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Intelligent materials—An overview

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Development in the area of materials research aims at incorporating intelligence into engineering materials, enabling them to sense the external stimuli and alter their own properties to adapt to the changes in the environment. This paper discusses possible forms of intelligence that may be incorporated in these materials. Three basic mechanisms of intelligent materials, namely, the sensor, processor and actuator functions, are described. Implementation of these in the microstructure of various materials, as well as associated algorithms and techniques are illustrated. Different models, control algorithms and analyses developed by various researchers are reviewed and their potential applications in engineering materials are presented.

1 INTRODUCTION

Engineering materials are used either for their inherent structural strength or for their functional properties. Often a feedback control loop is designed so that the mechanical response of the material is monitored and the environment that is causing such a response can be controlled. The evolution of a new kind of material termed 'Intelligent', 'Smart', or 'Adaptive' by various researchers, see, e.g. Ref 1 and 2, differs from this well known control loop mechanism whereby the material adapts itself to suit the environment rather than necessitating to control the same. The following sections present the concepts behind such materials, the forms of intelligence available, and the methods by which these could be incorporated into engineering materials to make them intelligent with respect to the operating environment.

1.1 Definition of an intelligent material

'Intelligent' or 'Smart' materials may be defined as 'Those materials which sense any environmental change and respond to it in an optimal manner'.[3] From this definition and the analogy of the *bionic* system of humans and animals, it can be seen that the following mechanisms may be essential for any material to be made intelligent:

(i) A sensing device to perceive the external stimuli (skin which senses thermal gradients, an eye that senses optical signals, etc.), termed as 'sensor' function.
(ii) A communication network by which the sensed signal would be transmitted to a decision-making mechanism (e.g. the nervous system in humans and animals), termed as 'memory' function.
(iii) A decision-making device which has the capability of reasoning (e.g. the brain), termed as 'processor' function.
(iv) An actuating device, which could be inherent in the material or externally coupled with it (e.g. stiffening of muscles in humans and animals to resist deformation due to external loading), termed as 'actuator' function.

All of the above mechanisms need to be active in real time applications for the material to respond intelligently. Another important factor in this whole process is the time of response. This is the interval between the instant when the sensor senses the stimulus and that of the actuator response. An optimum time interval is

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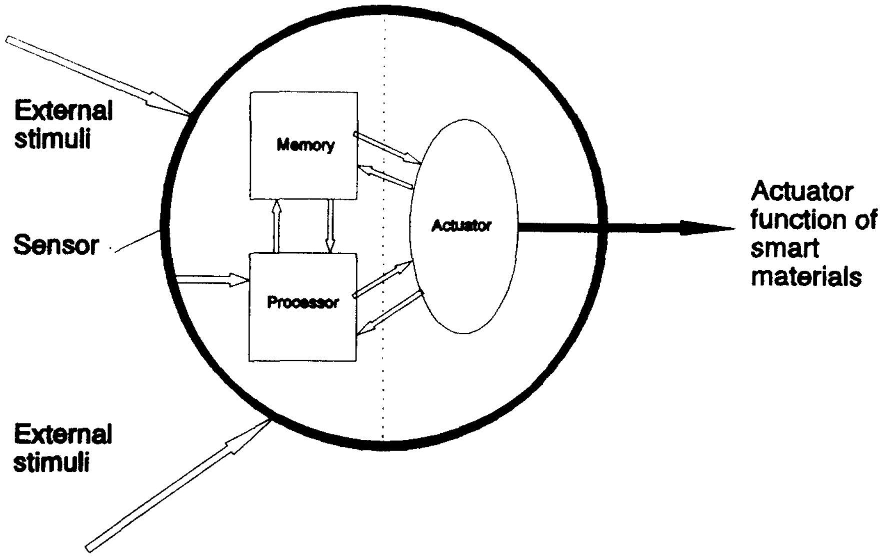

Fig. 1. Concept of an intelligent material.

crucial in the design of intelligent materials and is dependent on the type of application.

2 CONCEPT OF INTELLIGENT MATERIALS

Designing a material with sensor, processor and actuator functions is the fundamental step in the evolution of an intelligent material for achieving a desired response adaptable to the environment. This concept is illustrated in Fig. 1.

