CHARACTERISTICS AND PROCESSING OF SMART MATERIALS

Haydn N.G. Wadley
Intelligent Processing of Materials Laboratory
School of Engineering and Applied Science
University of Virginia
Charlottesville, VA 22903

SUMMARY
Smart materials are revolutionary new engineering materials/intelligent structures that sense and respond to their environment. Emerging concepts for mission adaptable wings, helicopter blades and the active suppression of submarine noise are reviewed and used to identify the important basic elements of these intelligent structures. The fundamental principles of the main sensing approaches (based on piezoelectric, fiber optic, luminescent and other phenomena) are described together with the physical principles underlying approaches to actuation (piezoelectric/electrostrictive materials, magnetostriiction, shape memory alloys and electrorheological fluids). The best methods for design and processing of affordable smart materials are only beginning to be addressed by researchers; concurrent engineering and intelligent processing of materials concepts will be essential to transition smart materials from the laboratory into applications.

1. Smart Materials and Structures
Smart (or intelligent) materials/structures are revolutionary new structural materials concepts that sense critical aspects of their environment and optimally respond/adapt to them[1]. The field has emerged in the past five years from increasingly intensive research and development activities in Japan, the USA and Europe. To better understand the idea of a smart materials/structures concept, consider three ongoing military application studies aimed at a) improving the performance of a bomber aircraft by the development of a mission adaptable wing (MAW), b) increasing the speed of attack helicopters by active blade vibration/twist control and c) active suppression of a submarine’s acoustic signature.

1.1 Mission Adaptable Wing
Both the lift and the drag of an airfoil (e.g. a wing) are a sensitive function of the wing geometry (characterized by its camber) and the conditions under which it operates (the velocity of airflow over the wing and the ambient gas temperature/pressure). Normally, a fixed wing geometry is used that optimizes the lift/drag for the particular set of flight conditions deemed to be most mission critical, Fig. 1 [2]. For example, a minimum drag camber is used for subsonic, low level penetration of air defenses whereas a maximum lift configuration is used during aggressive maneuvers. Fig. 1 clearly shows that no single wing camber is optimal for all phases of a typical bomber aircraft’s mission which involve both penetration and maneuvers.

One solution to this problem is a system of rotary actuators and linkages to hinge a flexible wing and thus change the camber, Fig. 2 [2]. This enables the camber to be adaptively controlled and the entire shaded region of lift/drag relations shown in Fig. 1 to be accessed with the mission adaptable wing. The resulting adaptive control surface can greatly improve maneuverability as shown in Fig. 3 [2]. The role of smart materials here is to replace the heavy slow mechanical system of actuation with smart adaptive panels that can be rapidly flexed over a wide range of angles [3,4]. This reduces weight allowing 30% higher payloads, 50% greater range and 30% increased maneu-
verability. The ability to continuously vary curvature over the airfoil without creating hinge lines also improves stealth performance.

1.2 Smart Helicopter Rotor Blades

There is a great deal of interest in expanding the flight envelope of future military helicopters. Today, this is very much determined by the dynamics of the rotor blades. In particular, the aeromechanical stability of the blades is a sensitive function of the inplane compliance of the blade - especially near the blade neck [5]. Soft inplane rotors give good aeromechanical stability, but the ideal compliance varies with flight conditions and a compromise is used in practice.

![Variable camber flight envelope](image)

**Fig. 1** Lift-drag relations for different wing cambers. By adaptively controlling the wing camber, the entire shaded region is accessible during a mission [2].

In addition, vibration and torsional deformations of the blades limit the airspeed of today's helicopters and contribute to significant fatigue damage requiring frequent overhauls and extensive maintenance [6]. By using smart materials whose effective compliance can be modulated, it will be possible to tune the blade neck stiffness for each flight condition encountered. Furthermore, the use of active patches and twist control "tendons" enables active compensation of vibrations and torsional deformations in future helicopter designs, Fig. 4 [3]. While these approaches will reduce noise and vibration, the weight savings from this approach are likely to be small, but could still significantly improve mission range. However, the largest pay-off will come from increased speed (from 160 to 200 knots) and greater maneuverability.

1.3 Active Coatings for Signature Suppression

Even today's most advanced submarines have acoustic signatures that emanate from the propulsion system, internal rotating machinery/
pumps and the flow of water over/around the hull. One of the most difficult problems to combat arises from the localized excitation of the acoustic modes of the hull. These couple effectively with the surrounding water and are readily detectable at long range. The role of smart materials here is as an active coating applied after the hull is assembled, Fig. 5 [3]. By embedding acoustic sensors in the coating, it is possible to measure the amplitude and frequency of an acoustic mode in the hull. If acoustic actuators are then built into the coating, it becomes possible to create 180° out-of-phase acoustic signals of an amplitude and frequency that match that of the acoustic mode. This results in destructive interference and a greatly reduced signal radiated into the surroundings.

