TRENDS IN MECHANICAL TESTING

Mechanical testing is intimately related to the materials being tested. So diverse and wide ranging are these new materials that this article should not be considered all encompassing, but rather as representative of the types of changes underway.

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Devices and structures critical for survival have been built for thousands of years, but prior to the 1920s, no one knew how strong a material ought to be for a given application. Nor did anyone understand the science behind how to change material composition to vary its strength. Back then, the solution to making it stronger was simply to add more material.

In 1920, A.A. Griffith applied the concept of surface energy to predict what the strength of a material ought to be. However, until recently, new materials were most often discovered by chance. Engineers determined their properties and put aside those that did not meet their needs.

Now we stand at the edge of a vast and great frontier where the ability to tailor materials structurally and chemically will generate an explosion of new materials that will drive innovation in the 21st century. We will be able to predict a material's properties before it has even been manufactured, thus greatly reducing testing and development time.

This article overviews advanced materials development, then describes the testing techniques and equipment needed to evaluate them.

Materials discovery and design

The immediate impact of the ability to tailor properties will be new materials that are greatly enhanced compared to those available today, as shown by the nanocoating on the slide in Fig. 1. As another example, lightweight batteries made of materials with high storage densities for electric automobiles are being developed. Piezoelectric materials with high energy densities for scavenging energy from wind and vibration are being deployed in wireless sensor networks.

Fig. 1 — Slide 1 is a piece of glass coated with silica nanoparticles. Slide 2 is an uncoated piece of glass. MIT Professors Cohen and Rubner have discovered that thin film coatings comprised of nanoparticles of glass that are about one million times smaller than a grain of sand interact so strongly with water that they force the condensing water droplets to spread out into an ultrathin sheet of water in a fraction of a second.

Since a sheet of water does not scatter light, the coating effectively eliminates the fogging problem shown on Slide 2. These anti-fogging coatings are nanoporous in nature. Since nanopores lower the refractive index of the coating, it also functions as a high performance anti-reflection coating. Image courtesy Michael F. Rubner, Professor of Polymer Materials Science and Engineering, Massachusetts Institute of Technology.

New ceramic-matrix composites, capable of maintaining excellent strength and fracture toughness at high temperatures, are being designed to maximize the efficiency of aircraft engines. Military uniforms are being designed with a new class of smart materials that are lightweight and flexible, but become rigid and impenetrable when impacted by a projectile.

Accelerating design

To accelerate the design of new materials, priority is being given to the study of improved synthesis techniques, to materials theory and modeling, and to advanced analytical techniques.

- **Synthesis:** The goal of improved synthesis techniques is to construct tailored materials from complex arrangements of atoms and molecules with the same precision and control as that for manufacturing semiconductors. The result will be materials with precisely defined, predetermined properties.
- **Computer modeling:** In materials science,

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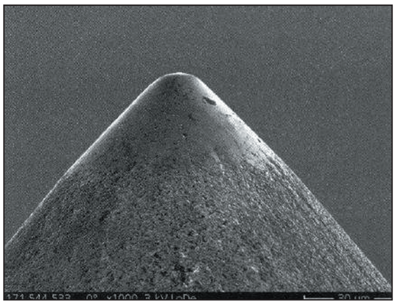

Fig. 2 — Scanning electron microscope photograph of spherical cone-shaped diamond indenter.

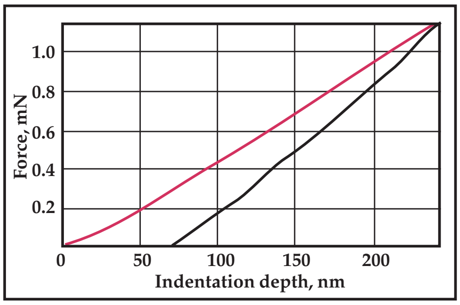

Fig. 3 — Typical force-indentation curve. The red line represents the loading and the blue line the unloading portions of the test.

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computational strategies are emerging that provide physical and chemical descriptions to predict structural and functional properties.

- **Analytical techniques:** The progress of materials science is intimately related to achievements in the development of powerful analytical techniques that enable examination of atomic and electronic structures at the nanometer level. They are particularly important in the area of materials synthesis, where they can also serve to manipulate and control structures in situ on the atomic and nano-levels. Mechanical instruments able to control to the nanometer level have only recently been developed.

