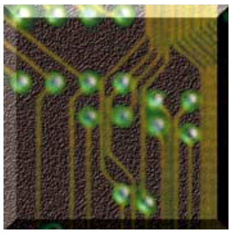

Advanced Materials: Challenges and Opportunities

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New materials, or new ways of using and combining existing materials, are being required to meet tomorrow's engineering applications. This need is compounded by pressures to stay competitive by keeping costs reasonable while continuing to make new material technologies available to our APL customers. The main challenges created by today's environment include the understanding and assimilation of the rapid technological advances being made by industry, the integration and application of these advances to APL customer needs, and preparation for the next set of requirements and applications made possible by maintaining a leading technical edge. The Technical Services Department is helping APL and its customers apply advanced material technology by providing a comprehensive central resource for material synthesis, fabrication, integration, characterization, and inspection. (Keywords: Characterization, Fabrication, Integration, Materials, Reliability, Synthesis.)

INTRODUCTION

Although many inventions represent innovative design concepts, it is the materials and the advanced processes of making and combining materials that increasingly help turn these concepts into reality. The ability to quickly and reliably lay down multiple conductive layers with ultrafine resolution has led to the miniaturization and low cost of most microelectronic components. Consider, for example, computers that used to take up an entire room and cost hundreds of thousands of dollars that have been replaced by inexpensive handheld calculators. Also, the advent and continued development of synthetic fibers have led to low-cost clothing and bulletproof vests. The combination of fibers with advanced polymer resins (modern-day composite materials) has resulted in dent-resistant automotive panels, lightweight fighter aircraft, and golf clubs with tailored flexibility. Things that could not even be conceived of a few decades ago are becoming a reality owing to the advances being made in materials.

Just keeping track of the new materials, processes, and resulting commercial products is time-consuming. In addition to the selection and integration of these technologies into new concepts and devices, the assessment of how their insertion into existing engineering applications affects overall performance can require considerable capability and capital resources. The Laboratory's Technical Services Department (TSD) offers a multidisciplinary staff with a comprehensive set of engineering tools to meet the expanding material needs of APL staff and its customers. This broad-based central resource (Table 1) spans the entire field of materials

Table 1. Summary of materials-related development, testing, and analysis resources within TSD's Engineering, Design, and Fabrication area.

Resources	Capabilities
Microelectronic characterization	Wire bond pull testing Die and ball shear testing Ionic contamination analysis Particle impact detection
Mechanical characterization	Quasi-static testing Fatigue testing Strain data acquisition Hardness testing (Rockwell, Brinell, Micro) Paint/adhesive bond pull testing
Chemical analysis	Fourier transform infrared spectrometry Phosphorimetry Gas chromotograph with mass spectrometry Inductively coupled plasma mass spectrometry Atomic emission spectrometry Energy-dispersive X-ray spectroscopy High-pressure liquid chromotography Capillary ion electrophoresis Secondary ion mass spectrometry
Thermal analysis	Quartz dilatometry Thermogravimetric analysis Differential scanning calorimetry Dynamic mechanical analysis Stress rheometry Temperature/humidity conditioning Temperature/vacuum conditioning Temperature/vacuum outgas testing
Metal fabrication	Standard and computer-numerically-controlled (CNC) machining Electrical discharge machining (EDM) wire cutting Welding/riveting Sheet metal Plating
Composites fabrication	Wet lay-up and repair Autoclave cure Polymer molding Spin casting Adhesive bonding Fused deposition molding (rapid prototyping) Tape wrapping Compression molding Resin injection Vacuum forming
Microelectronics fabrication	Multichip module (MCM) substrate fabrication (MCM-C, -D, -L) Gold and aluminum wirebonding Eutectic and epoxy chip attach Semi-automated surface-mount technology assembly Hand and machine soldering Printed circuit board (PCB) and rigid-flex fabrication
Nondestructive evaluation	Ultrasonic C-scan and acoustic microscopy Liquid penetrant testing Paint thickness testing Eddy current testing Film-based X ray
Failure analysis and microscopic evaluation	Scanning electron microscopy Optical microscopy/metallography Digital image capture Quantitative image analysis

from synthesis, fabrication, and integration to characterization, inspection, and failure analysis.

CHALLENGES IN THE NEW MILLENIUM

The Defense Advanced Research Projects Agency recently publicly acknowledged what has been long recognized by many—new material insertion "is a time consuming and costly endeavor … typically taking 15–20 years if it is successful at all."[1] Although various branches of the military have historically led this advance in the United States, their ability to do so has been hampered by declining defense budgets.

Since 1987, the total DoD budget has declined nearly 50%; its Research, Development, Test, and Evaluation portion has decreased 25% in that same period and is projected to lose another 10% by the year 2005.[2] The defense community, APL's traditional and largest customer, is being driven to sustain leading-edge technologies through upgrades and life extension while providing fewer but more pervasive, highly selective, and affordable new technologies.[3] To accomplish much of this, DoD hopes to tap into the "economies of scale, accelerated product improvements, and increased sustainability inherent in the commercial marketplace"[4] through dual-use technologies and acquisition reform policies.[5] APL is playing a significant role in this process by providing prototype system development and evaluation capabilities for both new and upgraded platforms without bias to either the defense or commercial industries. Our challenge will be to increase system performance without increasing risk or cost while reducing development time.