This “active stealth” approach promises to greatly reduce acoustic signatures by 60dB or more [7]. While the acoustic displacements in this case are small (micrometers), a key feature of this smart materials application is the need for omnidirectional sound suppression across a relatively broad range of frequencies. For this to be accomplished, it is necessary to distribute the active coating widely over the surface of the submarine’s hull and to use a coating that is carefully designed to span the range of vibrational frequencies encountered.

These three applications of smart materials/structures embrace the key aspects of many other near-term smart material concepts under study [1,7,8]. Sensors measure the stresses, strains, displacements and temperatures within the components. Control systems recognize these and command signals to actuators that change shapes, elastic compliances and acoustic radiations in order to achieve a predetermined optimal response to the mission environment. It is important to recognize that these applications are our first tentative steps at the development of a potentially powerful new structural materials/structures technology that may eventually pervasively impact society.

2. Components/Processing of Smart Materials and Structures

Smart materials and structures are load carrying components that contain arrays of sensors and actuators embedded in such a way that overall mechanical properties are not adversely affected. The host material is usually a polymer or polymer matrix composite, though in principle, flexible structures built from metals
and ceramics are also possible. In fact, metal and ceramic structures containing embedded sensors that detect damage are already receiving much study for condition monitoring [9].

There would be no smart material without sensors. The last twenty years has witnessed intensive sensor development, and we are now able to draw upon a growing suite of sensor materials that includes piezoelectric and electrostrictive ceramics/polymers [10], embedded fiber optics [11,12] stress dependent luminescent and perhaps magnetic “tag” particles/fibers [13], ultrafast optical switching materials [7], microelectromechanical devices (MEMS) [14,15], solid state millimeter/microwave detectors [16] and sensitive magnetic sensors based on metal multilayers that exhibit giant magnetic resistance [17].

The incorporation of actuators in the material enables a structure to optimally respond to the environment in which it performs. These actuators must therefore “enable” changes of shape, modifications of elastic modulus, increases in damping or the excitation of destructively interfering acoustic signals. Today, we rely upon piezoceramics [18], shape memory alloys [19], electrorheologic fluids [20] and magnetostrictors [20] to accomplish this. These materials are being configured in novel ways to accomplish adaptive changes of smart structures.

These sensors and actuators are easily damaged during the sometimes aggressive conditions encountered during the synthesis of a composite component. It is essential that the temperatures, pressures and chemical environments used during the processing of smart materials are suitable for the synthesis of a composite with acceptable mechanical properties but do not damage its sensitive sensors/actuators. Processing is further complicated by the need to maintain components at optimal locations in the component. This can be a significant driver of cost. One approach to this extends filament winding/tape laying with directed energy heating to synthesize a composite structure layer by layer, Fig. 6 [22].

A smart material/structure is not just a material containing sensors and actuators. The electrical signals to/from these devices must be routed through the component in a way that does not interfere with its performance, and the entire assembly must be placed under the authority of a closed loop feedback control system. Concurrent engineering design concepts [22], Fig. 7, and intelligent processing of materials [23] strategies for processing are enabling technologies for the affordable manufacturing of smart materials/structures.

3. Fundamentals of Embedded Sensing

A variety of approaches are available for sensing the environment within a smart material. They include the use of piezoelectric ceramics
Fig. 7 Smart materials/structures are designed using a concurrent engineering methodology that simultaneously addresses component functionality (performance) and manufacturability [22].

and polymers, electrostrictive materials, embedded fiber optics, luminescent fibers, MEMS sensors and various types of "tag" particles. The principles underlying the use of many of these are briefly reviewed below.

3.1 Piezoelectric Sensors

The application of a stress (or strain) to some materials results in the development of an electric charge on its surface; a phenomenon that is known as the direct piezoelectric effect. It is a property of most non-centrosymmetric structure materials. All crystalline materials belong to one of 32 symmetry point group classes. Twenty-one of these classes have unit cells that are non-centrosymmetric (i.e. the arrangement of atoms in the unit cell is different after inversion about the unit cells center) and twenty of these exhibit piezoelectric behavior. Piezoelectricity is thus a fairly widespread phenomenon found in many insulating ceramics (e.g. quartz, lead zirconate titanate, barium titanate, lead titanate, etc.), some polymers such as polyvinylecledene fluoride (PVF$_2$) and many semiconductors [24].

As an example, consider the high temperature perovskite crystal structure of barium titanate (BaTiO$_3$) as shown in Fig. 8 [25]. It is centrosymmetric and is not piezoelectric. However, below about 130°C (its Curie point), the titanium ion (which carries a 4+ charge) shifts in the X$_3$ direction, resulting in the non-centrosymmetric structure shown schematically in Fig. 9(a) [10]. This form of BaTiO$_3$ is piezoelectric, and the origin of the phenomenon is easily seen in Fig. 9(b)-(c). For example when a stress $\sigma_3$ (in Voight notation) is applied, the crystal is elongated in the X$_3$ direction, the 4+ charge on the titanium ion moves further upwards from the center of the cell, a positive charge appears on the upper crystal surface and a negative one is seen on the bottom surface.

