COVER STORY

Smart Materials Respond to Changing Environments

Scientists are focusing their research on various materials that can solve problems in diverse applications, among them medical and aerospace.

The materials most used in smart material systems fall into three classes: piezoelectric, magnetostrictive, and shape memory alloys (SMAs). All three undergo a reversible change in properties in response to an external stimulus. Piezoelectric materials transform electrical energy into mechanical energy when subjected to an electric field. Magnetostrictive materials' trigger is a magnetic field, which converts magnetic energy into mechanical energy. And SMAs switch phases when exposed to heat.

Although these materials are referred to as "smart," there is a debate in the research community as to how intelligent they really are. Some researchers feel that the term "smart" has been misused and that it is more accurate to call the materials adaptive or active. Others concede that they are not sure how smart the materials are but see a progressive increase in their responsiveness.

Fatigue in piezoelectrics

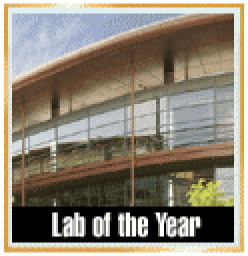
Gregory Carman at the Univ. of California, Los Angeles (UCLA), prefers to call the materials he works with active, prompting him to name the lab he started The Active Materials Laboratory. At this facility, scientists work with all three classes of materials to understand the basic phenomena responsible for their properties.

Among the approaches employed to gain this insight is modeling, which is used to map domain structures. "In a material, you have grains, and within the grains you have domains," says Carman. These domain-walls in piezoelectrics are electrically actuated and move around in the material. This domain-wall motion generates larger strains, which lead to larger deformations of the material.

Modeling reveals the internal stress states between the domains as well. These internal stresses are significant because they can cause a piezoelectric in a high electric field to fatigue as it is cycled. This degradation and the reason behind it have engendered a debate in the research community. One school of thought, to which Carman subscribes, believes that as piezoelectric materials are cycled, internal stress concentrations lead to cracking. These cracks prevent the propagation of the electric field through the material, shielding certain regions. Other scientists believe that by cycling the material, there is a charge buildup along the boundaries within the material. That charge buildup opposes the electric field being applied. Consequently, the domains lose their mobility and become "pinned." Once pinned, the domains do not produce any strain output.

Joining forces with various companies, Carman's group is now trying to get piezoelectrics into motor systems. "At the small scale, these motors are better than conventional electromagnetic motors, whose power output per unit volume goes down as the motor size decreases," says Carman.

Electronics increase functionality



Supplements

Product Solutions

Piezoelectric motors are also part of the research effort at Pennsylvania State Univ. (PSU), University Park, which largely revolves around ferroelectric materials. "One of our long-term goals is to make a 2-D steerable catheter that can be placed in the veins around the heart and image the plaque buildup in those veins," says Susan Trolier- McKinstry, director of PSU's W. M. Keck Smart Materials Integration Laboratory (SMIL).

The SMIL director believes that the interest in smart material systems is partially due to the fact that electronics are now cheap. "In many cases, you can significantly increase the functionality of a device by integrating it with electric circuitry," says Trolier-McKinstry. This has driven scientists to explore how a function—a response by a material—can be integrated with electronics and respond back to the environment to make controlled changes.

Ferroelectric ceramics and single crystals are being studied by Christopher Lynch, associate professor in the mechanical engineering dept. at the Georgia Institute of Technology, Atlanta. His efforts in this area revolve around three applications: morphing composites, compact actuators for helicopter trailing edge flaps, and piezoelectric-hydraulic pumps for morphing aircraft applications.

Echoing Carman's outlook, Lynch feels that smart materials may be a misnomer since "the intelligence is not really in the material. It is in the ability to control the material through smart electronics and microprocessors." Accordingly, he feels that "adaptive" is a better description of these materials' behavior.

Thin-film SMAs

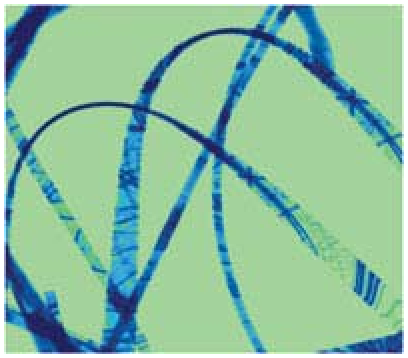
Shape memory materials are likewise being investigated by Carman's team at UCLA's Active Materials Laboratory. The research concentrates on thin-film SMAs, reflecting the migration in the last few decades toward micromachining. "If you can micromachine something, maybe you can use these materials in microactuators," says Carman.