2.1 Sensor function

The concept of a sensor function in a smart material is defined as the ability of the material to sense the response characteristics of self with respect to environmental factors such as mechanical loading, temperature, humidity and electrical inputs. An example of this function is that of a piezoelectric sensor embedded in a composite material. This sensor diagnoses the mechanical disturbance imposed on the material by generating a voltage which can be further measured and analysed.

2.2 Memory and processor function

This mechanism stores the signals sensed and transmitted by the sensor function. The characteristics of these signals are then compared with prestored acceptable values acquired during the 'training' process of the processor. The training process may be carried out using an artificial intelligence technique, e.g. pattern recognition method. Typically, this function is in the form of an executable artificial intelligence software that could produce a logical output in the form of an electrical voltage that could further be amplified and used to activate an actuator mechanism.

2.3 Actuator function

This mechanism is coupled with the material. It produces an output corresponding to the signal received from the processor function. This output is usually in the form of restoring stress, strain or change in temperature, or stiffness of the actuator mechanism that is coupled with the material. This change would be designed to neutralize the effect of the change in environment on the material, thereby adapting the material continuously to its environment.

A typical intelligent composite cantilever beam, which consists of sensor, processor and actuator functions, is illustrated in Fig. 2.

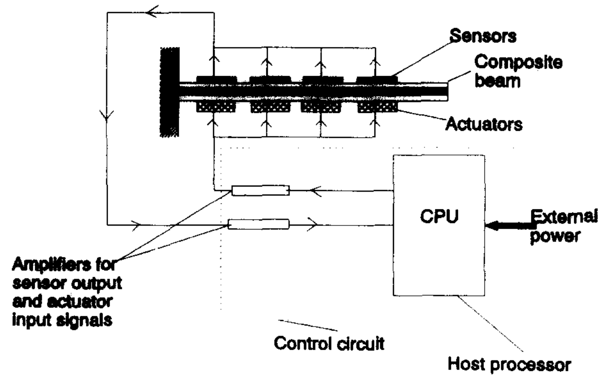

Fig. 2. Incorporation of sensor, processor and actuator functions in an intelligent composite beam.

3 ARTIFICIAL INTELLIGENCE IN MATERIALS

Different forms of substances that could be incorporated into the material as sensors and actuators are piezoelectric and piezoceramic devices. Optical fibres are used as sensors, shape memory alloys, and shape memory polymers, and electrorheological fluids are employed as actuators. The following sections describe the effectiveness of such materials as intelligent substances[4] and their successful implementation in real time applications.

3.1 Piezoelectric and piezoceramic devices

Piezoelectric and piezoceramic materials could be used as sensors and actuators in intelligent materials. These materials can convert a mechanical signal to an electrical voltage. Various researchers have developed models, through analytical and numerical simulation as well as experimental techniques,[5–13] to verify the concept of piezoelectric materials as intelligent sensors and actuators.

A piezoelectric material is a crystal in which electricity or electric polarity is produced by pressure. Conversely, a piezoelectric material deforms when it is subjected to an electric field. The first characteristic expresses the direct effect, while the second expresses the converse effect.[5,14,15] Following the above characteristics of a piezoelectric crystal, if the pressure on the crystal is replaced by a stretch, the sign of the electric polarity would be reversed accordingly. This is determined by the crystal structural 'bias', which establishes whether a given region on the surface is subjected to a positive or a negative mechanical effect. In the converse effect, the same unidirectional aspect determines the sign of deformation when the direction of an electric field is reversed in the crystal. It is this reversal of sign of mechanical strain with that of the electric field that distinguishes piezoelectricity from electrostriction.[14]

The basic quasistatic theoretical treatment of a piezoelectric material under loading is based on the definition of four parameters that describe the elastic and electric states of this material. These are the elastic stress (σ_{ij}), elastic strain (ε_{ij}), electric displacement (D_i) and electric field (ξ_i). Any two of these four parameters may be chosen to be the independent variables and the other two will accordingly be the dependent variables in the model. In addition to the above-mentioned parameters, the mechanical equilibrium equation ($\sigma_{ji,j} + f_i = 0$), Maxwell's equation ($D_{i,i} = 0$) and the electrical and mechanical boundary conditions would be specified for a complete description of the electro-mechanical state of the piezoelectric material.

3.1.1 Constitutive relationships

The phenomenon of piezoelectricity is assumed to be linear whereby the electric and elastic quantities are considered to be linearly related. Thus, the electric polarization (P_i) is seen to be related to the elastic stress σ_{ij} by the relation:

$$P_i = d_{ijk}\sigma_{jk} \tag{1}$$

where the components d_{ijk} are the piezoelectric strain coefficients.