In general, materials and systems will need to be smaller, lighter, stronger, more resistant to the environment, and longer lasting. Where existing materials do not meet projected requirements, new ones will have to be developed. Where materials are too difficult or costly to produce, new methods or equivalent materials will be needed. At the same time, new or replacement materials will have to conform to increasingly stringent and broadening environmental impact restrictions. Joining technologies for incongruous materials (e.g., metal to polymer) will have to be developed and validated. And where new materials are used, or even where conventional materials are to be used in unconventional or nontraditional ways, we will need to understand and predict their behavior to a much greater extent. Since fewer completely new systems are being procured, aging materials and infrastructure are an increasing problem. The challenge will be to devise methods to inspect, assess (service life or damage criticality), repair, or replace failing components and materials.

For many of these advanced engineering materials, the materials and the parts are formed simultaneously. The properties of materials such as composites, ceramics, intermetallics, etc., become dictated by the process, or even by scale and geometry (e.g., microelectromechanical systems or MEMS devices, antireflection coatings, nanocrystals). As the materials typically drive device/system performance and reliability, capabilities that measure their critical engineering properties, develop the interrelationships among these properties and the process variables, and intelligently control the process and the resulting geometry are undeniably necessary. Nondestructive evaluation (NDE) and inspection methods will also continue to be important tools for verifying that the desired results have been achieved. If not, then NDE will be needed to quantify which properties are achieved (as well as their local variability) and used as input to engineering analyses to assess the impact on overall performance and reliability.

MODERN MATERIALS IN APL PROGRAMS

Many of the technical programs being worked at APL deal with materials and materials issues. For instance, the Laboratory's TIMED spacecraft[6] contains a high-stability, temperature-insensitive bench made from a sandwich of aluminum honeycomb and composite skins with high-modulus, high-conductivity graphite fibers. This structure and these materials produce a lightweight yet incredibly stiff platform on which the spacecraft's optical components, including the star-tracking system used for guidance and attitude control, are mounted. The highly graphitized fibers were selected not just for their strength and stiffness, but also for the near-zero thermal expansion that is realized after fabrication.

In other instances, the use of composite materials results in lighter weight and provides greater environmental resistance (against, e.g., corrosion) than their metallic counterparts. Low-cost composites are therefore being considered for surface and underwater ship structures, armored vehicles, and long-range missiles. Reducing weight is also a convenient means of meeting increasing payload requirements for military aircraft and space satellites. Yet other performance issues must be considered as well. Because of the increasing speeds at which tomorrow's missiles will be operating, their exterior skins will have to survive the extreme temperatures produced by aerodynamic friction, particularly at leading edges.

Although not as severe, the survivability of APL's proposed MESSENGER[7] spacecraft under the thermal extremes it will experience while orbiting Mercury represents a critical technical challenge. Throughout

APL, staff are developing concepts and demonstrating their feasibility for multiple-role elements (integrated or smart structures) that will be needed for next-generation aircraft and submarines (stealth, vibration isolation), naval ship structures (health monitoring), and space stations/lunar colonies (environmental breach).

Recent rapid advances in electronics have had perhaps the most visible impact, particularly in portable, miniaturized systems. In APL's context, such shrinkage of circuitry and power systems can greatly benefit avionics and space electronics, but only if done within the quality and reliability constraints typical of APL programs. A comprehensive understanding of both the materials and the manufacturing processes involved is therefore critical, as are the needs for process control and verification, part qualification, nondestructive inspection, and reliability testing.

In addition to shrinking dimensions, the materials used for packaging are changing. Hermetically sealed electronics are being replaced by plastic-encapsulated versions. While this helps reduce component costs significantly, it creates substantial concern for the ability of the packaging to withstand radiation and moisture exposure, both critical to Navy and space missions. The smaller packages, the higher density of parts per board, and the use of new materials all introduce changes in the way the designer needs to address thermal issues throughout a part's life span. A comprehensive review of these microelectronics materials and packaging issues can be found in previous *Technical Digest* articles.[8,9]

In all of these efforts, the various aspects of materials science—synthesis, fabrication, integration, characterization, and inspection—play key roles in achieving success. Whether for creation of a new APL prototype or technology or for evaluating/assessing those of others, the need to combine the right mix of personnel and facilities in a timely, cost-effective manner is critical.

Synthesis

Perhaps the largest contributor to new technology for sensors is materials synthesis. Materials that are specifically sensitive to a target element or molecule are highly desired for a portable chemical analysis capability on spacecraft and DoD systems, environmental monitoring, and forensic analysis for law enforcement. In TSD, synthetic polymers known as molecularly imprinted polymers (MIPs) are one of the main focuses. This technology was discussed in detail in a previous *Technical Digest* issue.[10]

The production of these polymers requires an understanding of a diverse set of disciplines encompassing materials science, chemistry, and physics. A variety of methods are used to characterize these materials to verify that their properties will meet the requirements of each application. Other materials involved in the production of chemical sensors include metals, alloys, and nonmetallic conductors for electrode construction; optics, optical substrates, flats, and fibers for sensor construction; and a variety of plastics used in the fabrication of supports for both.

