My few selected examples will illustrate that only recently have adequate techniques become available to relate performance to composition and structure in many commercial materials.

Although a single instrument is highlighted for each example, investigations normally involve a variety of instruments to aid in interpretation. Electron microscopy is almost universal; both the transmission electron microscope (figure 1) and, increasingly, the scanning electron microscope have become the workhorses of the material scientists.

Fracture phenomena

The study of fracture surfaces is almost as old as steel making itself. By its very nature, fractography tends to deal with unsatisfactory performance; but, historically, it has provided some measure of process control in the melting of steel and other alloys. The "habit" of the fracture (that is, whether it is intergranular or transgranular) as well as gross defects and the texture resulting from mechanical working, can be determined optically. Such visual inspection of fractures could distinguish what were thought to be several types of crack initiation sites variously termed "blisters," "flakes," "fisheyes," "checks," "freckles" and "stringers." The scanning electron microscope, with its great depth of field and high resolution, has provided sufficient detail to reveal that some of these names refer in fact to the same fundamental phenomenon. That the first three terms are manifestations of hydrogen embrittlement (hydrogen-assisted crack growth) is indicated in figure 2.

Although optical fractography can reveal the grain size and shape of an embrittlement fracture surface, we need instruments sensitive to free elements if we are to determine the exact cause of fracture. I will illustrate this requirement in the following discussion of temper embrittlement, thermal embrittlement of maraging steels and oxygen embrittlement of refractory metals.

Temper embrittlement has been a serious problem in low-alloy steels prepared by air cooling (normalizing) from the austenite phase (face-centered cubic iron). Cementite (Fe_3C) is precipitated in lamellar form in ferrite (body-centered cubic iron), producing a pearlite structure with grain boundaries retained from the austenite phase (prior austenite grains). It has been known for decades that holding some steels of this type at elevated temperatures, say 375 to 500°C, for a period of time, could lead to "embrittlement," that is, loss of ductility at lower temperatures (see figure 3). It had been shown in the last century that arsenic, antimony and tin impurities in steel could lead to a brittle fracture characterized by bright crystalline faces. The exact nature of the embrittlement remained unknown, however; as recently as 1959, it was stated that, "In particular, no evidence has been found for any intergranular film or for any precipitation processed in the grain boundary region."[3] Since that time,

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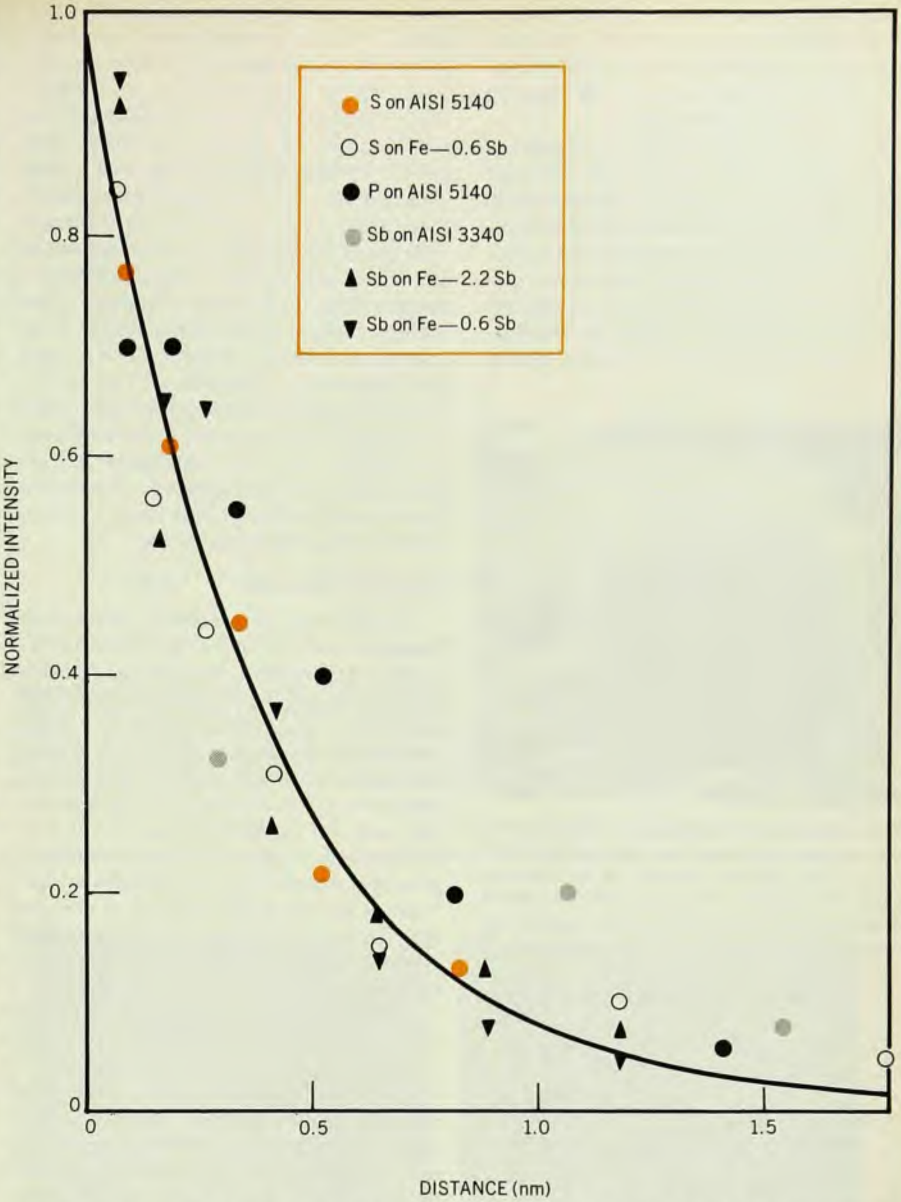
Auger electron spectroscopy, secondary-ion mass spectroscopy, field-ion microscopy and ion backscattering have all been used to identify with precision the segregation of minor impurities to grain boundaries (the prior austenite grains) following suitable thermal history.