The existence of such a polarization will result in an electric field ξ_i which would be linearly related to the polarization P_i through the relation $P_i = \varepsilon_0\chi_{ij}\xi_j$ where ε_0 is the universal dielectric constant and χ_{ij} are the electric susceptibility coefficients of the material. Therefore, the complete equation for the direct piezoelectric effect is written as

$$P_i = d_{ikl}\sigma_{kl} + \varepsilon_0\chi_{ij}\xi_j \tag{2}$$

or, in terms of the corresponding strains ε_{jk}:

$$P_i = e_{ijk}\varepsilon_{jk} + \varepsilon_0\chi_{ij}\xi_j \tag{3}$$

where the components e_{ijk} are the piezoelectric stress coefficients.

An alternative form to eqns (2) and (3) is expressed in terms of the electric displacement, i.e.

$$D_i = d_{ikl}\sigma_{kl} + K_{ik}\xi_k \tag{4}$$

where K_{ik} is the permittivity tensor.

In the converse effect, strains (or stresses) are produced. They are assumed to be linearly related to the imposed electric field ξ_i, i.e.

$$\varepsilon_{jk} = d_{ijk}\xi_i \tag{5}$$

$$\sigma_{jk} = -e_{ijk}\xi_i \tag{6}$$

The occurrence of a stress (or strain) would further evoke a corresponding mechanical response in the crystal. The total stress contribution of a converse piezoelectric effect is, thus, expressed as:

$$\sigma_{ij} = E_{ijkl}\varepsilon_{kl} - e_{kij}\xi_k \tag{7}$$

The corresponding strain contribution is given by

$$\varepsilon_{ij} = C_{ijkl}\sigma_{kl} + d_{kij}\xi_k \tag{8}$$

where, in eqns (7) and (8), E_{ijkl} and C_{ijkl} are the elastic modulus and compliance tensors, respectively.

Table 1 describes the utilization of direct and converse effects as applied to the sensor and actuator functions of intelligent materials.

3.1.2 Piezoelectrics as sensors and actuators

As mentioned in the foregoing, mechanical displacement and electrical voltage are the varying parameters of the intelligent material when using piezoelectrics as sensors and actuators. Mechanical disturbance is converted into electrical voltage by a piezoelectric sensor. On the other hand, a piezoelectric actuator is activated by an electrical input to produce specific mechanical effect (e.g. strain or vibrations) through proper control algorithms.[7] Such mechanical effect would then be used to compensate or control undesired effects, such as deflections and excessive vibrations caused by the external stimuli on the engineering material or structure with which the intelligent material is incorporated. Ha *et al.*[7] and Honein *et al.*[8] have successfully demonstrated that this active mechanical control could be affected on laminated composites by the use of distributed piezoelectric materials. Fundamental relationships have been derived from the basic principles, presented by eqns (1)–(8) in Section 3.1.1. A three-dimensional finite element procedure was adopted and supported by experimental results. These researchers succeeded in completely eliminating an axial deflection of 0·5 mm by applying 46 V. It is apparent from their work that the finite element analysis, when integrated with a suitable control algorithm, can simulate a response of the sensor/actuator structure under active control.

3.1.3 Piezoelectric polymer as intelligent sensors and actuators

Poly(vinylidene fluoride) (PVDF) is a piezoelectric polymer that can be used for sensor/actuator functions. The piezoelectric polymer may be embedded inside a structural member to control actively, for instance, the vibrations by dissipating the elastic energy imposed on the member.[16] For this, a long bar of the test specimen, coupled with a layer of piezoelectric polymeric substance, has been considered, with the lateral dimensions much smaller than the length. The polar direction is taken along the length of the specimen. The attenuation of mechanical vibrations in a passive absorbing element has been studied. This attenuation is achieved by converting a large fraction of elastic energy into electrical energy using the piezoelectric coupling effect and then dissipating the electrical energy using a simple resistive element. For efficient damping characteristics, the coupling coefficients must be large. In order to determine the damping factor (tan δ), constitutive equations of piezoelectric material coupled to the structural member were derived in a dynamic environment, where a harmonic plane wave propagating inside the material specimen has been considered. The results of the study indicate that it is possible to dissipate the mechanical vibratory energy imposed on the material through passive damping by piezoelectric polymers. It has also been proven through experimental work[17] that it is possible to shift the peak damping to the frequency range of interest.