Several MIPs have been successfully synthesized that are sensitive to particular materials, e.g., metal ions to detect nerve agents Sarin/Soman,[11] ferrous ions to detect medical iron toxicity,[12] lead ions for waste water evaluation,[13] uranyl and uranium ions for sensing and recovering nuclear waste,[14] and TNT and its variants for explosives detection. A prototype explosive sensor made from a MIP is shown in Fig. 1. This technology has also been successfully proposed as a future screening method for steroid use in Olympic competition.

Fabrication

Perhaps the most widely used of the main resources offered by TSD is its fabrication capabilities. The Steven Muller Center for Advanced Technology (Bldg. 13) has extensive facilities for creating a variety of microelectronics, from custom printed and rigid-flex circuit boards[15] through MEMS devices such as APL's xylophone bar magnetometer.[16] Additionally, the center has facilities for conventional and comprehensive metal machining and shaping for fabricating spacecraft

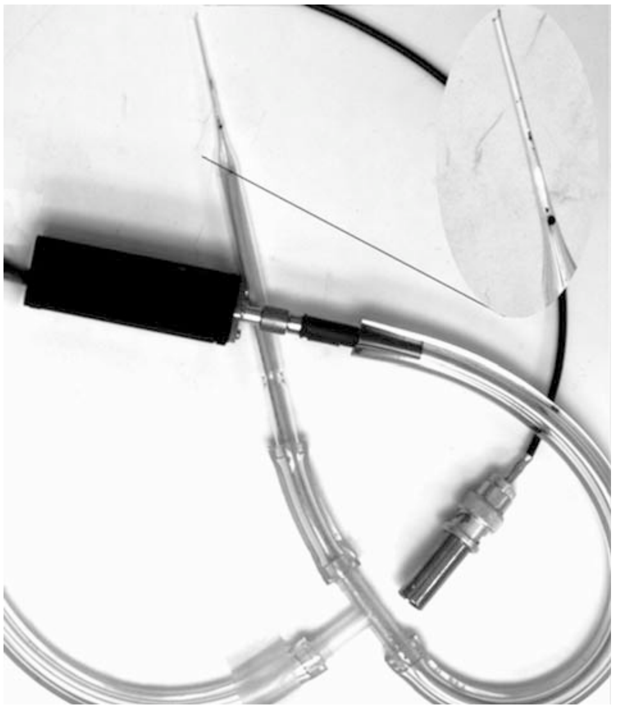

Figure 1. A prototype explosives detection sensor using molecularly imprinted polymer synthesis technology developed at APL.

and engineering prototypes (see the article by Wilson et al., this issue).

Another growing area of fabrication is the Composite Materials Fabrication Laboratory. Autoclave or hot press curing is available for high-performance aerospace applications (e.g., the TIMED spacecraft optical bench[17]) that require high temperature and stability resin systems such as cyanate ester and polyimides. To meet the cost objectives of our customers, lower-cost methods such as Resin Transfer Molding (RTM) and its variants (vacuum-assisted RTM and the Seeman Composites Resin Infusion Molding Process[18] or SCRIMP®) are being used. This technology has been applied to great advantage in the Advanced Natural Gas Vehicle Integrated Storage System Program[19] and for the submarine sensor fairings used on SCAMP (Fig. 2). Another method brought onboard by TSD to both decrease turnaround time and lower costs is rapid prototyping (Stratasys Fused Deposition Molding System). This technology is discussed in more detail in the article by Wilson et al., this issue.

Integration

Combining "old" or conventional materials with newer technologies has resulted in an interesting tradeoff—improved performance versus interconnection nightmares. Materials integration is a cornerstone of many near-future technologies such as structural health monitors[20,21] and adaptive or "smart" structures. Quartz crystal microbalances have been used for years to detect contamination on spacecraft in orbit, most recently on APL's MSX Program.[22,23] Adapting and integrating this technology into the tight spaces and power requirements of an exo-atmospheric missile, for the purpose of determining the contamination threat of deployment and material alternatives to tracking components, was demonstrated by APL this past year.[24]

Biomedical devices also require a healthy component of materials integration (biocompatibility).[25,26] For example, APL has constructed a catheter-deployed MRI antenna (Fig. 3) that folds together—into a single, integrated structure—a thin metal layer for electrical conductivity, an insulating coating to isolate the antenna from the body, and a nickel/titanium (NiTi) wire backbone that provides the elastic shape change necessary to form the MRI antenna. To function within a catheter, the device must be flexible enough to navigate twisting pathways without deforming permanently and without exerting excessive pressure on the walls of veins or arteries. Shape-memory alloys are a relatively new class of engineering materials whose applications are only beginning to be fully exploited.[27] In its superelastic form, NiTi has been used for years for catheter guide wires because of its extreme flexibility, resistance to kinking, and biocompatibility. It is perhaps more commonly used for arch wires in orthodontic braces and superdurable eyeglass frames. With the use of a superelastic composition, the coil merely springs into shape when pushed out from inside the catheter and collapses when pulled back in.