Harris Marcus and Paul Palmberg[4] used Auger electron spectroscopy to measure concentration of elements on embrittled and unembrittled samples fractured in high vacuum. The steel was a modified AISI 3340 (0.38 C, 1.69 Cr, 3.5 Ni, 0.066 Sb)—a medium carbon steel with alloys added to control kinetics of phase transformation in large sections. Although the antimony was below detection limits in the body of the control sample, it was readily measured on the surface of the embrittled samples. Argon sputtering with Auger electron spectroscopy showed that the antimony was strongly segregated to within approximately 10 Å of the surface. Figure 4 is a composite of segregation measurements of sulfur, phosphorus and antimony made during these investigations.

Maraging steel (from "*mar*tensite *aging*") is an alloy designed to transform during slow cooling to martensite (in this case a fine-grained bcc) to achieve (after aging) yield strengths in excess of 200 000 psi while maintaining substantial fracture toughness. When forged in large enough sections, the cooling rate at the interior is sufficiently slow to cause embrittlement. As recently as 1971, David Kalish and Henry Rack[6] were unable to identify the precise cause of this embrittlement. The likely candidates appeared to be TiC or TiN precipitation, but selected area diffraction studies with a transmission electron microscope were unable to determine which of the two was the causative agent, because the difference in the lattice spacing was less than the resolution of the instrument. In 1973, Bill Johnson and Dale Stein[7] reported a definitive identification by Auger electron spectroscopy of titanium carbide as the segregant at the grain boundary, a finding that correlates with this embrittlement phenomenon. The titanium concentration at the grain boundary of a suitably aged specimen fractured in vacuum was more than fifteen times that in the bulk. Using inert ion sputtering, Johnson and Stein found the concentration to drop off rapidly with depth, with an effective thickness of about 200 Å.



Normalized Auger electron intensities from segregated antimony, sulfur and phosphorus as a function of material removed from grain-boundary fracture surfaces by argon-ion sputtering. A sputter yield of unity is assumed, and the black curve is drawn for an exponential with a characteristic depth of 0.45 mm. (Data of H. L. Marcus and P. W. Palmberg, reference 5.) Figure 4

D. A. Smith and G. D. W. Smith[8] studied embrittlement in tungsten by comparing wire specimens that had been heated to 1300°C for six hours in high vacuum with specimens that had been similarly heated in 10^{-5} torr of oxygen. The vacuum-annealed samples retained high ductility, whereas those exposed to oxygen became extremely brittle. They used a field-ion microscope to study the boundary region between grains. Characteristic bright image spots associated with an oxygen solute in tungsten were the basis for an estimate of 0.12 monolayer of oxygen in the grain boundary of the brittle specimens annealed in oxygen compared with about 0.004 monolayer of oxygen in the ductile samples annealed in vacuum. No wonder it has taken so long to identify the precise cause of these embrittlement phenomena!

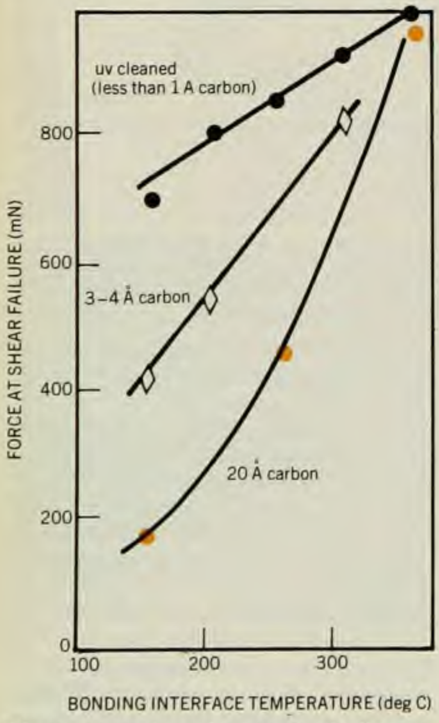
What is the practical importance of such knowledge? Small alloy additions to the steel may be used to tie up chemically, or to immobilize, the offending embrittlement impurity, just as aluminum is used to tie up oxygen in steels. Recently we have learned that some embrittlement processes in low alloy steels have incubation time constants of several years—and it is these very alloys that are being selected for use in supposedly high-reliability components such as rotors and pressure vessels. Only a detailed understanding of the pertinent mechanisms involved can guarantee long life without failure.

The concepts of fracture mechanics, which originated in glass technology, have been highly developed for metals and are again being applied to glass and ceramics. Bob Eagan has found that fracture toughness (the resistance to propagation of an existing crack) of borosilicate glass increases about 50% as the ratio of boron oxide to sodium oxide increases from 0 to 0.75 in a glass of composition $(40 - x)$ $Na_2O \cdot xB_2O_3 \cdot 60SiO_2$. Morton Milberg and his coworkers[9] have used nuclear magnetic resonance to show that this same ratio of boron to sodium determines the boron coordination to oxygen. For ratios greater than 2, the fraction of boron atoms in fourfold coordination is equal to the reciprocal of B/Na and there are essentially no nonbridging oxygen atoms.