![Perovskite structure (idealized)](image)

Fig. 8 The high temperature (T>130°C) structure of BaTiO$_3$. It has a centrosymmetric structure and is not piezoelectric [25].

The strength of the piezoelectric effect can be quantified using a piezoelectric modulus (or piezoelectric strain coefficient), $d$, defined by
\[ \Delta P = d \sigma \]

Where \( \Delta P \) is polarization charge (coulomb) per unit area (m\(^2\)) and \( \sigma \) is the stress (Nm\(^{-2}\)). Thus the units of \( d \) are CN\(^{-1}\). Since the polarization is a vector and stress is a second rank tensor, \( d \) is a third rank tensor. In Voight notation, it can be written as a matrix with components \( d_{ij} \) where \( i \) is the direction of polarization and \( j \) is the stress direction (see Fig. 9).

If a piezoelectric crystal is attached to, or embedded within, a smart material, any mechanical stress (static or dynamic) introduced into the crystal causes a polarization to develop. This can be sensed by monitoring the resulting voltage that is developed across the crystal. It is related to the electric field, \( E \), developed across the crystal, and so a figure of merit for a piezoelectric stress (or strain) sensor is the piezoelectric voltage coefficient tensor, \( g \), (units of VmN\(^{-1}\)) given by

\[ g = \frac{d}{\varepsilon \varepsilon_0} = \frac{E}{\sigma} \]

where \( \varepsilon_0 \) is the free space permittivity (8.85x10\(^{-12}\)Fm\(^{-1}\)) and \( \varepsilon \) is the dimensionless dielectric constant (the dielectric susceptibility divided by the free space permittivity). Tensor component values for some commonly used piezoelectric materials are given in Table 1 [26].

Many of the best piezoelectric materials are polycrystalline. They are synthesized by con-

---

**Table 1: Piezoelectric and Relative Permittivity Constants for Selected Piezoelectric Materials [26].**

<table>
<thead>
<tr>
<th>Material System</th>
<th>Piezoelectric Strain Constants (x10(^{-12})C/N)</th>
<th>Relative Permittivity((\varepsilon))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barium Titanate</td>
<td>(d_{33}) (d_{31}) (d_{15})</td>
<td>(\varepsilon_{33}) (\varepsilon_{11})</td>
</tr>
<tr>
<td>Barium Titanate*</td>
<td>37 -34.5 392</td>
<td>168 2920</td>
</tr>
<tr>
<td>Lead Zirconate Titanate*</td>
<td>152 -60 440</td>
<td>450 990</td>
</tr>
<tr>
<td>(PZT-2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead Zirconate Titanate*</td>
<td>593 -274 741</td>
<td>3400 3130</td>
</tr>
<tr>
<td>(PZT-5H)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithium Niobate</td>
<td>6 -1 68</td>
<td>30 84</td>
</tr>
</tbody>
</table>

*Uniaxially poled polycrystalline material.
solidating and then sintering ceramic powders [24]. Usually, this results in no overall piezoelectric effect because the polarization vectors of individual grains are random. However, by cooling these materials through their Curie points under a strong uniaxial electric field, the polarizations of each domain can be lined up, creating large values of the piezoelectric constant, Fig. 10, and enabling the sensitive detection of transient stresses associated with elastic wave propagation/vibration of structures. Because the poling effect only disappears upon reheating a polycrystalline piezoelectric ceramic above its Curie point, these materials can also be used for some elevated temperature applications (e.g. up to about 300°C for PZT-5H). Higher temperatures are achievable with single crystal materials. For example, lithium niobate (LiNbO₃) can be used up to 600°C in reducing environments and at much higher temperatures in the presence of small oxygen partial pressures (its Curie point is 1138°C).

![Fig. 10 Cooling a polycrystalline piezoceramic in a strong uniaxial field results in an overall piezoelectric effect.](image)

The piezoelectric sensors are used to convert transient mechanical stresses to voltages that can be amplified and used to monitor the vibrations of a structure. It is important to realize that the signal from these devices may not faithfully replicate the amplitude of the transient stresses in the structure. This arises because the transducers themselves are finite dimensional structures and so exhibit elastic resonances of their own. The sensitivity of the transducers is a maximum near these resonances and are governed by the geometry of the sensor. Since the basic process of transduction involves the propagation of transient elastic stresses from the structure (or its environment) into the piezoelectric sensor element itself, a second design criterion is minimization of elastic wave reflections at the sensor’s surface. These increase as the difference in the acoustic impedances (the product of density and acoustic velocity) of the sensor/surroundings increases. The acoustic impedance of a typical piezoceramic sensor, \( Z_s = 30 \times 10^6 \text{ Kg m}^{-2}\text{s}^{-1} \), while that of say water is \( 1.5 \times 10^6 \text{ Kg m}^{-2}\text{s}^{-1} \). Polymer transducers such as polyvinyletedene fluoride (PVF₂) have \( Z_s = 3.22 \times 10^6 \text{ Kg m}^{-2}\text{s}^{-1} \), and are much better matched to water, but they are less sensitive than PZT. One solution is to use composite transducers made up of arrays of ceramic sensors embedded in a low acoustic impedance polymer, Fig. 11 [26].