Another APL example of integrating a variety of materials requirements for new and old technology is the Composite Card Cage Enclosure (Fig. 4).[28,29] Traditional metal card guides were mated to a composite assembly. However, thermal and vibration considerations required the innovative use of thermally conductive fibers[30–32] and mechanical stiffeners.[33,34] Finally, an integral, electrically conductive fiber mat was needed for adequate electromagnetic interference (EMI) shielding.[35,36] Initial screening studies indicated that a configuration could be achieved that would significantly enhance both mechanical and thermal performance. The result was a simple three-piece prototype card

Figure 2. Low-cost composite fabrication technique (SCRIMP®) being used to produce hydrodynamic submarine fairings to protect sensors during operational trials for the Navy's SCAMP Program. The APL-prepared fairings were the first known demonstration of this processing technology at sea.

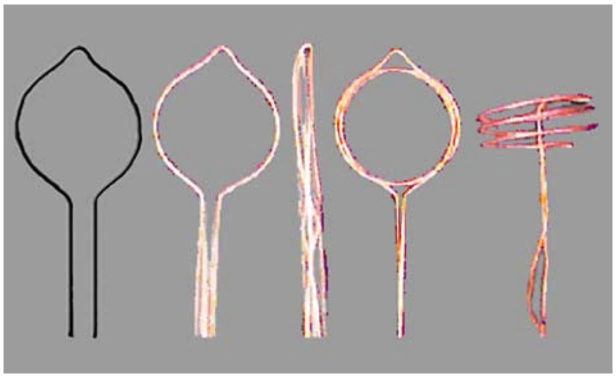

Figure 3. A superelastic shape-memory alloy (SMA) being considered for antennas for an MRI-guided, catheter-deployed biomedical device. Center coil is shown in retracted position (leftmost coil represents an uncoated SMA, remainder are copper plated; multiturn coils are shown at right).

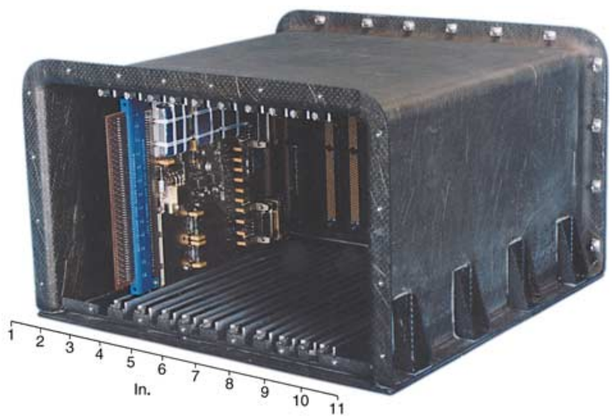

Figure 4. The Composite Card Cage Enclosure, also called the Integrated Electronics Module, made predominantly of carbon-fiber–reinforced composites.

cage with integral mounting flanges that could be easily and reliably fabricated and assembled using adhesives. The weight reduction achieved was more than 30% compared to an equivalent aluminum card cage and approximately 50% compared to an aluminum card cage using the standard design approach.

Characterization

As with most engineering applications, the designer must consider more than one set of performance requirements. For the Composite Card Cage Enclosure, electronic requirements such as EMI shielding effectiveness, surface resistivity, and RF conductivity had to be met. One key requirement for assembled spacecraft components is to maintain a suitable ground across mating surfaces with a standard limit of 2.5 mΩ. To accomplish this objective, a variety of embedded conductive surface layers were evaluated such as copper mesh, aluminum mesh, solid aluminum plating, as well as graphite fibers coated with both nickel and silver.[36] The characterization results indicated that composite panels could be made comparable to solid aluminum for EMI shielding (Fig. 5a), but that their surface resistivities generally fell short (Fig. 5b). Although the best candidate for EMI shielding was found to be nickel-plated graphite fiber, its surface resistance of 215 mΩ was much higher than permissible. However, one of the candidates, aluminum foil, measured a nearly acceptable surface resistance of 3.5 mΩ. TSD engineers are confident that, by altering and improving the design of joints and contact points, the required resistivities and shielding will be mutually achieved.