When the ratio is less than 2, the fraction of nonbridging oxygen atoms increases. Further work may relate fracture toughness to the completeness of the oxygen lattice in borosilicate glass.

Fracture toughness is just as important in plastics as it is in metals, but different diagnostic techniques are appropriate in determining the underlying mechanisms. Jacob Schaefer[10] has used the latest advances in pulsed nuclear magnetic resonance to study the relation of impact strength in glassy polymers to nuclear-spin relaxation times of carbon atoms, both in the main chains and in the cross links. To achieve assignment of a resonance line to a chemically unique carbon, very narrow line resolution is needed. Such resolution is accomplished by a combination of sample spinning and strong hydrogen decoupling with cross polarization. The rotating frame relaxation times ($T_{1\rho}$) of C^{13} contain information about the motions of the polymers in the 10–50 kHz region, comparable to response times under impact loading. The cross polarization relaxation times (T_{CH}) contain information about motion at very low frequency. The ratio of T_{CH} to $T_{1\rho}$ for protonated carbons in the main chain of each polymer turns out to have a direct correlation with the toughness for all seven polymers investigated. Faster relaxation in the 10–50 kHz range is associated with greater toughness.

Scanning electron micrograph of a microsphere on the surface of a hot crack of a weld in Ni 200 alloy. The sphere diameter is 50 microns. Note the dendritic structure indicative of the thermodynamic conditions when the sphere was formed. (Reference 12.) Figure 5



Effect of organic surface contamination on strength of thermocompression ball bonds of 25-micron diameter gold wire bonded to gold–chromium metallization. The effective carbon thickness of the organic layer on the substrate metallization before bonding was determined at ambient temperature by Auger electron spectroscopy. (J. L. Jellison, ref. 15.) Figure 6

Joining of materials

Joining is an ever-present problem in the application of materials, because virtually every product, structure and device requires the joining of similar or dissimilar materials. In most designs the joint controls the mechanical behavior. By its very nature, the weld, bond or adhesive is much more complex than the bulk material, and our understanding of it is less satisfactory. Supported by a wealth of practical experience, detailed investigations of joining with a variety of new instrumental techniques have provided guidelines for the solution of practical problems.

Fusion welds are essential to the steel industry, which accounted for about 97% of all metals smelted in the US in 1973.[11] The conditions of solidification for fusion welds and their complex thermomechanical histories often result in extreme heterogeneities, in both composition and microstructure, on a scale unresolvable by classical analytic techniques. The scanning electron microscope is now a powerful aid in weld analyses. Grain and phase boundaries and the morphology of inclusions, precipitates, pores, and microcracks are routinely examined by this technique. It permits definition of many details that could not be examined by the earlier transmission electron microscope. For example Carl Lundin and Robert Bennett[12] in a diagnostic scanning-electron-microscope examination of weld cracks in nickel-200 alloy, observed microspheres exhibiting dendritic structure (see figure 5). These microspheres, which could not be replicated for examination in transmission because of the sharp reentrant angles at their base, are evidence of hot cracking, a separation that occurs during late stages of solidification. The scanning electron microscope operating as a microprobe (for analysis of characteristic fluorescence) revealed that the chemical composition of the microsphere was significantly different from the cracked surface. A definitive model for the thermodynamics and kinetics at the critical time of cracking has not yet been developed.

The Mössbauer-effect backscattering method has been useful in the study of phases in stainless-steel welds. The high-temperature, nonmagnetic, austenitic form of iron is retained at low temperatures by iron nickel-chromium alloys; the ferritic structure may also occur, depending on exact composition. In fusion welds, a suitable proportion of the ferrite has a beneficial effect (for instance, resistance to cracking in heavy sections) on the physical and mechanical properties of the stainless-steel weld. The magnetic properties of ferrite cause line broadening of the 14-keV gamma rays from Co^{57}. Lydon Schwartzendruber and his colleagues[13] have used the Mössbauer technique to make quantitative measurements of the ferrite content for a group of test samples, thereby providing a standard for the more readily applied "Magna-Gage" (a simple device to measure magnetic susceptibility).

In contrast to fusion welds where melting is involved, solid phase welds are achieved by bringing metal surfaces sufficiently close together to engage short-range interatomic forces. Obviously, thin films could constitute a barrier; but without adequate instrumentation, identification of barriers remained uncertain. For example, in the case of gold-to-gold bonding, oxygen and water were once incorrectly identified as the important barrier films.[14] Recently, Auger electron spectroscopy has shown that adsorbed organic films are the more common barriers to solid-phase welding of the gold used in microcircuits.[15] Carbon layers a few angstroms thick cause significant bond degradation (figure 6) and account for the strong dependence on bonding temperature usually observed. Sure knowledge of the organic nature of the bond barrier led to development of an ozone cleaning procedure to ensure reliable bonds.[15]

Joining glass to metal to form seals is a common industrial practice. The approach is to make the thermal expansion coefficient to the bulk glass equal to or slightly lower than that of the metal so that the glass boundary will be in compression. The most common problem is fracture at the interface associated with tensile stress in the glass. A good seal requires dissolution of the metal oxide in the glass, but the dissolved metal changes the thermal expansion coefficient of the glass. To study this problem, Joseph Pask and his coworkers[16] have used an electron microprobe in a quantitative determination of the distribution of the metal oxides in the glass within the first 200 microns of the metal surface. The system studied was a sodium disilicate glass with cobalt oxide sealed to iron. Cliff Ballard has used this information to formulate bulk quantities of a disilicate glass in which the iron and cobalt oxide concentration is the same as found at various distances across the interface. The aim is to measure thermal expansion coefficients, and thus provide guidance for a modification of the glass formulation to achieve the desired expansion coefficient with metal oxides in solution.