**Composite Transducer**

![Fig. 11 Example of a composite transducer in which PZT rods/disk sensor elements are distributed in a polymer matrix](image)

### 3.2 Fiber-Optic Sensors

The emergence of optical fiber communications technologies in the 1970’s has enabled the development of embedded optical sensors for process condition monitoring and for smart materials/structures applications [27]. Most concepts have addressed the measurement of strain. Strain affects the refractive index (i.e. the optical velocity) of the fiber [28] and
changes the fiber's dimensions. Several techniques have been developed to exploit both of these effects [29], and many applications are underway using commercially available sensors [30,31].

The simplest case to consider is the two fiber Michelson interferometric fiber optic sensor shown in Fig. 12 [29]. In this approach a coherent laser signal is optically propagated along two fibers of differing lengths. The ends of each optical fiber are silvered to ensure almost complete reflection of the signal back to a photodetector. The two signals travel different distances and so their individual signals are out of phase resulting in interference. If a strain is now applied to the body in which the fiber ends are embedded, the extra change in length and the strain induced refractive index change of the longer fiber results in a change in the degree of interference which is registered as a voltage change from the photodetector that is related to the strain.

![Fig. 12 A Michelson interferometric fiber optic sensor for measuring strain.](image)

While this type of sensor has been successfully used in laboratory settings for measuring acoustic emission [31], it is not well suited to smart structural applications because it requires the embedding of a pair of sensors which can seriously weaken a structure, its common mode rejection is weak (both fibers may "see" the strain field and so cancel the differential response) and it is quite noise sensitive. The latter issue can be very serious in some applications because if one arm of the interferometer experiences a significant disturbance, the photodetector signal changes and the strain sensitivity changes. As a result, commercially available sensors are based upon one of four different approaches: Fabry-Perot cavities, two mode fibers, polarimetric sensors and intracore Bragg gratings.

The Fabry-Perot approach is very simple yet sensitive and can be designed as a single-ended device or as part of a continuous fiber, Fig. 13. In either case, a coherent optical signal is reflected from two reflectors and the reflections are combined at a detector. Path length differences result in interference at the detector and an output signal that is a function of the spacing and refractive index between the reflectors. Multiple reflections in the cavity then result in a sensor with very high strain sensitivity.

![Fabry-Perot fiber optic sensor configurations](image)

Fig. 13 Fabry-Perot fiber optic strain sensors use multiple reflections between pairs of reflectors to create an interference signal that depends linearly upon axial strain [32].

Suppose a Fabry-Perot sensor is embedded in a body to which a load is applied in the fiber direction. This results in a uniaxial stress, \( \sigma_z \), in the fiber direction. If the fiber does not perturb the stress field of the body, and Hooke's law is obeyed, the uniaxial strain in the body, \( \varepsilon_z = \sigma_z E \) where \( E \) is the body's Young's mod-
ulus (Pa). For a well bonded fiber, the matrix
and fiber axial strains are the same for axial
loading of the body, and so the phase change is
given by
\[ \Delta \Phi = Sl\varepsilon_z \]
where \( l \) is the gauge" length and \( S \) is a phase-
strain sensitivity index. For the "extrinsic" type
of sensor in Fig. 13(b) (of the Michelson type),
\[ S = k\varepsilon_z \left( 1 - \frac{n^2 P_e}{2} \right) \]
where \( k = \) the free space propagation constant,
\( n = \) the refractive index of the fiber core and \( P_e \)
is an effective strain optic coefficient. For iso-
tropic materials, \( P_{11} \) and \( P_{12} \) are the only two
independent strain optic coefficients [33] and it
can be shown that
\[ P_e = \left[ P_{12} - \nu(P_{11(12)} + P_{12}) \right] \]
where \( \nu \) is the Poisson's ratio of the fiber.
This simple theory predicts a linear relation-
ship between phase change and axial fiber
strain. It even gives a good estimate (within
5%) for \( \varepsilon_z \) when the loads are axial. However,
for a general loading, the fiber does perturb
the strain field of the host and a more complicated
analysis is needed [12]. The detector voltage is
also a nonlinear function of the phase differ-
ence so this sensor's output is a nonlinear func-
tion of strain.

The interferometric sensor can be improved
by using an e-core two-mode fiber in the gauge
section to maintain the optical polarizations
(and so avoid polarization fading). These ellipt-
ical cored fibers [34] change the transverse
spatial mode distribution of light within the
sensor. The basic idea [29] is to propagate a
lowest order transverse mode in the lead-in
fiber and then transmit this into a short section
of e-core optical fiber that allows two trans-
verse optical modes to propagate at the wave-
length of the single lead-in fiber mode. This
can be accomplished with simple fusion splic-
ing. Polarimetric sensors use the change of
polarization of light travelling in a high birefrin-
gence fiber to sense strain [32]. They require
quadrature detection, special demodulation
schemes, and are, as yet not very practical.