Table 1. Piezoelectric sensors and actuators

Type	Piezo effect	Input	Output	Applications
Piezoceramic (PZT)[a]	Direct	Stress	Voltage	Sensors for mechanical loading
	Converse	Voltage	Strain	Actuators for deformation control
Piezoelectric polymer (PVDF)[b]	Direct	Mechanical loading (static and dynamic)	Voltage	Sensors for static and dynamic loadings. Also, as passive vibration absorbers
	Converse	Voltage	Strain	Strain rate control

[a] Lead zirconate titanate piezoelectric ceramics.
[b] Poly(vinylidene fluoride).

Active vibration control of a cantilever beam using distributed piezoelectric polymers and ceramics was studied by Honein *et al.*[8] Lee *et al.*[9] and Bailey and Hubbard.[12] All these studies included similar expressions derived from the fundamental principles of piezoelectricity, where piezoelectric sensors and actuators were used with a control algorithm to suppress the vibrational excitement.

3.1.4 Strain rate control algorithm

Lee *et al.*,[9] used 'strain rate control feedback mechanism' for the control algorithm. Based on the linear piezoelectric theory, the one-dimensional electrical displacement D in a piezoelectric material can be related to the mechanical strain ε in the same direction via the relationship:

$$D = dE\varepsilon = e\varepsilon \tag{9}$$

where d is the one-dimensional piezoelectric strain per charge constant, E is Young's modulus and e is the one-dimensional piezoelectric stress per charge constant. A piezoelectric PVDF film was used in this work as both sensor and actuator. Using a current amplifier to interface with the high impedance output of the piezoelectric material, piezoelectric strain rate sensors were created.

Bailey and Hubbard[12] developed an active vibration damper for a cantilever beam using distributed parameter actuators on the basis of distributed parameter control theory. The distributed parameter actuator was the piezoelectric polymer (PVDF). The control algorithm for the damper was based on the work done by Kalmann and Bartram[18] on 'Lyapunov's second method' for distributed parameter systems.

Numerous other papers have been published in the area of active vibration control of intelligent structures. Crawley and Luis,[11] for instance, have presented the use of piezoelectric actuators to suppress vibrational excitation in three different test specimens namely, aluminium, glass epoxy and graphite epoxy. Both analytical and experimental methods are presented and a scaling analysis has been performed to demonstrate the effectiveness in transmitting strain to the structure. Electronic damping of a large optical assembly has been studied by Forward *et al.*[19] In this, piezoelectric ceramic strain transducers were used as sensors and actuators, and the data taken during the study indicated the effectiveness of the devices even at high levels of acoustic and vibrational noise.

3.2 Optical fibres as sensors

Optical fibres have been used effectively as sensors in intelligent materials. Optical fibres may be classified, in general, into the following two types:

(i) An extrinsic sensor which operates only as a transmitting medium for light, but performs none of the sensing functions.
(ii) An intrinsic fibre optic sensor which utilizes some intrinsic property of the fibre to detect a phenomenon or to quantify a measurement. A list of intrinsically measurable variables through the use of optical fibres is given in Table 2.

Glass and silica fibres form a basis for a broad range of sensors. The latter utilizes fibre properties to provide signals indicative of external parameters such as force, temperature and deflection that are to be measured.[20] The intrinsic properties of glass and silica qualify fibre optics as smart materials. Optical fibres are capable of performing as a sensor as well as a

Table 2. Applications of optical fibres

Variable	Methodology	Applications
Stress	Photoelastic effect	Fibre composites embedded with optical fibres can detect mechanical loading and vibrations
Strain	Change in optical power due to deformation	Strain could be sensed in structures embedded with optical fibres
Temperature	Thermal change in refractive index	Thermal state of fibre composites could be monitored during manufacturing by embedded optical fibres

transmitter of the sensor's signal. Claus *et al.*[21] developed an optical wave guide embedded in composites that can be used to determine the two-dimensional dynamic strain levels to which the material specimen is subjected to. This was carried out by using the change in the optical power transmitted in the fibre due to the induced strain in the structure and processing the resulting signal.