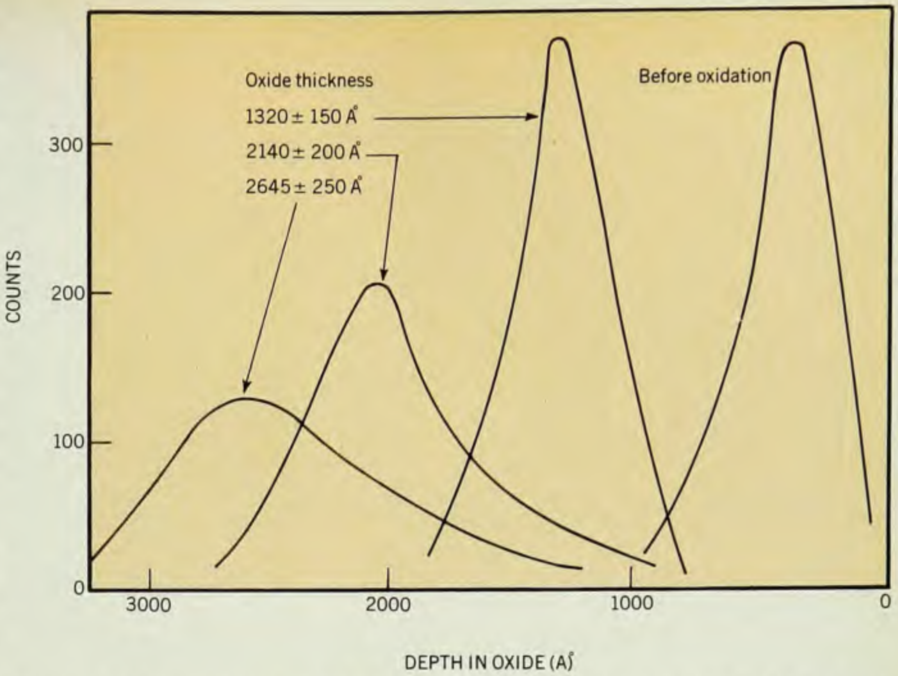
Adhesion of polyethylene and other nonpolar polymers to bonding resins is generally poor but it can be improved markedly by etching in chromic acid ($K_2Cr_2O_7$:H_2O:H_2SO_4). Dave Briggs and his colleagues[17] have used x-ray photoelectron spectroscopy (also called "electron spectroscopy for chemical analysis" or ESCA) to determine the chemical nature of the improved bonding. The sensitivity of the binding energy of the core electrons to the valence states, as measured in this technique, allowed semiquantitative identification of several polar groups near the polyethylene surface after etching: $-SO_3H$, $-COOH$, $C{=}O$ and $C{-}OH$. The relatively low polarity of 5% oxidation gave a thirteenfold increase in adhesion.

Compatibility

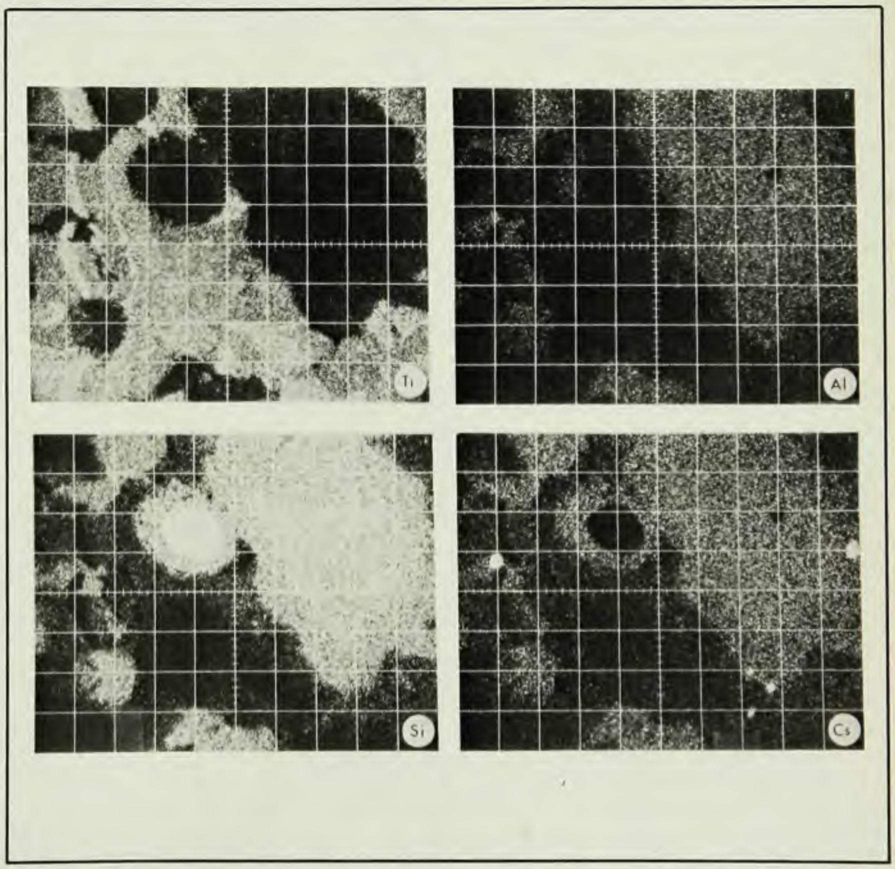
The term "compatibility" can be used to mean the ability of two or more materials to remain together in a device or system without degradation of the intended function. Clearly an important requirement in critical applications where high reliability is required (say, military designs), it is also significant in large energy systems where safety is essential over long periods. Compatibility studies aim to eliminate any unexpected degradation by development of a detailed understanding of the ways in which materials may interact.