The intracore Bragg grating fiber optic sensor
approach shown in Fig. 14 is much more
attractive for smart structures and is widely
used [32,35]. These sensors use a periodic
grating that modulates the refractive index of
the fiber core. The back reflected spectrum has
a sharp peak whose wavelength, \( \lambda_B \), is given by
\[ \lambda_B = 2n\Gamma \]
where \( n = \) the core's effective refractive index
and \( \Gamma = \) the modulation length. Strain in the
axial direction changes \( \Gamma \) and \( n \) and so shifts
the peak position. Measures [36] has shown
that the peak shift for a particular linearly
polarized mode is given by
\[ \Delta \lambda = \lambda_B [1 - P_e] \varepsilon_z \]
where \( \lambda_B \) and \( P_e \) are for the Bragg wavelength
and effective strain optic tensor for the polariz-
ation mode of observation. The output of this
sensor \( (\Delta \lambda) \) is thus a linear function of the
strain, though again, the effects of a general
state of stress will complicate analysis.

These fiber optic sensors respond to both strain
and temperature. The latter is usually unknown
in a smart materials application and is thus a
potential source of error. One method for deal-
ing with this is to use a second fiber to monitor
temperature only (i.e. by decoupling) it from
the strain field. This can be simply achieved by
inserting the sensing end of a fiber in a hollow
capillary prior to embedding in the host (see
Measures et al [32] for further discussion).

3.3 Luminescent Fibers

Several techniques have been developed for
measuring stress using the luminescence of
Cr\(^{3+}\) ions in \( \alpha\text{-Al}_2\text{O}_3 \) [13,37]. The approach is
based upon the quite strong stress dependence
of the R1 and R2 emission frequencies from
chromium-doped alumina. The level of Cr\(^{3+}\)
doping can be quite small and most commer-
cial grades of alumina contain more than
Fig. 14 The Intracore Bragg Grating fiber optic sensor uses a shift of Bragg frequency to sense strain.

enough chromium for this sensor application. The recent development of techniques for synthesizing single crystal alumina fiber with moderately good optical propagation characteristics now enables sensors to be embedded in composites (even metal and ceramic matrix composites processed at 1000°C and above) and their internal strains sensed.

Luminescence arises from the radiative decay (emission of a photon) from an excited electronic state. The conditions for luminescent emission are rather stringent and only a relatively small percentage of molecules luminesce. In the case of Cr$^{3+}$ embedded in the $\alpha$-Al$_2$O$_3$ lattice decay occurs from two crystal field split excited states resulting in two emission peaks with wavelengths of about 693 and 694 nm. The positions of both peaks are a function of stress. When the c-axis of the alumina crystal is aligned with the $\sigma_3$ principal stress, the line shifts $\Delta v$ are given by

$$\Delta v = \Pi_{11}(\sigma_{11} + \sigma_{22}) + \Pi_{33}\sigma_3$$

where for the R1 line, the piezospectroscopic coefficients, $\Pi_{11}$ and $\Pi_{33}$ have values of 3.0 and 1.8 cm$^3$/GPa respectively. Thus, the peak shifts are linearly related to stress, and are sufficiently large to be measurable using a spectrometer with a fine spacing grating. The approach is being used to interrogate residual stress fields in composites and has been used in the laboratory to measure stresses induced by applied loads. When alumina powder is dispersed as tag in a suitably transparent matrix, the technique could also be used to observe stress distributions in structures under load provided the matrix is optically transparent.

<table>
<thead>
<tr>
<th>Table 2: A comparison of actuators for smart materials.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Actuation Mechanism</td>
</tr>
<tr>
<td>Max Strain ($x 10^6%$)</td>
</tr>
<tr>
<td>Young’s Modulus</td>
</tr>
<tr>
<td>Bandwidth</td>
</tr>
</tbody>
</table>

(m) = martensite (a) = austenite
4. Actuators

The actuators in a smart material/structure provide the mechanism for the structure to adapt to its surroundings by suppressing vibrations or changing the structure’s shape. In the future, one might imagine that more sophisticated needs will emerge (e.g. self healing of damage, active dielectric property control, local thermal control, etc.). However, even current needs are challenging since they require actuation authority over a broad bandwidth spectrum (from a few Hz for MAW’s to hundreds of kHz for active vibration suppression) and over a wide range of displacement amplitudes (e.g. from tenths of micrometers for vibration control to millimeters/centimeters for a MAW application). A variety of approaches are available/emerging including piezoelectrics/electrostrictors, magnetostrictive devices, shape memory alloys and electrorheological fluids (see Table 2 for a comparison of their capabilities).