3.3 Shape memory alloys

Shape memory alloys (SMAs) possess an interaction between the state of loading they are subjected to, the resulting strain and the thermal environment in which they are loaded. If these alloys are deformed at one temperature, they will completely recover their original shape when their thermal state is raised to a higher temperature. On the other hand, if the alloys are constrained during recovering, they can produce a mechanical effect (a recovery force) that is related to their temperature of transformation. Several alloy systems exhibit the phenomenon of shape memory.[22] A number of such alloy systems and their characteristics are given in Table 3.

SMAs have emerged as an alternative choice for situations involving dynamic control of large structures, which would often require vibration suppression and deflection control induced by an adverse environment.[23] The mechanical deformation and thermal cycling of a SMA is illustrated by a stress–strain–temperature diagram in Fig. 3.

As shown in Fig. 3, the SMA is mechanically deformed to a plastic strain of 4% and the load is then removed (curve OAB). To regain its original shape, the alloy is heated above its austenite end of the transformation temperature A_f (curve BCO'). The 4% strain is recovered between the temperatures of start and end of austenite transformation, A_s and A_f, respectively.

Table 3. Alloy systems exhibiting shape memory effect (SME)

SME alloy systems	Transformation temp.[a] (K)	Recovery force for 2% strain in (kg/mm^2)
Nitinol[b]	373	17
Cu–Zn–Al[c]	350	9
CANTIM 75[d]	480	14

[a] Temperature of transformation depends upon the composites of the alloy system.
[b] 49·93% nickel and 50·03% titanium.
[c] 25·9% zinc, 4·04% aluminium and remainder copper.
[d] 11·68% aluminium, 5·03% nickel, 2·00% manganese, 0·96% titanium and remainder copper.

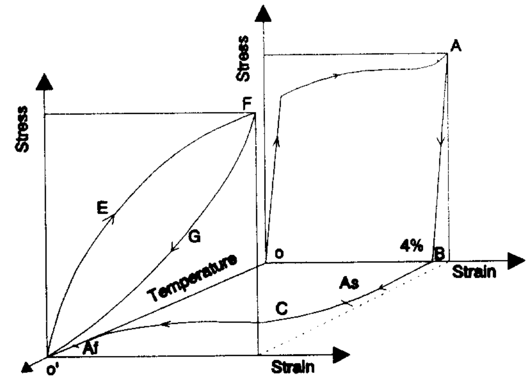

Fig. 3. Stress–strain–temperature diagram for a SMA. (After Wayman.[24])

Martensite forms at a temperature below the temperature of martensite formation M_s, when the SMA cools under no stress. Martensite can also form at temperatures above the temperature M_s if a stress is applied at such temperatures and the formed martensite is termed as 'stress induced martensite' (SIM). If the alloy is stressed at a temperature above that of the austenite end of transformation A_f, the alloy goes into a super elastic loop (O'EFGO') as illustrated in Fig. 3. This means that the strain of 4% is recovered completely on removal of the load, and the material behaves perfectly elastic.

The variation in the stress to produce SIM increases linearly with temperatures above M_s and obeys the modified Claussius–Clayperon relationship.[4]

$$\frac{d\sigma_a}{dM_s} = -\frac{\Delta H}{\theta \varepsilon_{Trans}} \tag{10}$$

where σ_a is the applied stress above the Martensite formation temperature M_s to induce SIM, θ is the ambient temperature, ΔH is the latent heat of phase transformation, and ε_{Trans} is the transformation strain of the super elastic loop.

So far, shape memory effect has been considered only as a one way effect, where an SMA wire, for instance, deformed below the temperature of the martensitic end of transformation M_f temperature, can regain its original shape when heated to a temperature above that of A_f. However, when cooled again to the temperature of the martensite start of transformation M_s, the wire's original shape remains and the material does not assume the 'deformed' shape. This is 'one way shape memory effect'. In the case of 'two way shape memory effect', however, a deformed SMA material below the M_f regains its undeformed configuration when heated to a temperature above the temperature of the austenite end of transformation A_f.[25] However, the undeformed configuration spontaneously attains its deformed shape when cooled below M_f. The specimen can, however, recover its undeformed configuration if heated to temperatures above A_f. Thus, it is possible to produce two geometric configurations of the material, by subjecting it to thermal cycling. The latter is termed as the 'trainability of two way shape memory effect'.[41]

3.3.1 Intelligence in the form of SMAs

A thermomechanical environment subjects materials to cyclic thermal loadings, leading to fatigue and other undesirable mechanical effects. If the shape memory material is made to alter its mechanical properties with respect to a mechanical loading, many of the induced strains could be controlled. In this case, the thermal environment is sensed by an incorporated sensor, and the SMA material acts as an actuator by changing its mechanical response properties when heated (e.g. by passing an electric current through the SMA material).