One very common problem is corrosion, either chemical or electrochemical in nature; interdiffusion or adsorption are sometimes problems. There are particular sensitivities, such as the embrittlement of metals by hydrogen, the embrittlement of plastics by certain solvents, and the sensitivity of many materials to chloride ions in water. Ideally, compatibility studies should be performed before the fact as the following four examples show, but they often involve technical detective work as the final example demonstrates.

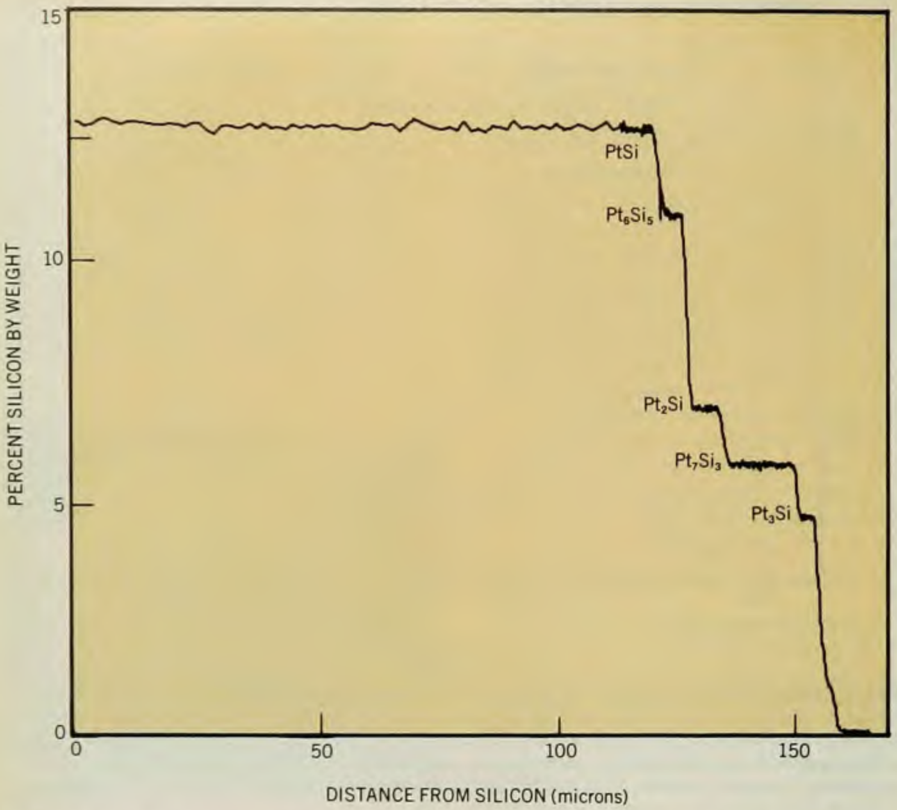
Investigators at Chalk River and Harwell have used ion backscattering to study the basic mechanisms in the oxidation of aluminum. Geoffrey Dearnaley and his coworkers[18] implanted impurities of different electronegativity to a depth of 400 Å in separate aluminum samples prior to oxidation. Adjacent unimplanted areas provided a reference. Porous oxide films of various thicknesses were formed by anodic growth in a 2% oxalic-acid solution. Ion backscattering provided a convenient, sensitive, measurement of the depth distribution of the impurity atoms and of the oxide thickness. Bismuth, tin, lead and



Gold impurity profiles in a porous Al_2O_3 film at successive stages of growth of the oxide as determined by backscattering of 2.90-MeV helium ions. 10^{15} gold atoms per cm^2 were implanted in aluminum prior to anodic oxidation in a 2% oxalic-acid solution. Comparable profiles for krypton and bismuth are markedly different, reflecting the influence of valence of the impurity on transport properties. (From C. Towler, R. A. Collins and G. Dearnaley, reference 18.) Figure 7



Electron microprobe scans of the identical section of titanate ceramic waste form showing four elements. The grid size is 50 microns. Top left: titanium. The most dense areas are TiO_2, the remaining, a mixture of waste compounds. Top right: aluminum. This is aluminum in alumina-silicate from the zeolite. Bottom left: silicon. The bright spot is metallic silicon from an original particle added to avoid formation of water-soluble Cs_2MoO_4. Bottom right: cesium. One of the difficult radioactive species, cesium appears to correlate with aluminum and silicon in alumina-silicate, where it is tightly bound. Figure 8



Quantitative electron microprobe scan across a silicon–platinum junction following 96 hours at 700 deg C. The dominant compound is PtSi at this temperature. At temperatures below 575 deg C, Pt_2Si is the dominant compound. The details of kinetics for each intermetallic must be taken into account in making a life prediction. Figure 9

thallium (with higher valency than aluminum) were shown to be most effective in enhancing oxygen uptake, and gold, copper, chromium and silver (with lower valency) most effective in reducing the rate. That the motion of the impurity was clearly followed is illustrated for gold in figure 7, where it can be seen that the gold moves inward with the growth of oxide. The results are consistent with the oxide behaving as an n-type semiconductor, with electron transport being the rate-determining factor.