4.1 Piezoelectric/Electrostrictive Actuators

Piezoelectric materials not only develop a polarization when subjected to a strain, they deform when an electric field is applied. The sign of the displacement is determined by the polarity of the field. This converse piezoelectric effect can be used to transmit acoustic signals and to suppress structural vibrations. If a strong electric field is applied (or weaker fields if the temperature just above the Curie point), the ferroelectric domains lose their polar alignment and become aligned with the new field. This domain flipping gives rise to a strain that then depends only on the magnitude of the electric field (and not on its polarity as with piezoelectricity) and is known as electrostriction [25].

Typical (polycrystalline) piezoelectric ceramics like PZT are able to generate strains of 0.1-0.2% (at about 10kV/cm) before the applied voltage reaches the threshold for dielectric breakdown. However, these large fields can change the poling and lead to a form of piezoelectric fatigue so that the strain obtained reduces with the number of electric field cycles. Electrostrictive materials such as lead magnesium niobate (PMN) are able to achieve similar strains but show no effect of cycling [10]. The magnitude of both the piezoelectric and electrostrictive contributions to deformation are a function of the ceramics’ microstructure - the largest deformations are almost always obtained from single crystal materials, and are motivating research aimed at affordable methods for their synthesis.

The Sonofanel™ concept is a recent example of a piezoelectric smart material application [38]. These panels are used in underwater applications for active surface control. They are based upon a two dimensional array of axially poled PZT cylinders, Fig. 11. The array is fabricated using low cost injection molding, Fig. 15. This is followed by firing in air to both burn out the organic binder and to sinter the ceramic powders. The sintered preforms are then poled by cooling through the Curie point in an axial electric field. The region between the piezoelectric rods is subsequently filled with a castable polymer polyurethane that may contain up to 40% hollow polymer microspheres to increase elastic compliance and reduce density. Both surfaces are then ground flat to expose the piezoelectric rod ends. PZT piezoelectric accelerometers (sensors) are introduced and the assembly is bonded to glass-reinforced polymer (GRP) face sheets using a conducting epoxy. Shielding (to avoid cross talk) is also added prior to a final encapsulation in polyurethane, Fig. 16 [38].

Piezoelectric actuators can also be used to control vibrations in say helicopter rotors. These applications require the actuator to counteract the different modes of bending/torsion for a beam-like structure. This can be accomplished using pairs of piezoelectric sheets bonded to either side of a beam, Fig. 17.

4.2 Magnetostrictive Actuators

When most solids are placed in a magnetic field, they change their length [39]. For many materials the effect is very small, but for ferromagnetic materials below their Curie points,
Fig. 15 A schematic diagram showing the injection molding process used for low cost manufacturing of ceramic cylinder array. (1) Hot powder-binder mixture in a nozzle. (2) Injection of mix into die. (3) Mix cools to form a solid (green) part. (4) Net-shape array is ejected [38].

Fig. 17 Bending (a) and torsion (b and c) of a rectangular cross-section beam can be controlled with piezoelectric uniaxial/shear strain layers bonded to either side of the beam [5].

Fig. 16 Schematic cut-away view of a 0.1m x 0.1m Sonofane\textsuperscript{TM} smart panel showing integrated velocity sensors (accelerometers) and the piezoelectric actuator array [38].

larger magnetostrictive strains of \(-10^{-3}\)\% are possible, and in a few of the rare earth systems, strains of more than 0.1% can be achieved\cite{21}. The atomic origin of the phenomenon arises from spin-orbit coupling of the outer electrons. The effect is shown (in greatly exaggerated form) in Fig. 18 \cite{39}.

At a more macroscopic level, magnetostriction is associated with the field-induced movement of magnetic domain walls, Fig. 19. These domain walls are defined by the angle between the magnetization vectors of adjacent domains on either side of the wall. Two types exist: 180\(^\circ\) walls and non-180\(^\circ\) walls (usually called 90\(^\circ\) walls for simplicity). In Fig. 19, as in most polycrystalline ferromagnetics, both types exist. The movement of 180\(^\circ\) walls reverses the direction of magnetization and does not cause a length change (see Fig. 18) and so magnetostriction arises from the motion of the 90\(^\circ\) boundaries.

The largest (~1\%) magnetostrictions are observed in hexagonal rare earth compounds containing Tb and Dy which have very anisotropic 4f electron distributions. However, their Curie temperatures are too low (T\(_c\),<240K) for most smart materials/structures applications. In the last twenty years or so TbFe\(_x\) (terfenol) and SmFe\(_x\) (samfenol) Laves phase compounds have been synthesized with magneto-
Fig. 18 A row of four atoms is shown together with their magnetic moments. Above the Curie temperature ($T_c$), the moments are randomly oriented and the material is paramagnetic. Below $T_c$ the moments spontaneously align because of spin-spin coupling and a “spontaneous” magnetostriction occurs even when the magnetic field intensity, $H$, is zero. Applying a magnetic field perpendicular to this spontaneous alignment realigns the moments and results in a field-induced magnetostriction [39].

Fig. 19 Magnetostriction of a cubic ferromagnetic occurs by the movement of 90° domain walls.

Magnetostriction

Iron Crystal Magnetostriction

Fig. 20 A prototypical magnetostrictive actuator [40].