Another example is the TIMED optical bench, noted earlier, where the need for thermal stability (zero thermal expansion) was just as important as its structural stiffness. Although most of the relevant material properties necessary for adequate design and structural analysis can be extracted from vendor data sheets, almost all of them can be significantly affected by processing variables. For this reason, TSD has a comprehensive materials characterization facility for generating the necessary property data such as shown in Table 2. However, unlike many testing services that thrive on turning out large volumes of data quickly, TSD staff members take the time to assess the appropriateness,

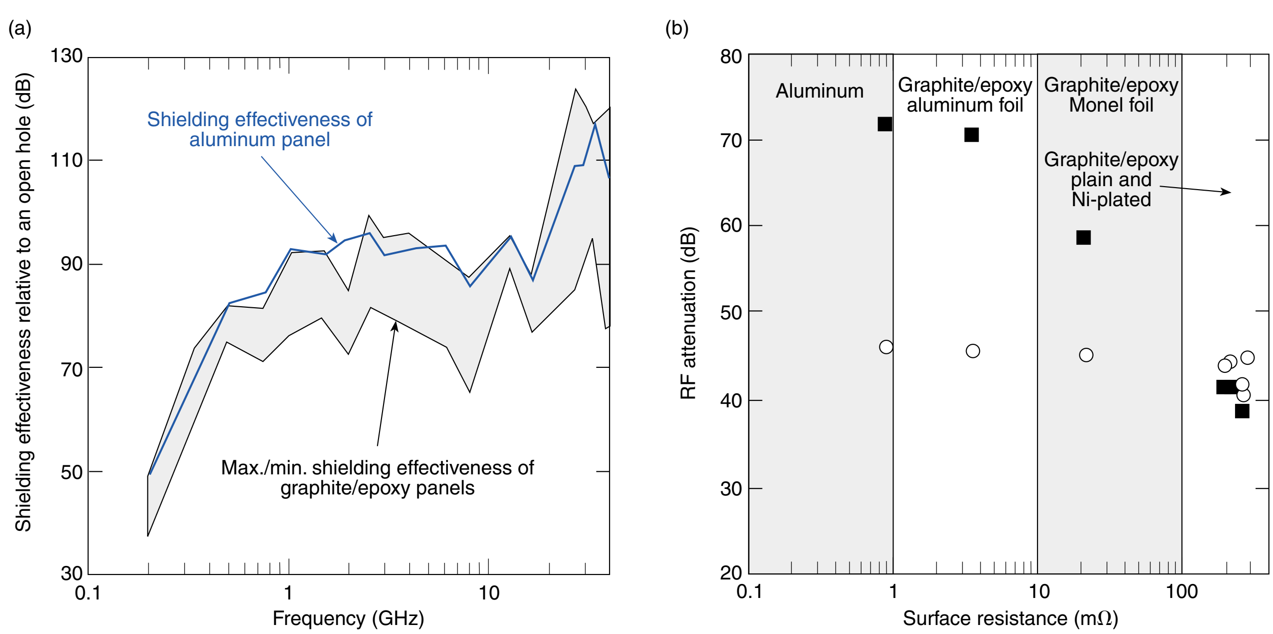

Figure 5. Comparison of results for aluminum to surface-modified composite panels for (a) EMI shielding effectiveness and (b) surface resistance (squares and circles are 1 and 25 MHz RF frequency, respectively). The materials were evaluated for potential use in a spacecraft electronic enclosure.

Table 2. APL-measured properties for several high-performance composite material systems.

Properties	Material system (fiber/matrix)[a] K13C/ EX1515	K135/ EX1515	K139/ EX1515	IM7/ EX1515	AS4/ EX1515	E-glass/ EX1515
Conductivity, K (W/m K)[b]	188	43	64	4.7	2.6	0.5
Thermal expansion (ppm/°C)						
Longitudinal (0°)	−0.1	—	−1.5	—	0.4	—
Transverse (90°)	38		43		45	
Tensile modulus (long.), E_1 (Msi)	130	90	110	42.5	33.5	5.5
Tensile strength (trans.), σ_1 (ksi)	—	255	237	324	237	132
Tensile modulus (long.), E_2 (Msi)	0.87	0.82	0.8	1.09	0.92	1.4
Tensile strength, σ_2 (ksi)	2.31	4.65	3.66	8.44	8.49	8.66
Compressive modulus (long.), E_1 (Msi)	—	57.2	41.8	—	—	5.22
Compressive strength (trans.), σ_1 (ksi)	—	41.8	—	168	182	186
Compressive modulus (long.), E_2 (Msi)	—	1.03	1.04	1.60	—	1.59
Compressive strength (trans.), σ_2 (ksi)	—	18.1	—	31.4	30.8	31.9
Shear modulus (long.), G_{12} (Msi)	0.62	0.77	0.62	0.83	0.73	0.57
Shear strength (trans.), τ_{12} (ksi)	5.8	12.2	11.6	13.1	13.5	11.2
Short beam shear strength (trans.) (ksi)	4.06	4.35	4.77	9.39	9.28	—

[a]Highly graphitic coal tar pitch–based fibers (K13C, K135, K139) are manufactured by Mitsubishi Corp.; polyacrylonitrile (PAN) based fibers (IM7, AS4) more commonly used in commercial composite applications are manufactured by Hexcel (formerly Hercules, Inc.). All materials were purchased pre-impregnated with the EX1515 cyanate ester resin (Bryte Technologies) from well-known distributor YLA, Inc. (Bernicia, CA).
[b]Thermal conductivity taken from vendor data sheets for comparison purposes only.

accuracy, and validity of their data. For instance, in a recent benchmarking exercise of APL's ability to accurately measure the coefficient of thermal expansion (CTE) with its obvious importance to the TIMED spacecraft, identical samples were sent to three external organizations with quite surprising results. Whereas APL's data ranged from about 5% scatter for high CTE values (>5 ppm/°C) to disappointingly greater than 20% for low CTE values, the data scatter from the other sources faired no better and were often much worse. Although this degree of potential error, uncertainty, and/or variability may not be desired, it at least allows for a fair assessment of the engineering system being studied.