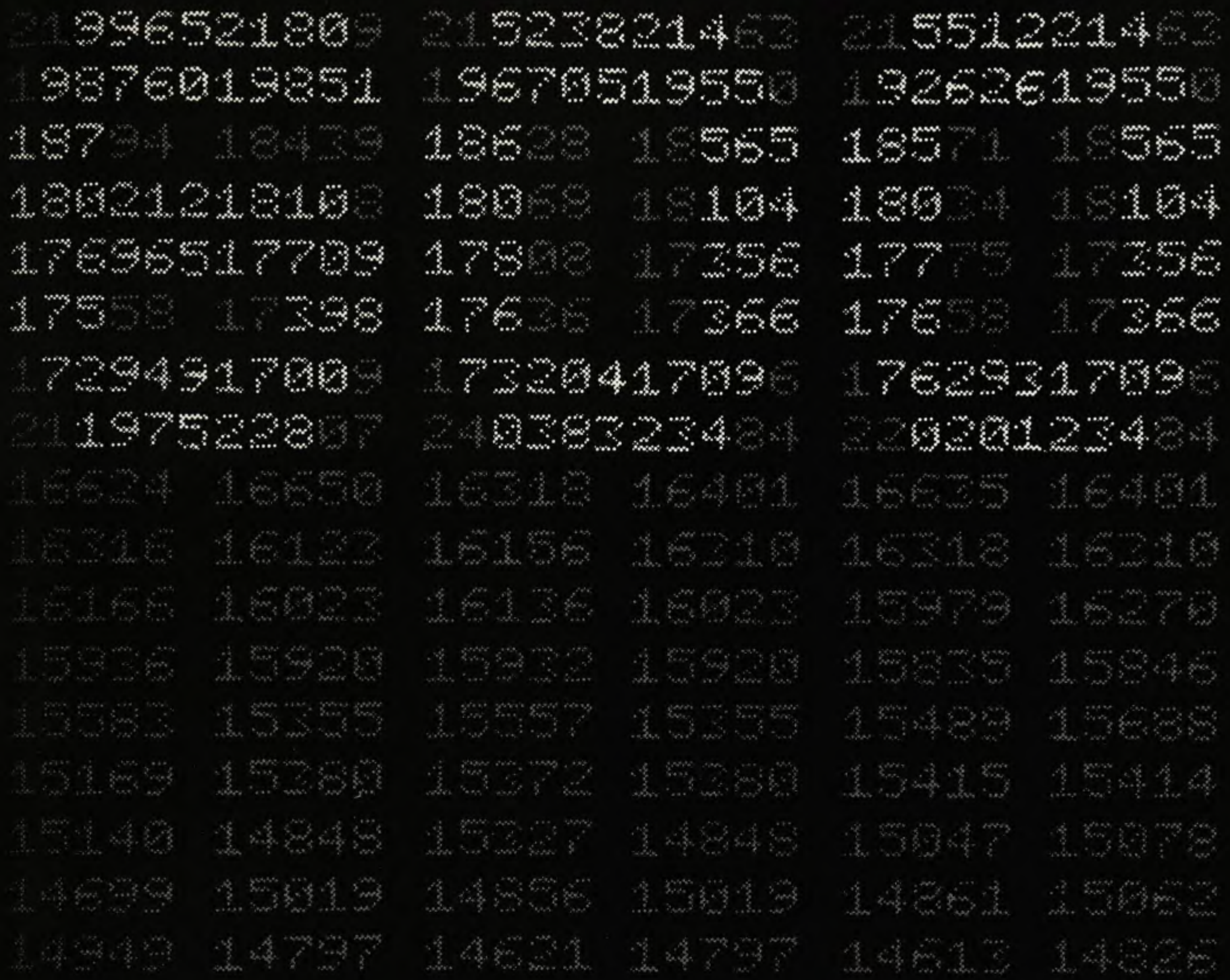
The same backscattering technique may prove helpful in studying the hot corrosion of the nickel- or cobalt-based superalloys used for turbine blades. Although the alloys develop a protective oxide layer, under certain operating conditions sulfur diffuses through the oxide to form a brittle layer of metallic sulfide leading to spallation of the protective layer. The precise mechanism for transport is not well characterized.

Stainless-steel surfaces subjected to high temperatures in a vacuum lose their corrosion resistance. To find out why this is so, Ron Musket and Walter Bauer[19] have used the technique of proton-induced x rays to study the depletion of chromium in 304L stainless steel (19%-Cr, 10%-Ni, 1.5%-Mn, <1%-Si, <0.05%-P, <0.03%-C, <0.03%-S by weight). They probed the first half micrometer of the surface with 200-keV protons. Above 1250 K annealing temperature, the ratio of Cr($K\alpha$) to Fe($K\alpha$) x rays drops sharply. When the same stainless steel is exposed to 1200 K in air, a chromium-oxide layer, resistant to corrosion, forms. The thickness of the oxide can also be determined from the proton-induced x rays. Detailed studies such as these may help reduce pressure on scarce supplies of chromium by showing the way to create an adequately rich chromium surface layer even though the bulk content is reduced.

