A Survey of Actuating Materials

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The conversion of input energy to mechanical work is practically interesting because of the need for actuators in many types of devices.

Mechanical work in common machines and appliances are most commonly gained through electromagnetic motors. However, some limitations of conventional motors, such as low power-to-mass ratios, low efficiencies, and the need to convert rotary to linear motion, allow opportunities for actuating materials in a variety of niche applications. For example, as we scale down devices so that they operate in the mesoscopic world, we will need to tap into alternative actuation strategies. The use of actuating materials is an alternative strategy that may be important where conventional strategies fail.

Several classes of materials have been discovered that couple light, chemical energy, heat, a magnetic field, or an electric field to mechanical motion of useful magnitudes.[1] A survey of these materials will hopefully help us understand the opportunities which exist in this field.

In piezoelectric ceramics, the most widely used of the materials reviewed, the change in dimensions of unit cells caused by the polarization induced by an electric field results in a change in dimensions of the bulk material.[3-7] Ferroelectric ceramics are a class of piezoelectric ceramics in which the polarization of the unit cell is reversible—this allows for a greater range of unit cell lengths, which translates macroscopically into larger strains. Electrostrictive ceramics operate by a similar effect, but unlike piezoelectrics, whose strains vary linearly with field, strain in an electrostrictive varies quadratically with field. Current interest in these materials come from their use in micro- and nanoelectromechanical systems, for which their high actuation precision and frequencies make them well-suited.

In shape-memory alloys, mechanical work can be done by a specimen as its shape changes from a temporary to a permanent shape. This shape change in the thermal shape-memory alloys is induced by heating past a transition temperature. Above this transition temperature, a cubic phase, called austenite, is thermodynamically stable, but below this temperature, a tetragonal phase, called martensite is stable (Figure 1).[8] Though shape-memory alloys have been studied for over half a century, how the memory of the permanent structure is stored is not yet fully understood. It is thought that the atoms in a martensite state retain a correspondence to the atoms in its parent austenite state.[9] However, ab initio calculations have shown that atoms in the minimum energy martensite structure can transform into two different austenite states with equal probability, which would result in a partial loss of the shape-memory with each transformation cycle.[10] An atomistic understanding of this mechanism may be helpful in miniaturization of shape memory alloys for use in microelectromechanical systems. Current actuating applications of these alloys exploit their high work density, such as for actuators on spacecraft.

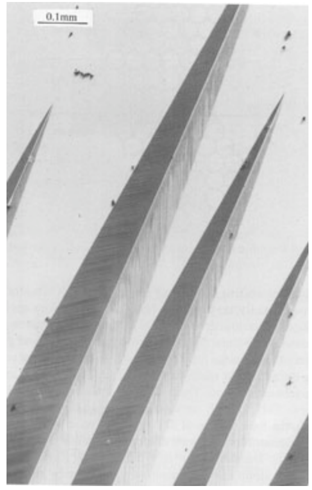

Figure 1: Martensite in Cu-Al-Ni alloy.[7]

A host of actuating polymers have also been developed, and may prove important in certain medical applications and as valves or pumps in microfluidic systems. Polymers have advantages over ceramics and alloys in that they are light, inexpensive, flexible, and can be processed into complex shapes. Many polymeric actuating materials however, have the disadvantages of low frequencies and stresses.

Ionic polymer-metal composites are films of ionic polymers coated on each face with a metal electrode. The ionic polymers used have negatively charged ionizable groups, and swell when exposed to solvent. The application of a voltage causes migration of mobile cations toward the anode, causing preferential swelling of that side of the film, which results in the bending of the film.[11] These gels can only produce low stresses, but may be useful for large displacement, low force applications.