Automatic data acquisition

Four advances in the late 1970s and 1980s made automatic data acquisition, control, analysis, and report generation possible. They were:

- **Late 1970s**: Embedded microprocessors with enough memory and speed for operation with dedicated digital indicators and controllers.
- **1981-1982**: An inexpensive op-amp that enabled stable DC strain gage measurements.
- **1985-86**: The first personal computers with the Intel 80286 microprocessor, the MS-DOS operating system, and enough hard disk space to do something useful.
- **Late 1980s**: The 16-bit A/D converter provided enough resolution to meet load and extensometer calibration requirements with a single calibration table.

Soon afterwards, PC-based materials testing systems and digital indicating systems were being offered at affordable prices. These advances for the first time made automated testing possible, and enabled test results to be automatically calculated.

Another significant advance was the introduction of Microsoft Windows 95, the first 32-bit operating system, plus software development tools such as Visual Basic, Visual C++, and the Microsoft Foundation Classes. The 32-bit operating system and software development tools standardized and simplified application development, improved product reliability, and enabled developers to focus on new features and product enhancements.

However, for many testing or quality control labs, networks and the Internet are an untapped or underutilized resource. Many do not use networks or the Internet, and are still manually writing down results and typing reports. The push to ship product faster, to eliminate errors and reduce costs, has only recently caused people to look more closely at improving their testing processes.

Where does mechanical testing go from here?

In new materials design and discovery, instruments must be capable of manipulating and controlling materials on the atomic and nano-levels. Optical and atomic microscopes are also required to help make sense of mechanical measurements at these levels. Systems capable of relating macroscopic stress-strain states to microscopic materials changes are also required.

The bulk of mechanical testing today is still done on twin screw or hydraulic testing machines at large loads and according to ASTM specifications. Some testing is required for R&D; however, much is done by quality control departments to verify the integrity of their materials and products.

Thus, the need for advanced analytical instruments at the nano-level for R&D, and the need to improve productivity in the quality testing lab are two distinct requirements.

Testing at the nano-level

Nanocomposites are polymer-based materials that have significantly enhanced mechanical performance, as well as other properties such as electrical conductivity, thermal conductivity, resistance to permeability, and abrasion resistance. The mechanically significant multiphase structures cannot be adequately reproduced ex situ in large specimens. This restricts conventional mechanical characterization approaches such as uniaxial tension or compression tests.

However, instrumented indentation provides a means for measuring the mechanical properties of each phase. Such data is a critical requirement of multiscale mechanical modeling efforts that would predict mechanical performance for a given composition and microstructure.

Indentation testing

It has been established that the response of a material to contact loading-then-unloading by an indenter (Fig. 2) provides access to its elastic properties. The technique consists of establishing contact between an indenter of known geometry and mechanical properties (typically diamond), and the indented material for which the mechanical properties are of interest.

An instrumented indenter is needed to record the continuous change in penetration depth h, as a function of increasing and then decreasing indentation load P, (P–h curve). Properties are extracted by applying a continuum scale mechanical model to derive two quantities: indentation hardness H, and indentation modulus M, from the P-h curve (Fig. 3). Optical, scanning electron, or atomic force microscopes are also required to select a specific indentation site and to view post-indentation surface deformation (Fig. 4).

Indentation is likely the only current technique that allows quantitative measurements of nanoscale mechanical properties. An indication of its growing importance is shown by the fact that around the year 2000, there were approximately five nanoindenter machines in the world. Today, there are at least five manufacturers of nanoindenters.

Almost all universities have at least one indenter, as it is becoming a standardized test, and both ISO and ASTM have issued draft versions of test standards. Typically, indenters are capable of 1200 mN maximum force with 0.1 µN resolution and 200 µm maximum displacement with 0.02 nm resolution.

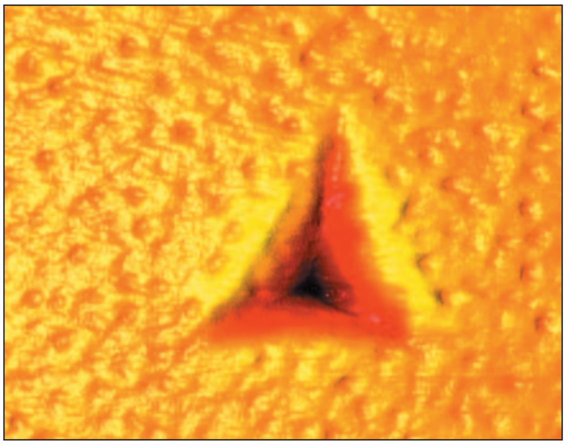


Fig. 4 — Indenting on a polymer, 750 nm scan. Image courtesy K. Van Vliet, MIT.