The final disposal of radioactive wastes from the reprocessing of nuclear fuels requires a scheme that will prevent entry of radioactive elements into the biosphere. Bob Dosch has developed a system that would tie up the radioactive elements chemically and physically in a ceramic, where they would be virtually inert to air or water environments.[20] Before committing this (or any other system) to use, susceptibility to corrosion, leaching and radioactive damage must be determined. One step towards this goal is the determination of the structure, phases and compounds of the ceramic with the aid of the scanning microprobe and transmission electron microscope. Sample runs of simulated liquid waste were passed through a sodium-titanate ion-exchange column with interspersed silicon, and then through a synthetic zeolite column specific to cesium. Following the capture of all cations, the columns were thoroughly blended and hot-pressed at a temperature of 1100°C and a pressure of 13.8 MPa for ten minutes to form a dense stable ceramic. Figure 8 shows four microprobe elemental scans of the identical area of a polished section of the ceramic. Together with similar scans of other elements, these displays furnish considerable qualitative information about the ceramic body. More detailed information is available in figure 1 where a transmission electron microphotograph reveals the variety of titanates formed in the process of stabilizing approximately thirty different radioactive elements present in spent reactor fuel. Only a few titanates, such as strontium and uranium titanate, have been previously studied in any detail with regard to structure, stability, and other important properties. While the full characterization of such a material is obviously a tedious process, it would be virtually impossible without powerful analytical tools such as the electron microscope. With this instrument, it is possible to perform both diffraction and elemental analyses on the individual crystallites shown in figure 1. Thus the electron microscope is an essential ingredient in understanding some of the important features of radioactive waste not only when it is first formed but also following transmutation and associated chemical change.

The scanning electron microprobe can also be used to infer chemical compounds by electronic counting and standardized corrections to determine relative quantities. For example, the thermopile for a small thermoelectric generator is constructed of alternate bars of p and n type SiGe (80% Si) diffusion bonded at the hot and cold ends with platinum. One of the compatibility questions is whether that bond will deteriorate during long life at the hot shoe temperature; diffusion of silicon into the platinum could occur to the extent that Kirkendall voids would cause mechanical failure. To investigate the interdiffusion of the intermetallics, thermocouples of SiPt that had been exposed to various temperatures and times were sectioned and analyzed on the scanning microprobe by Bill Chambers. As figure 9 shows, the major intermetallic at 700°C is PtSi, but below 575°C it is Pt_2Si. A simple high-temperature accelerated test, therefore, will not predict service life at 350°C; however, an analysis of the various compound kinetics as a function of temperature can provide essential information for the prediction of long life performance on the basis of short-term experiments.

One prototype of a heliostat mirror for the solar energy program was fabricated by attaching a cadmium-plated steel focusing plate to the mirror with a silicon rubber adhesive that contained an ester-blocking agent derived from acetic acid (acetoxy). A simulation exposure of such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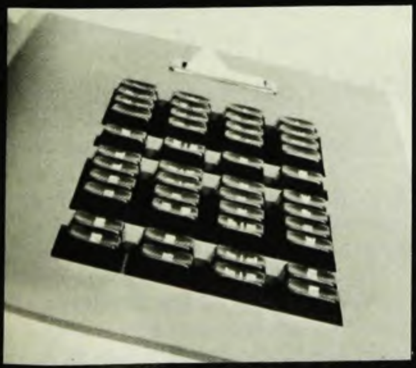


a mirror to high humidity showed that corrosion occurred in the cadmium plating, raising the question of identification of the corrosion products. A mass spectrometer provided the only definitive identification, but gas chromatography is often a preliminary step in such detective work. The complex spectrum was completely accounted for by cadmium acetate, molecular weight 230. In hindsight, it is easy to predict the incompatibility between cadmium and the acetic acid evolved by the curing acetoxy-blocked silicone rubber. The value of this work, however, is that it also provided an opportunity to assess the severity of the problem, to describe the degradation process and to suggest alternative materials.

Opportunities

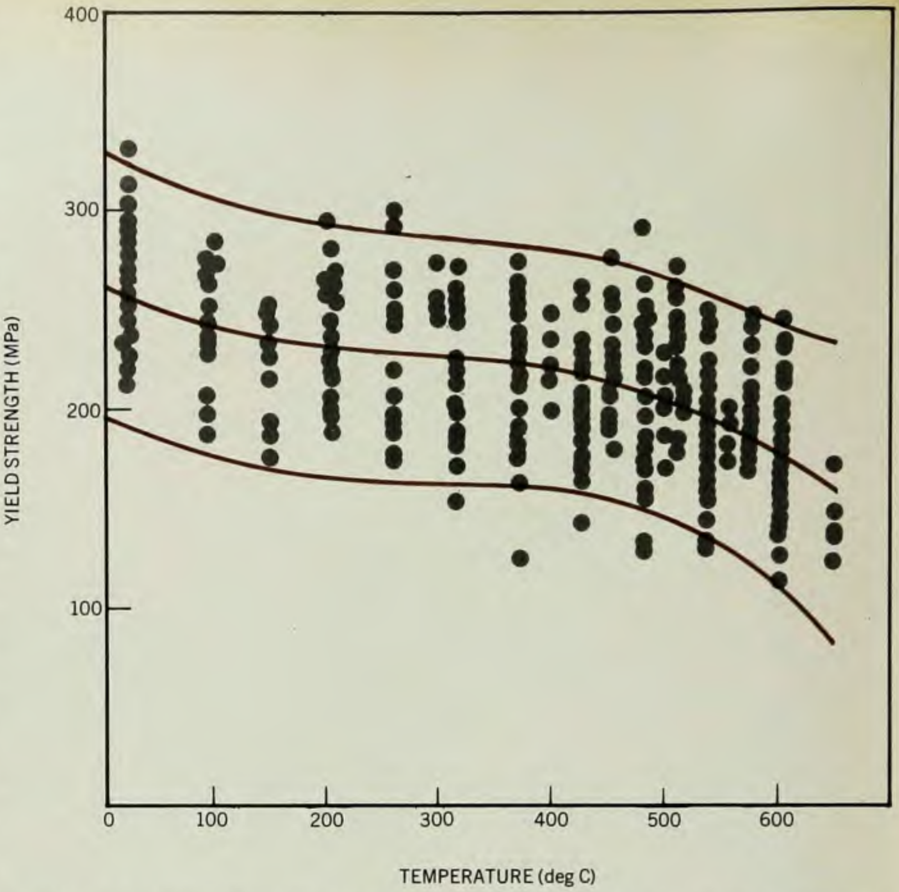
The contribution of instruments and instrumental techniques to the field of materials has already been great, but remaining opportunities are even greater. Although little can be said about solutions, it is easy to list a few examples of serious problems in the materials field.