Electrostrictive polymers are semi-crystalline polymers which can be polarized by applying an electric field.[12] The crystallites dispersed within amorphous regions adopt different volumes in their polarized and unpolarized states, due to the changes in polymer conformations that accompany polarization.[13] The changes in volume in the crystalline regions are translated into macroscopic volume changes. A major disadvantage of electrostrictive polymers is hysteresis: when the electric field is removed, there is remanent polarization, and strong fields in the opposite direction are needed to erase it. Recent work in electrostrictive polymers has been in decreasing hysteresis for room temperature operation by electron irradiation[14] and terpolymerization [15] with bulky monomers. Both methods serve to decrease the coherence between the crystallites.

Actuating materials may see increasing interest for use as actuators in areas where conventional actuators are unsuitable, such as in micro- and nanoscopic devices. Knowledge of strategies for effecting macroscopic shape change by manipulating molecular shape and orientation may help us in designing future actuating materials.

Jargon to be used in the talk are collected below:
Strain: change in length divided by original length—quantified as a percentage.
Stress: force applied per cross-sectional area of the material—in MPa.
Specific power: Power output per mass per actuating stroke—in W/kg.

References

1. (a) Madden, J. D. W.; Vandesteeg, N. A.; Anquetil, P. A.; Madden, P. G. A.; Takshi, A.; Pytel, R. Z.; Lafontaine, S. R.; Wieringa, P. A.; Hunter, I. W. Artificial muscle technology: physical principles and naval prospects. *IEEE J. Ocean. Eng*. **2004,** 29, 706. (b) Gandhi, M. V.; Thompson, B. S. *Smart Materials and Structures*; Chapman & Hall: London, 1992.

2. Uchino, K. Piezoelectric and Electrostrictive Actuators. *Sixth IEEE International Symposium on Applications of Ferroelectrics*, **1986**, 610-618.

3. Cao, W. Ferroelectrics: The strain limits on switching. *Nature Materials* **2005,** 4, 727-728.

4. Haertling, G. H. Ferroelectric Ceramcis: History and Technology. *J. Am. Ceram. Soc*. **1999,** 82, (4), 797-818.

5. Bhattacharya, K.; Li, J. Y.; Rogan, R. C.; Üstündag, E. Domain switching in polycrystalline ferroelectric ceramics. *Nature Materials* **2005,** 4, 776-781.

6. Uchino, K. *Piezoelectric Actuators and Ultrasonic Motors*. Klewer Academic Publishers: Boston, 1997; pp 1-72.

7. Otsuka, K.; Wayman, C. M. Mechanism of shape memory effect and superelasticity. In *Shape Memory Materials*. Otsuka, K., Wayman, C. M., Eds.; Cambridge University Press: Cambridge, UK, 1998; pp 27-49.

8. Bhattacharya, K.; Conti, S.; Zanzotto, G.; Zimmer, J. Crystal symmetry and the reversibility of martensitic transformations. *Nature* **2004,** 428, 55.

9. Ackland, G.; Huang, X.; Rabe, K. Crystal structures and shape-memory behavious of NiTi. *Nature Materials* **2003,** 2, 307.

10. Shahinpoor, M. IPMCs as biomimetic sensors, actuators, and artificial muscles--a review. *Smart Matererials and Structures* **1998,** 7, R15.

11. Harrison, J. S.; Ounaies, Z. *Piezoelectric Polymers*; CR-2001-211422; NASA: 2001.

12. Lovinger, A. J. Ferroelectric Polymers. *Science* **1983,** 220, 1115-1121.

13. Zhang, Q. M.; Bharti, V.; Zhao, X., Giant Electrostriction and Relaxor Ferroelectric Behavior in Electron-Irradiated Poly(vinylidene fluoride-trifluoroethylene) Copolymer. *Science* **1998,** 280, 2101-2104.

14. Huang, C.; Klein, R.; Xia, F.; Li, H.; Zhang, Q. M.; Bauer, F.; Cheng, Z. Y., Poly(vinylidene fluoride-trifluoroethylene) Based High Performance Electroactive Polymers. *IEEE Trans. Dielectrics and Electrical Insulation* **2004,** 11, (2), 299-311.