The group has started designing a pumping system for fluids based on thin-film SMAs. In addition, the scientists are using this material to help pediatric cardiologists replace heart valves in patients. "To do that right now, you have to cut the chest open and replace the valve," says Carman. "What we've started designing are percutaneously placed nickel titanium (Ni-Ti) heart valves." Thus, instead of opening the chest, a catheter would be inserted and guided up to one of the arteries to the heart, and once there, it would be allowed to expand.

The main challenge to working with thin-film active materials is fabrication. The sputtering process currently used results in the loss of Ti and a non-uniform composition. To address that issue, the UCLA researchers developed an approach using a heated target, which produces more uniform deposition.

Aerospace SMA application

At Continuum Dynamics, Ewing, N.J., the work has focused chiefly on the use of SMAs for different tasks in the aerospace and marine fields. In these two sectors, the interest in SMAs stems from their ability to provide a "high-force, high-strain, all-electric alternative to conventional actuation technologies, such as hydraulics," says Todd Quackenbush, senior associate at Continuum Dynamics. This capability results in "otherwise unobtainable actuation performance."



Georgia Tech's Z. L. Wang and his group discovered zinc oxide nanobelts in 2001. These nanobelts define a new group of nanomaterials for applications in nanoelectronics, nanosensors, nanoactuators, and biosensors

This performance is demonstrated in the company's two-position tab, which can be mounted on the trailing edge of a helicopter rotor blade. It replaces the standard mechanical tabs that are manually adjusted between flights to balance the rotor blades and minimize vibration.

The two-position tab exploits a patented self-locking mechanism that keeps the device in one of two stable positions and employs SMA wire actuators to affect the change in state. "Implementation of a closed loop system of vibration minimization using these SMA tabs would save a large number of maintenance man-hours and mitigate vibratory loads and crew fatigue," says Quackenbush.

Hybrid systems

SMAs, along with monolithic piezoceramic materials and the patented Metal Rubber and Macro Fiber Composite actuators, are used at the Center for Intelligent Material Systems and Structures (CIMSS) at Virginia Tech, Blacksburg, to solve engineering problems. "For instance, we combine the piezoelectric effect and the SMA effect with some electronics to form a self healing system," says Daniel Inman, director of CIMSS.

The applications he's involved in focus on structural health monitoring for nuclear reactors, aircraft, shuttle thermal protection systems, and civil infrastructure. The driving force behind this work is Inman's desire to address the engineering defects that result in tragic events. Examples of these events are the loss of the shuttle due to undetected damage in its thermal protection system and the recent structural collapse at Charles de Gaulle airport, Paris, France. "Both of these could have been detected in time to take action to prevent failure and save lives had

(Image: Z. L. Wang, Georgia Tech)

they been recognized earlier as problems," says Inman.

One of the applications of MnemoScience's polymer platform technology is in the medical field for the creation of stents.

Synthetic analogs of nature

Regardless of the type of materials engineered, Jeff Brinker, a research fellow at Sandia National Laboratories, Albuquerque, N.M., believes that the right balance of different properties has to be achieved in fabrication. "Making a material that is responsive, reversible, and rapid is still a balancing act between different types of forces," says Brinker.

This balancing act has been perfected by nature, however, whose living systems scientists try to mimic. "We can look to nature to see what sorts of interactions and architectures support switchability," says Brinker. A good biological model is a protein. When heated, a protein denatures. When cooled down, it will refold to its original configuration in some cases. "So that's sort of a memory material. But how do we build that kind of behavior into synthetic materials?" says Brinker.

In his pursuit of such synthetics, the Sandia researcher works with materials that can be actuated by environmental stimuli, such as temperature, stress, or light. A prime example is a nanostructure that incorporates gelatinous materials—hydrogels. These hydrogels shrink and expand in response to a change in the local temperature, pH, or ionic strength. "So if you make a gate in a nanopore that has this hydrogel material in it, you can open and close the gate in response to the stimuli," says Brinker.

The gating action can also be achieved when light is used as a stimulus with the optically actuated azobenzene. When UV or visible light hits this molecule, it switches back and forth between its trans and cis isomers. So "if we can put these materials onto an electrode, we can directly monitor the change in the transport through the pores to the underlying electrode surface," says Brinker.

Hydrogels, along with piezoelectrics and SMAs, are of interest to Midé Technology Corp., Medford, Mass., as well. The company uses these materials to develop "solutions to a plethora of problems that can save weight and/or cost," says Attila Lengyel, COO at Midé.