Variations in the properties of steel from one furnace batch (heat) to another can be very large, as figure 10 shows[21] for the alloy tested ($2\frac{1}{4}$ chrome–1 Mo steel). This alloy has been proposed for the pressure vessels in the liquid-metal fast-breeder reactor. Because of the wide variation in mechanical properties, the designer can utilize only 60% of the maximum strength obtainable with the best practical composition and process. Obviously, closer control would result in considerable material saving.

The role of impurities and inclusions in determining the properties of practical interest, such as strength, formability and weldability, are known generally; the challenge, however, is the development of instruments and theories that can characterize the *collective* influence of a multitude of elements in steel, so as to allow the control of important parameters during volume production. This problem will increase in importance as the continued recycling of materials increases the variety of impurities found in processed steels.

Ceramics are made from readily obtainable raw materials, are resistant to high temperatures and corrosive environment and, therefore, hold great promise for various applications in the energy program. Because ceramics do not blunt crack tips by plastic flow, we need a method of detecting extremely small flaws in structural members. Appropriate techniques would greatly facilitate the increased use of ceramics.

Shear-induced crystallization kinetics are of first importance in the manufacturing process for aromatic polyamide fibers which undergo oriented crystallization during spinning and thereby achieve very high strength. The phenomenon is not understood, partially for lack of appropriate instrumentation.



Yield strength at various temperatures for $2\frac{1}{4}$ Cr–1 Mo steel (annealed) from many sources (from reference 21). The designer can only use the lower limits. If all heats could be held above the present median, 30% less material would be required; new instrumentation techniques may help us reach this objective. Figure 10

Some of the most exciting research in biomaterials is at the interface between liquid and solids, where we lack the sophisticated array of instruments comparable to those that have been developed for studying vacuum–solid boundaries.

Although a number of new instruments have had a profound effect on the development and application of materials, instrumentation by itself does not solve problems. Concepts, often from the field of physics, are needed to guide and interpret the more sensitive and detailed measurements. In the world of engineering materials, we also need a comprehensive knowledge of practical experience so as to relate idealized experiments to real applications, in which gross impurities or thermal mechanical history may dominate the determination of material performance.

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Materials-related employment opportunities

In the May 1976 issue, PHYSICS TODAY, at the suggestion of and with help from the APS Professional Concerns Committee, began the occasional practice of listing employers in the field covered by an article to assist readers interested in jobs in that field. Because work on materials is almost universal in manufacturing industry, it is not realistic to attempt to list employers here. We felt it would be useful, however, to point out that there are many areas, in organizations responsible for materials development and application, where a physicist equipped with a good understanding of fundamentals and with the capability to learn new instrumentation techniques and the willingness to understand practical problems could make important contributions. Here are just a few examples:

Nondestructive testing
- Acoustic emission
- Acoustic microscopy
- Neutron radiography
- Ion surface analysis

Ceramics and glasses
- Electrical properties
  Breakdown; charge-transport mechanisms
- Optical properties
- Thermophysical properties
- Bonding to metals
- Mass transport in relation to corrosion and cracking

Materials preparation and processing
- Crystal growth for electronic properties
- Molecular-beam epitaxy
- Castings—solidification
  Nucleation: thermal transport on crystallographic axes
- Thermodynamics, phase relations
  Heat transfer; Multiphase flow and energy transfer
- Laser tools
  Surface treatments (eg, glazing); joining; milling

Corrosion
- Chemical composition at surface on atomic scale
- Kinetics of transport of passivating elements to surface

Radiation damage and transmutation
- Influence of voids, interstitials, impurities, on metallurgical properties
- Synergistic effects

High-voltage, high-power insulators
- Breakdown mechanisms in nanosecond regime
- Surface flashover
- Polymer aging

Joining
- Surface states influencing cleaning
- Role of fluxes
- Physical-chemical nature of bond
- Microstructure in fusion region

Coatings
- Nucleation of growth
- Unique surface compounds
- Characterization of physical deposition parameters

Polymers
- Structural parts
  Domain growth and morphology; thermal properties; viscoelastic properties
- Molding
  Rheology
- Seals
  Diffusion; solubility
- Biomaterials
  Mechanical and electrical properties; surface reactions *in vivo*

Composites
- Suppression of defects in intermetallic fiber production
- Solid-state interaction at fiber-matrix interface

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