In a multilayered composite laminate with embedded SMA fibres, excellent vibration suppression could be achieved when the laminate is subjected to dynamic loading.[23] Varying the mode shapes of induced vibration could be also achieved by varying the stiffness of SMA fibres. This is accomplished by utilizing the large force created on constraining the micromechanical phase transformation from deformed state to undeformed state. Figure 4 illustrates, for instance, the effect of temperature on the variation of stiffness of nitinol fibres.

It is also possible to use SMA fibres as simple thermomechanical actuators rather than integrating them into a fibre–matrix system.[27] This is achieved by coupling the thermomechanical actuator with the structural member externally. By ensuring proper coupling between the actuator and the structural member, the effects of the SMA actuator could be transferred to the parent material. Thus, SMAs can be used effectively as actuators in intelligent materials when coupled with proper sensor and control algorithms.

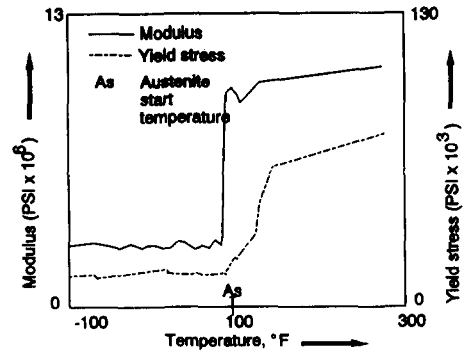

Fig. 4. Approximate stiffness variation of Nitinol with temperature. (After Jackson *et al.*[26]).

3.4 Shape memory polymers

Polymeric materials are generally viscoelectric in response behaviour and have the capability (e.g. Fig. 5) of changing their dynamic properties (storage modulus (E'), loss modulus (E'') and loss tangent ($\tan\delta$) with variations in environmental factors such as temperature, frequency and time.[28–31] Thus, polymeric materials have the capability of smart materials. This is accomplished by a sensor/actuator mechanism that could be incorporated in a structural member so that external stimuli such as mechanical vibrations could be sensed. Through a suitable control mechanism, the dynamic moduli of the polymeric material could be made to change (to adapt itself to the new environment).[32] This could be achieved by shifting the loss factor ($\tan\delta$) towards the frequency spectrum that matches the imposed vibrational frequency, so that the absorption of the imposed vibrational frequency would be maximized. This shifting could be carried out by varying the loss modulus (E'') or the loss factor ($\tan\delta$) of the polymer damper with respect to temperature or frequency.

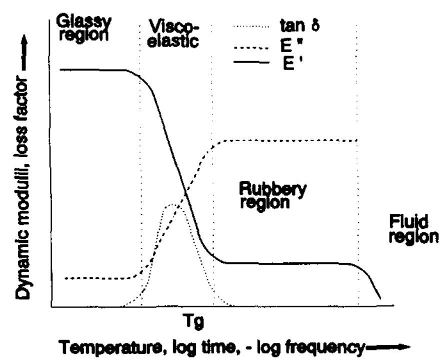

Fig. 5. Schematic illustration of the variation of dynamic moduli of a polymer.

3.4.1 Mechanism of shape memory in a polymer

Shape memory polymers are unique polymeric materials, which can recover their original shape before deformation at lower temperature (below the glass-transition temperature T_g), upon heating them to a temperature above T_g.[33] This is an apparent advantage over ordinary polymers. An ordinary polymer, when stressed, may not recover completely to its original undeformed configuration if the stress is released, thus resulting in permanent deformation. In a shape memory polymer, however, the recovery loop is completed upon heating. Thus, a shape memory polymer is able to revert back to its original shape without undergoing any permanent deformation.