The performance requirements of today's engineering applications are becoming more difficult to achieve with existing materials and designs. Safety factors of 10 or more are less common; a few applications are even requiring their materials to function above traditionally established limits. In addition, engineering systems are being asked to maintain their performance levels longer than their original design lifetimes (extended service life). However, most current predictive methodologies fall short of yeilding the desired levels of reliability. Determining whether this is because of uncertainties associated with the measurement techniques themselves or variability in the material caused by processing parameters becomes critical. Our understanding of the materials on a fundamental level will direct our efforts to achieve the desired reliability and performance goals. Characterization methods such as thermogravimetric analysis (TGA), dynamic mechanical analysis (DMA), and stress rheometry are anticipated to become more widely used as their results lead to accepted insight and understanding.[37,38] These methods can be used to help characterize newly synthesized materials to facilitate their development or verify the claims of vendors for their materials and permit quick and direct comparison to existing material selections (Fig. 6). In microelectronics, these techniques may be used to evaluate the performance of new adhesives, solders, and conformal coatings.

Inspection

Recent microelectronics miniaturization is a direct result of new technologies in both circuit boards and device packaging. Most of the new technologies were discussed recently in *Technical Digest* 20(1). Circuit boards (including traditional rigid boards), polyimide "flex" boards, and older ceramic-based substrate technology now use "blind" and "buried" connections (i.e.,

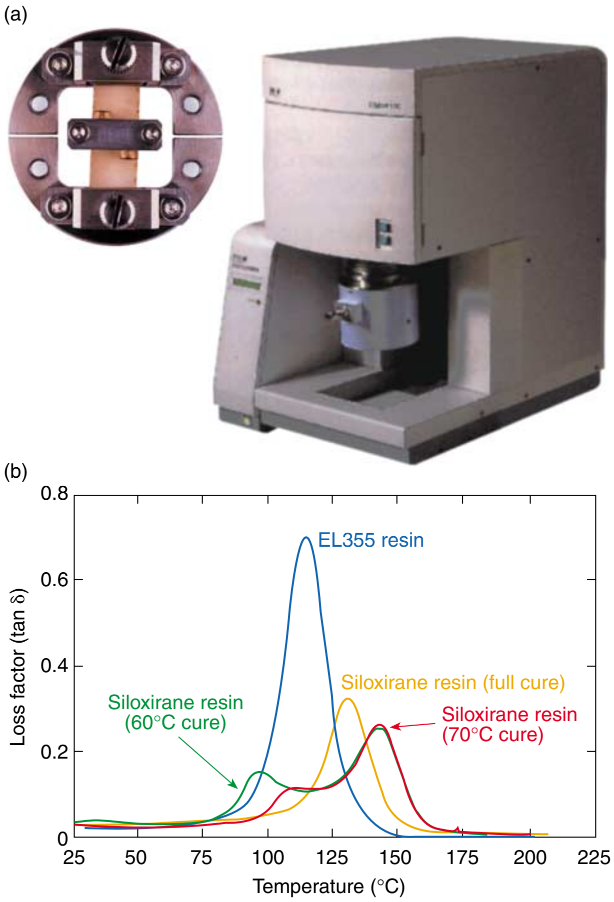

Figure 6. Complete characterization of viscoelastic materials, such as new polymeric resin systems, requires techniques like dynamic mechanical analysis (DMA). TSD's newly acquired Seiko DMS6100 unit (a) has a three-point flexure sample and fixture. Representative data on two high-performance resin systems are presented in (b).

having one or no surface connections, respectively, instead of two). Packages for many current devices break with tradition by using contacts placed over the entire bottom area or in myriad new lead configurations. These include ball grid arrays among others and chip-on-board types of molded or encapsulated chip protection methods.[9] Variants of such area array packages are the small flip chip devices often generically called chip scale packages. Such devices are semiconductor circuits which have little or no packaging and use small solder bumps on the semiconductor device's top (active) surface that function as both the leads and the means of attachment. The challenge in using these newer technologies in the Laboratory's high-reliability applications lies in demonstrating that no defects or failure modes are built into the circuit by its packaging or induced by its use conditions.

Because many of the features that determine microelectronics reliability are buried within parts or in the board structure, many of these newer devices and assemblies require examination with an assortment of sophisticated analytical tools and techniques. Encapsulated or plastic parts are a good example.[39] Since the functional part is encased in molding compound it cannot be checked visually. Destructive lot evaluations can be done using hot-acid decapsulants to reveal internal features; however, the process itself can attack the items being evaluated, making the results ambiguous.