Properties vs. behavior

Referring back to the nanocomposite example, it is vital to understand the connections between the mechanical properties of each phase and the mechanical behavior of the bulk material. To help make that connection, palm-sized tension, compression, or flexural testers that fit into a microscope (optical, scanning, or atomic force) are required.

The testers exert forces as small as a few grams, or as much as 5 kN, on specimens that are generally tens of millimeters in size. Optional heating and cooling units enable testing at different temperatures.

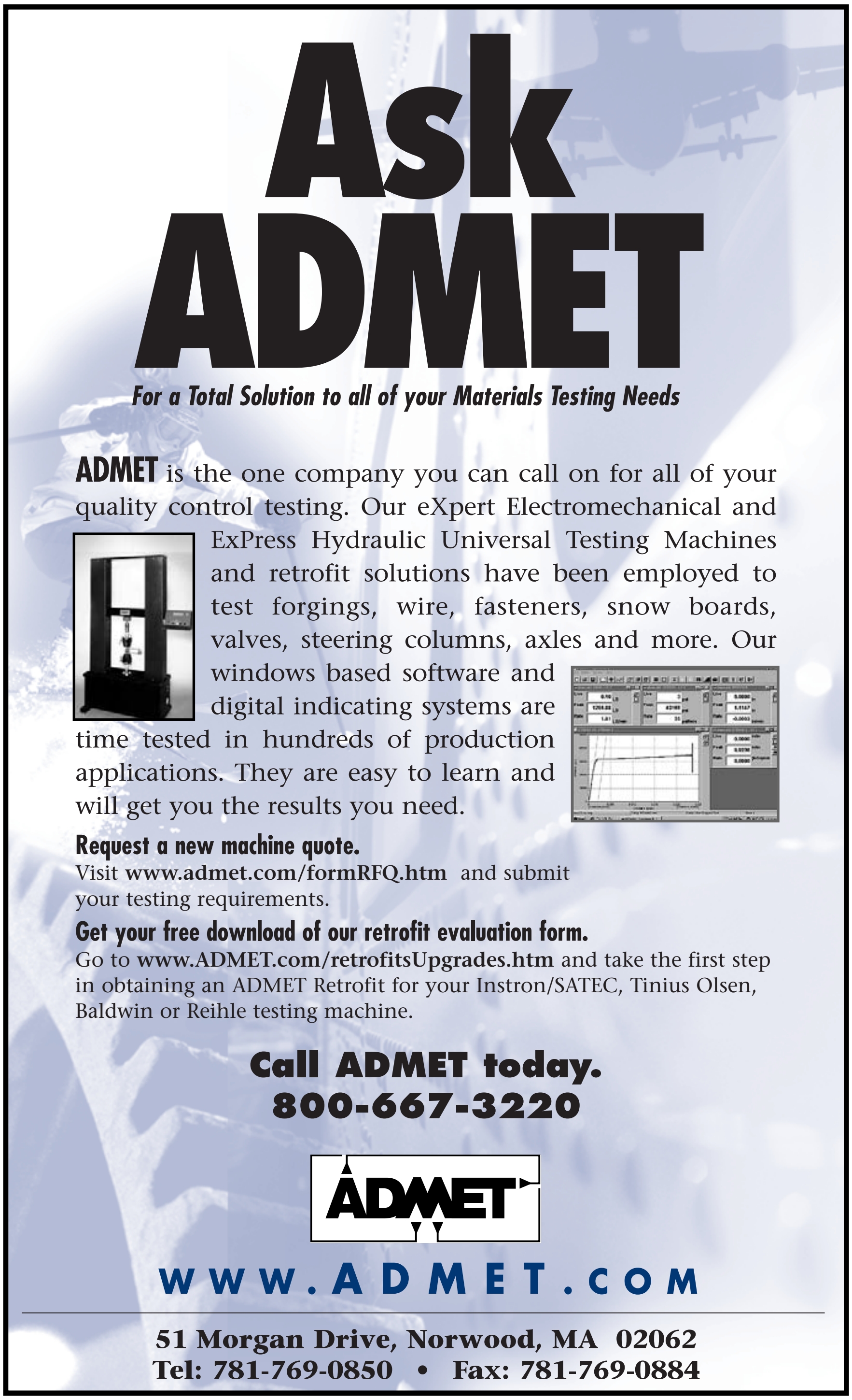
To measure macroscopic mechanical properties, the frames are outfitted with a load cell, strain measuring device, and a Windows/PC-based control and data acquisition system. Real-time images of the grain structures are aligned with the macro stress-strain data to connect the microscopic changes to the macroscopic behavior.