3.5 Electrorheological fluids

The viscosity of certain fluids is influenced by the applied electric field. This phenomenon, termed as the 'electroviscous effect' was reported around the turn of the century.[34] Researchers[35] have found an increase in the viscosity of conducting polar liquids of up to 100% upon application of electric fields of the order of 1 to 10 kV/cm. For the electroviscous effect to occur, both polar molecules and conducting impurity ions are needed to be present. Large increases in viscosity, due to an applied electric field, for suspensions of finely divided solids in low viscosity oils was found as early as 1949. This effect, termed as the 'Winslow effect', is attributed to field induced fibre formation of the particles between the electrodes, thereby requiring additional shear stress for flow.[36]

The above mentioned phenomenon has recently been termed as 'electrorheology':[37] and has been applied in the development of actuator mechanisms in intelligent materials. When used with suitable sensors and control algorithms, electrorheological fluids can be made to change their properties by the application of an electric field upon them.

The electrorheological behaviour of a suspension of fine silica particles in napthenic acid is governed by the Newtonian fluid flow principle (without an externally applied electric field). This principle is expressed as

$$\tau = \eta\dot{\gamma} \qquad (11)$$

where τ is the applied shear stress, $\dot{\gamma}$ is the shear strain rate, and η is the Newtonian viscosity.

When an electric field (ξ) is applied, the shear stress (τ) was found to increase to a critical value (τ_c) which must be overcome before any significant flow of the fluid occurs.[38,39] That is,

$$\tau = \tau_c(\xi) = \eta\dot{\gamma} \qquad (12)$$

where τ_c is independent of $\dot{\gamma}$, but increases with ξ.

Klass and Martinek[38] used suspensions of silica particles in napthenic acid, and Uejima[39] used cellulose in insulator oil, to verify this phenomenon experimentally. The experimental verification indicates that τ_c is proportional to the square of the field, i.e., $\tau_c \propto \xi^2$. In the electrorheology phenomenon, the magnitude of the electric field is the important parameter rather than, for instance, the spacing between the electrodes.[36]

3.5.1 Electrorheological fluids as intelligent materials

With reference to Fig. 6, a mechanical structural member which contains electrorheological fluid, when not activated, has a very low composite stiffness. This state represents the undisturbed configuration.

When an environmental input (e.g. mechanical loading or a difference in thermal gradient) causes, for instance, deflection in the structural member, it would be desirable to increase the stiffness to control the deflection. This is achieved by sensing the external mechanical loading through incorporated sensors. The sensed signal is then processed in a microprocessor, which activates an auxiliary electrical input to produce a desirable voltage. This voltage, when applied to the electrorheological fluid contained in the mechanical structural member, increases the viscosity of the fluid, thus practically converting it into a solid. As a result, the overall stiffness of the specimen is increased,

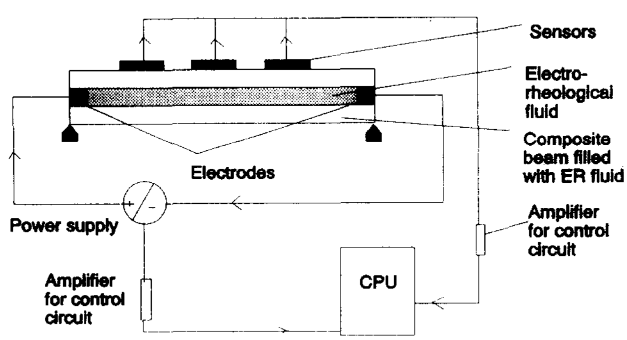

Fig. 6. Electrorheological fluid as actuator in a smart beam.

resisting the external loading and preventing deformation. The above mentioned process could be made to take place in 0·001 s. Experimental investigations conducted, for instance, by Gandhi and Thompson[37] have verified the concept of electrorheological fluids as intelligent material actuators. These authors were able to illustrate that robot arms could be made adaptable to external loading via changing the stiffness.

4 CONCLUSION

Smart materials have the ability to improve mechanical structures to become more advanced and reliable. Although the concepts of the techniques described in this paper were discovered decades ago, it is only recently that such techniques have emerged as potential constituents in intelligent materials methodology. The formulations for piezoelectrics indicate the nature of direct and converse effects and their possible use in sensor and actuator technologies. Discussions relating to SMAs, shape memory polymers and electrorheological fluids illustrate the usage of these materials as actuators in smart material systems. The increase in stiffness of SMAs and the change in the dynamic moduli of shape memory polymers with temperature offers distinct advantages in controlling the static and dynamic state of mechanical structures. Also, the development of different feedback mechanisms based on control algorithms and the increase in sophistication of microprocessor technology and pattern recognition methodology will definitely play an important role in the advancement of processor function.

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