Nondestructive methods available are primarily X-ray and acoustic imaging. X-ray techniques are used to show proper internal wiring or other metal features. But for heat dissipation and moisture protection, adhesion of the encapsulant to the internal integrated circuit is crucial. Since X-ray methods show the presence of a material but not its adhesion, recently developed acoustic microscope methods are being used to image cracks and other discontinuities internal to a part. These images show the acoustic impedence along a path. As discontinuities represent a sharp change in acoustic appearance (Fig 7), these methods are excellent indicators of any voids, gaps, or other

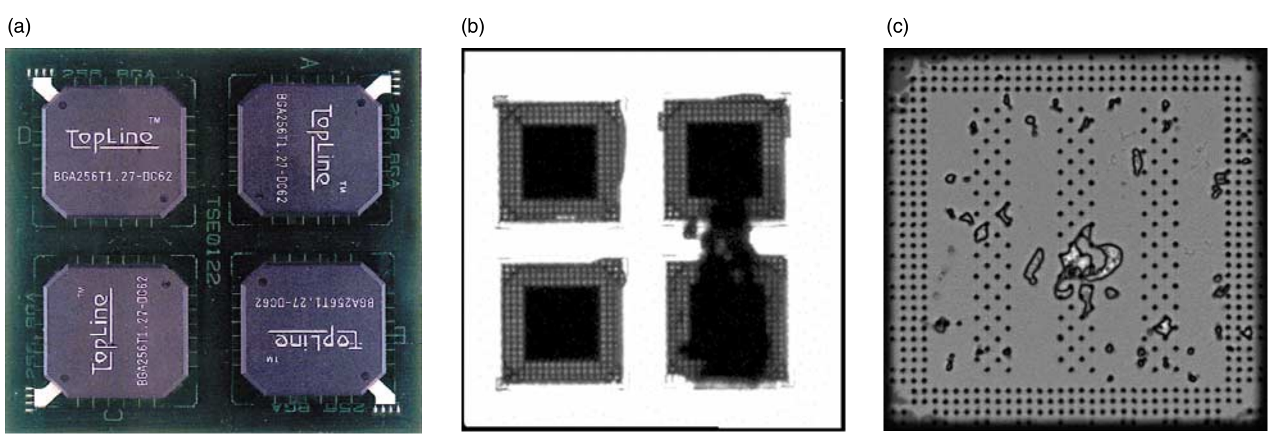

Figure 7. Inspection and part screening of microelectronics using C-mode scanning acoustic microscopy (CSAM) with TSD's upgraded SONIX HS-1000 unit: (a) image of a ball grid array, an example of a high-density interconnect technology, (b) a CSAM through-transmission image of printed circuit board delamination, and (c) CSAM reflection image of a flip chip showing underfill flaws.

discontinuities within the encapsulant or in the bond between the encapsulant to other surfaces. Acoustic methods are also valuable in evaluating the integrity of composite parts, welds, adhesive bond lines, and most accessible interfaces in engineering structures, large and small.

Diagnosis of a materials problem found during inspection is the first step to resolving the underlying problem. This is where materials analysis becomes crucial. For instance, high-power applications require a fast-acting electronic switch that must be housed in a copper package because of its ability to rapidly remove heat from high-power transistors. Because mission-critical components may only be available from one source, alternate sources occasionally need to be qualified.

Take, for example, an alternate source which first attempted to develop the package for a switch from a Navy package drawing. This required a pure copper base with a bolt on the bottom for mounting to a circuit board frame. When the initial package prototypes were bolted into a frame, the package bent far enough to break the large internal power transistors. A quick look at the materials properties of pure copper showed the likely reason: the empty package had been made by brazing ("hard-soldering") the bolt and feed-through eyelets for the leads in place. Unfortunately, pure copper loses about 80% of its yield strength at the brazing temperature. A simplified finite-element model of the package (Fig. 8) duplicated the observed distortion, validating both the model and the softening theory.

This model became very useful. First it showed that the simplest solution was to use a material that had similar properties to pure copper but retained strength during brazing. That material was a "dispersion-strengthened" copper. It is a pure copper with a small addition of fine aluminum-oxide powder, commercially called "GlidCop"; it can be brazed just like pure copper, retains its yield strength at brazing temperatures, and still has 90% of the thermal conductivity of pure copper. When this package material was used, the small bending measured during mounting was well within allowable limits, as predicted by the model.