4.3 Shape Memory Alloys

When high forces or large displacements are required in a smart materials application (e.g., to change the camber of a mission adaptable wing), designers are increasingly making use
Table 3: Material Systems that exhibit the shape memory effect [42].

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Composition</th>
<th>$M_s$ ($^\circ$C)</th>
<th>Transformation Temperature Hysteresis ($^\circ$C)</th>
<th>Ordered or Disordered</th>
<th>Volume Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>AgCd</td>
<td>44–49at.%Cd</td>
<td>190–50</td>
<td>15</td>
<td>ordered</td>
<td>-0.16</td>
</tr>
<tr>
<td>AuCd</td>
<td>46.5–50at.%Cd</td>
<td>30–100</td>
<td>~15</td>
<td>ordered</td>
<td>-0.41</td>
</tr>
<tr>
<td>CuAlNi</td>
<td>14–14.5wt.%Al 3–4.5wt.%Ni</td>
<td>140–100</td>
<td>~35</td>
<td>ordered</td>
<td>-0.30</td>
</tr>
<tr>
<td>CuAuZn</td>
<td>23–28at.%Au 45–47at.%Zn</td>
<td>190–40</td>
<td>~6</td>
<td>ordered</td>
<td>-0.25</td>
</tr>
<tr>
<td>CuSn</td>
<td>~15at.%Sn</td>
<td>120–30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CuZn</td>
<td>38.5–41.5wt.%Zn</td>
<td>180–10</td>
<td>~10</td>
<td>ordered</td>
<td>-0.5</td>
</tr>
<tr>
<td>CuZnX (X=Si,Sn,Al,Ga)</td>
<td>few wt.% x</td>
<td>180–100</td>
<td>~10</td>
<td>ordered</td>
<td></td>
</tr>
<tr>
<td>InTi</td>
<td>18–12at.%Ti</td>
<td>60–100</td>
<td>~4</td>
<td>disordered</td>
<td>-0.2</td>
</tr>
<tr>
<td>NiAl</td>
<td>36–38at.%Al</td>
<td>180–100</td>
<td>~10</td>
<td>ordered</td>
<td>-0.42</td>
</tr>
<tr>
<td>TiNi</td>
<td>49–51at.%Ni</td>
<td>50–100</td>
<td>~30</td>
<td>ordered</td>
<td>-0.34</td>
</tr>
<tr>
<td>FePt</td>
<td>~25at.%Pt</td>
<td>~130</td>
<td>~4</td>
<td>ordered</td>
<td>0.8–0.5</td>
</tr>
<tr>
<td>FePd</td>
<td>~30at.%Pd</td>
<td>~100</td>
<td></td>
<td>disordered</td>
<td></td>
</tr>
<tr>
<td>MnCu</td>
<td>5–25at.%Cu</td>
<td>250–180</td>
<td>~15</td>
<td>disordered</td>
<td></td>
</tr>
</tbody>
</table>

of shape memory alloys (SMA's). The shape memory phenomenon is the ability of a material to remember its original shape either after suffering a mechanical deformation (the so-called one-way effect) or upon heating/cooling (the two-way effect) [42]. This remarkable phenomenon is exhibited by several materials that undergo thermelastic martensitic transformations, Table 3. Today, materials based upon equiatomic NiTi alloys (Nitinol) are being extensively studied for a variety of applications [43].

Hornbogen has developed a scheme to simply show the various constitutive behaviors that can be encountered with a shape memory alloy. Fig. 21 shows the typical (normal) behavior found in many single phase materials: linear elasticity up to the yield strength ($\sigma_y$) of the $\beta$-phase. The material also exhibits normal thermal expansion/contraction strains on heating/cooling. This behavior is found in all SMA's when they are used at a temperature

![Temperature / Stress / Strain](image)

Fig. 21 The various types of constitutive response exhibited by a SMA that exhibits a $\beta \rightarrow \alpha$ martensitic transformation on cooling.
well above that where the martensitic transformation occurs. As the temperature is lowered (but still above the martensitic start, Mₐ, temperature) a stress can induce a transformation of the β-phase to the martensitic (α phase) at a stress σₜₐₐ. This gives a large strain increment which is recovered upon unloading as the α-phase retransforms back to β. The thermal strains are still "normal" in this test temperature region. If the test temperature is reduced further, Fig. 21(c), the reverse transformation does not occur on unloading and a permanent strain (ε₁ₚₐₐ) remains. This can be removed (and the material returns to its original shape) upon heating and is the origin of the one-way shape memory effect. Thus, material in the form of say a spring (made by annealing a wire in die at T >> the austenite finish temperature, A₁) in the β-phase condition can be loaded (to a stress as high as σₜₐₐ) and it will inelastically deform an amount ε₁ₚₐ. The original spring length is then returned upon heating (with an electric current perhaps). Since σₜₐₐ can be quite high (~500MPa), large stresses and big strains can be achieved via this effect. The two-way effect, Fig. 21(d), is very useful because it allows a large strain (up to 6%) to be repeatedly exerted by just heating or cooling the alloy through the β→α and α→β temperature region. This can be done (by a training procedure) so that the body returns to an original shape after each thermal cycle.