One of these solutions involved the use of Midé's hydrogel to develop a shaft seal for ships. The seal is needed to extend a rotating shaft to the propeller through the ship's hulls, while ensuring that water does not pass from one side of the bulkhead to the other. Since "the seal activates only in the presence of water, its operating life is increased," says Lengyel. Hydrogels have also been employed to develop a wetsuit material, Smart Skin, which takes advantage of the gel's characteristics. When a diver moves from warm into colder water, the gels are activated and begin to absorb water—like a sponge. The suit then swells a little, compressing against the skin of the diver. "This action increases the overall insulation of the suit, thus protecting the diver from cold temperatures," says Lengyel.

Z.L. Wang, director of the Georgia Tech Center for Nanoscience and Nanotechnology, Atlanta, is also working with nanostructures. He studies nano-scale semiconducting and piezoelectric structures, such as zinc oxide (ZnO). "I have been focusing on ZnO nanostructures because it is an ideal semiconducting and piezoelectric nanomaterial at the nanoscale, has many novel nanostructures, and is biosafe and biocompatible," says Wang.

Reversibly swelling PEMs

Studies on materials that mimic the action of a sponge are likewise being conducted by a research team led by Michael Rubner, director of the Center for Materials Science and Engineering (CMSE) at the Massachusetts Institute of Technology, Cambridge. The group is working with polyelectrolyte multilayers (PEMs), which are polymer thin-films placed on surfaces one molecular layer at a time.

One of the materials studied that has potential in the biomedical field swells to a certain level when placed in water, absorbing water like a sponge. "Its level of swelling as a thin film depends on its previous history, and that's where it's smart," says Rubner. "It remembers where it's been before it went into water, then swells to a level that is dictated by that prior history."

When this film is placed in water at a low pH, dried, then placed in neutral water, a very high level of swelling is obtained—over 700%. If, on the other hand, that same film is treated at high pH, dried, then put in neutral water, it only swells by 10%. "So even though it's been dried, it keeps molecular memory of its previous treatment in water. It remembers and then expresses that state when it goes back into neutral water," says Rubner.

One application for the CMSE material is in drug release. "The problem with PEMs is that if you load a drug into the multilayer, when you place it into a solution that mimics the body, within an hour or so, the drug is released," says Rubner. The reason behind this rapid release is the multilayer, which swells so much in a buffered solution that it quickly releases a drug. But with the reversibly swelling CMSE materials, once a drug is loaded into them at a non-physiological pH and then placed in neutral pH—depending on how they were treated—they will slowly and linearly release the drug.

The key to the swelling behavior of this material lies in its fabrication. The material exhibits the swelling behavior only when assembled at a very high pH (9.0 or higher). At such a pH, many of the polymer chains are non-charged and hydrophobic, forming domains that hold the film together. As long as these domains are in place, the film cannot swell. However, when the pH is reduced, the units within the domains become charged. Once a critical charge density is reached, the association of the hydrophobic domains is broken and the domains expand, resulting in swelling.

Controllable degradation
A polymer platform technology that can confer a shape-memory effect has been developed at MnemoScience GmbH, Aachen, Germany, as well. When applied, the technology produces "polymers that have a shape-memory effect, elasticity, and change of elasticity during an application" says Viet Otto, Managing Director at MnemoScience. Additionally, the degradation time of these polymers can be changed from months to years, if necessary.

The shape-memory effect involves a permanent and a temporary shape, with the switching to the permanent shape being achieved through a change in temperature.

—Danielle Sidawi

Resources

Continuum Dynamics, 609-538-0444, www.continuum-dynamics.com
Georgia Institute of Technology, 404-894-2000, www.gatech.edu
Massachusetts Institute of Technology, Center for Materials Science and Engineering, 617-253-6850, http://web.mit.edu/cmse/www
Midé Technology Corp., 781-306-0609, www.mide.com
MnemoScience GmbH, 49-(0)-241-9632250, xwww.mide.com
Penn State Univ., Materials Research Institute, W. M. Keck Smart Materials Integration Laboratory, 814-863-8407, www.mri.psu.edu
Sandia National Laboratories, 505-272-7627, www.sandia.gov
Univ. of California, Los Angeles, The Active Materials Laboratory, 310-825-9564, http://aml.seas.ucla.edu
Virginia Tech, Center for Intelligent Material Systems and Structures, 540-231-2900, www.cimss.vt.edu