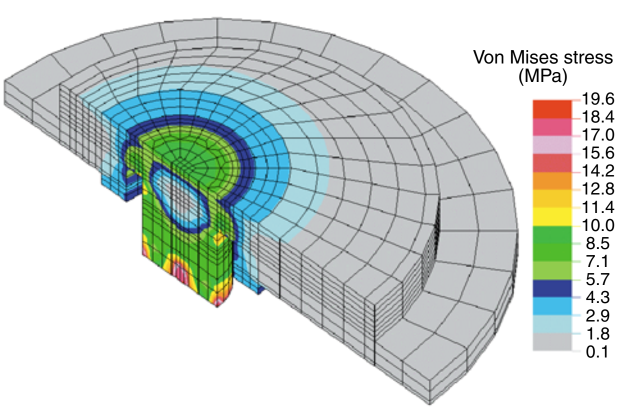

Figure 8. Finite-element analysis of a high-power transistor package design showing a concentration of stress at the center ring caused by the brazing of pure copper. Stress was alleviated by changing material to a copper alloy, which retains greater yield strength after brazing.

The second use of the model was to show that the strength of the first vendor's package was due not to the copper body, but to the molybdenum shims upon which the large power transistors sat. Based on this information, this condition, only tolerable during a prototype phase, was corrected in time for the production phase. Again, a possible "show stopper" was solved by APL's engineering expertise in materials.

THE FUTURE OF MATERIALS

Materials are still being used today in relatively conservative manners, despite all of the progress that has been made. Although methods of analysis are more sophisticated and accurate than ever before—with formulations for nonlinear elasticity, plasticity, linear viscoelasticity, hyperelasticity, etc.—simple linear elastic solutions are most commonly used. However, as performance requirements and engineering application needs become more complex and closer to the materials' limits, more advanced analyses will be required more frequently. This evolution will require better and more comprehensive materials characterization data (e.g., thermal expansion) in order to yield the accuracies attainable by the analytical methods. New characterization methods will also be needed to define new materials and identify experimental parameters as analytical and experimental solutions continue to evolve. In the near term, measurements will be required to accurately describe impact and high load rate scenarios, increase the accuracy and reliability of service life predictions (polymeric aging), and monitor the health of structures.

As advanced design and analysis tools make their way into the mainstream of engineering, the specific capabilities of selected materials will be used to optimize the design. An example of this shown here was the weight reduction achieved by the Composite Card Cage. In the future, the use of asymmetric composite laminates—which reshape themselves to their stress-free state after cure—might be useful in fabricating complex geometries without the need for equally complex molds. Intelligent processing of materials will also become more commonplace, although this evolution is expected to be much more gradual than that of design and analysis tools.

The current trend for lighter, smaller, more durable, and less expensive systems will continue—miniaturization of equipment and sensors will perhaps be the fastest growth area. New materials that can provide the same function in less space, much like transistors replaced vacuum tubes, will be needed to accomplish this. New processes for integrating existing materials on a smaller size scale will also likely be needed. Methods of joining dissimilar materials, and doing so reliably in a lasting fashion, will become a critical enabling technology. MEMS devices will become more and more prevalent as applications are found that can take advantage of their capabilities. This is already beginning to happen in the field of biomedical devices. Intelligent processing and service life determinations will profit from miniaturized and integrated sensors (embedded), and it is expected that monitoring of structural health will become a reality for buildings, aircraft, and bridges. Sensor technologies are already becoming small enough and cheap enough (temperature, pressure, and humidity sensors are readily available in microchip form) for use in automobiles and personal computers.

As smaller and more multilayer structures are designed and fabricated, however, they will present increasing difficulties for those who must characterize and inspect them. The methods used to inspect tomorrow's products will need to improve both in resolution and sensitivity. As we learn to understand the limits of these methods, it is expected that the materials and systems of the future will begin to incorporate elements that will recognize when they begin to fail and either notify the user of expended shelf life or initiate self-healing. Many of the smart materials concepts that are being proposed today point toward self-diagnostic and automated response systems. While known to many of us only in toy form, mechanisms that "transform" from one function or form to another will find their way into engineering applications. Space exploration already requires many components to function on multiple levels. Thus, components that can adapt and evolve for successive missions or in response to changes in environment will be needed.

SUMMARY

Our ability to solve the engineering challenges of today and tomorrow is still being driven by cost and availability. Materials and processing methods that yield equivalent or improved performance at lower cost, such as the SCRIMP®, rapid prototyping, and other technologies referred to in this article, are being actively pursued. Additional streamlining and optimization of the design process will be needed to further reduce the cost of implementing new materials, to have confidence in their ability to perform as intended, and to take full advantage of their properties. Our understanding of how materials interact, how they can be reliably joined or integrated, which ones to select or avoid for specific applications or environments, and even how to change or tailor their properties is expanding daily.

The challenges, as well as the opportunities, will be in all areas of materials development: synthesis, fabrication, integration, characterization, and inspection. Sensor development will continue to require new, targeted materials. Fabrication methods will be driven to less costly and faster processes. Next-generation ("smart") materials will need to continue to function over time when joined or even intimately integrated with other components. New and especially existing materials will need to be characterized in more depth and with greater accuracy so that their performance can be pushed to the limits more reliably. Finally, designed and integrated materials will most likely present more difficulties in verifying their integrity and reliability by conventional means than ever before. TSD will continue to support APL's mission areas by maintaining and expanding its capabilities to keep pace with advances in materials and associated technologies.

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