Figure 5 shows a force-deflection hysteresis curve for a polymer loaded by an Ernest F. Fullam tensile stage mounted in a scanning electron microscope. The two curves illustrate the data acquisition and control capabilities for measuring macroscopic mechanical properties.

Quality testing labs

The efficiency and accuracy of testing systems for steels, plastics, concrete, and other materials according to existing ASTM standards must be improved. More lab managers and testing machine operators want to:

- Automatically transfer test results from their testing machines into the company computer system or database, to eliminate data entry errors.



- Automatically calculate test results, to reduce test times.
- Verify test results, to ensure that no calculation errors were made.
- Verify that a test was carried out according to specification, to ensure the loading rates or rates of travel were correct.

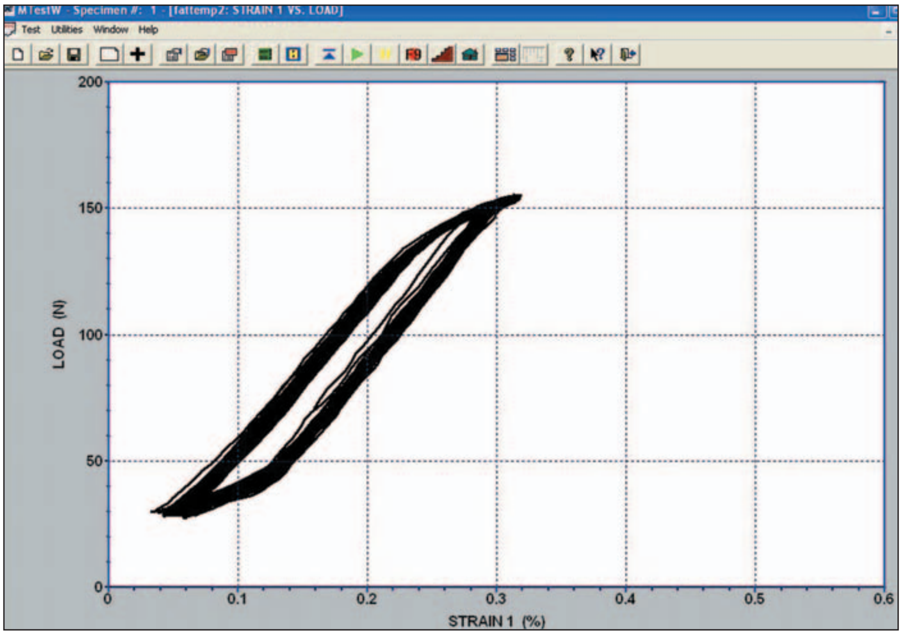


Fig. 5 — Force-deflection hysteresis curve recorded by ADMET's MTEST-Windows on an Ernest F. Fullam tensile stage.

Easily compare old test results to more recent test results.

- Efficiently transfer results and data to customers so that they can authorize product shipment more quickly.
- Simplify test procedures to reduce test times.
- Improve the accuracy and reliability of the testing machine.

Purchasing new machines is one way to make improvements. Another option is to retrofit or upgrade existing equipment. The overwhelming reason for upgrading is to achieve performance equal to or greater than a new machine, at a lower cost. By adding digital controllers or Windows-based software, test labs may continue to use the most expensive and durable component of the testing system — the load frame.

Networks and the Internet

In the future, systems will be required to automatically carry out tests according to specification, automatically calculate results, and seamlessly communicate with other computers and programs. The goal is to reduce operator workloads, eliminate the potential for data entry errors, and speed the time to product shipment. To achieve these productivity gains, manufacturers want test results to be automatically calculated, then electronically transferred to a database.

Lab supervisors need to generate specimen files that include specimen dimensions and a unique specimen identifier. Then, they can electronically share the specimen file with all testing machines in the lab, so that operators do not have to manually enter the dimensions at the machine.

Testing laboratories that submit thousands of test reports annually are also installing systems that automatically calculate results, and database programs that automatically generate reports in Adobe Acrobat pdf format. They then place the reports on secure web servers that have separate secure folders for each client. This technology saves significant amounts of time while reducing errors and improving efficiency. ◆

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