We have not addressed the issue of how a SMA is able to perform in such an unusual way. The reason lies in the mechanism by which the change of shape is achieved. We usually think that dislocations are responsible for inelastic deformations in malleable metals. Because of dislocation tangling, their deformations are usually not recoverable (beyond a very small amount associated with the Bauschinger effect). In SMA's, the deformation is achieved by a martensitic transformation. Fig. 22 shows how this can be achieved for the pseudelastic and one-way effect cases of Fig. 21(b) and (c).

The two-way effect is a little more complicated and is based on the existence of many slightly different martensitic variants. The application of a load to a pre-existing martensite can result in twinning/stacking fault formation and the creation of a different martensite variant, Fig. 23. By repeatedly deforming (training) the material, defects are introduced and retained in the structure. These predispose the selection of variants and result in a repeatable change of shape upon thermal cycling through the α→β→α transformations.

SMA actuators can be designed using either the one- or two-way effect. Two-way (push-pull) behavior can be achieved with a one-way alloy behavior by using a "bias" force technique. For example, a two-way actuator using a spring to provide a bias is shown in Fig. 24. These materials are beginning to be introduced.
Fig. 23 In the two-way effect a training procedure is used to select the martensitic variants that give a desired shape change.

into MEMS devices creating a whole new range of future smart materials uses. Regardless of which type of SMA effect is used, these materials suffer fatigue degradation during prolonged use — especially when the loads are high. Furthermore, many processing operations can introduce undesirable microstructure changes and large residual stresses, and so the incorporation of these materials into a structure can be challenging.

Fig. 24 A two-way actuator can be built using the one-way SMA effect and a simple spring.

4.4 Electrorheological Fluids

Electrorheological (ER) fluids are materials whose rheological properties (i.e. apparent viscosity) can be changed by the application of an electric field [20, 44, 45]. Fig. 25 shows an example of this for a typical ER fluid. We see that the viscosity, \( \eta \), (defined as the change in stress per change in shear strain rate, \( \dot{\gamma} \)) changes only slightly when an electric field is applied; what really changes is the shear stress \( \tau_y \) needed to initiate flow. To a reasonable approximation a Bingham model describes the shear flow stress:

\[
\tau_y = \tau(E) + \eta \dot{\gamma}
\]

where \( \tau(E) \) is an electric field (E) dependent flow stress obtained as \( \dot{\gamma} \to 0 \). ER fluids consist of a liquid dielectric (e.g. oil), polarizable particles (e.g. cornstarch) and an activator such as water. In a no field state, the particles are randomly distributed and the viscosity is governed by Newtonian flow around the particles. However, when a field is applied, the particles line up along field lines creating a more rigid structure that better resists shear.

Fig. 25 Shear stress versus strain rate for an ER fluid with and without an electric field. The shear stress to initiate a shear strain is a strong function of the electric field.

General Atomics has recently developed a novel “smart material” by combining an electrorheological fluid with a very compliant elastomer to create an electro-active elastomeric structure (EAES) [46]. This avoids the need for fluid seals and results in a bulk material that can be applied as coating. By integrating acoustic sensors and electrodes into the material, it is possible to sense incoming acoustic signals in a marine environment and to then modify the elastic/damping characteristics of
the coating (using the ER effect) with millisecond time response.

Fig. 26 shows a schematic diagram of the General Atomics EAES smart material concept. It is composed of a soft silicone elastomer with an open cell structure. The cells are filled with an ER fluid consisting of polydimethylsiloxane silicone oil terminated with nonreactive CH₃ groups, polarizable particles (cornstarch) and water. Normally the EAES is soft (elastic modulus ~3500 Pa), but when an electric field is applied, the polarizable particles line up and the structure stiffens considerably. By varying the volume fractions of the constituents and the cell morphology of the elastomer, the properties of this material can be widely varied and tailored to suit specific applications, e.g., to control flow noise in hydroacoustic environments or acoustic isolation of hull mounted sonar systems.

Fig. 26 A schematic diagram of the General Atomics EAES smart material concept [46].

5. Conclusions

This lecture has sought to introduce some of the emerging applications of smart materials and structures. The important concepts underlying these revolutionary new materials (sensing, recognizing and responding to the environment) have been reviewed. The need has been emphasized for sophisticated (concurrent) design and affordable synthesis/processing methodologies to enable these emerging materials concepts to become cost effective solutions to engineering problems.

Acknowledgments

I am grateful to Dr. Robert Crowe of the U.S. Defense Advanced Research Projects Agency for very helpful discussions about ongoing programs in smart materials and structures.

References

1. Steven Ashley, Mechanical Engineering, November, 1995, p. 76.
3. R. Crowe, Private Communication.
11. T. Sato, H. Ishikawa and O. Ikeda,
21. A.E. Clark, ibid, p. 387.