

# Comments on the physical basis of the active materials concept

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## ABSTRACT

During the last decade constant improvements have been made in materials and structures design and control. But now some performance objectives cannot be achieved using classical technologies and require the use of the ‘smart materials concept’. But it is at the actuation end of the equation that smart materials and structures present the greatest challenge. It is here in particular that improved and even new materials have a leading role to play. Piezoelectrics, electrostrictives, photostrictives, magnetostrictives, electroactive polymers, shape memory materials, carbon nanotubes, rheological fluids,...all have their important contributions to make. So this paper aims to perform a brief review of the physical basis of the ‘active’ materials behaviour.

Keywords : smart materials, actuators, electroactive materials, shape memory materials, rheological fluids

## 1. INTRODUCTION

The idea of ‘smart’ materials and structures evolved in the early 1980’s as the potentially viable solution to the problem posed by the next generation of -particularly military- aircraft. At the same time, the concept of ‘intelligent ‘ and even ‘wise’ materials was pioneered with the purpose of establishing a new area in materials science which would take into account the relationship between materials, the natural environment, and society.<sup>1</sup>

Action Effects	Optical	Mechanical	Electric magnetic	Chemical	Thermal	Biochemical
Optical	Photochromic Non linear optics materials Photoreactive and fluorescent mat.	Mechanochromic paints	Electrochromic materials Liquid crystals Non linear optics Electroluminescent Cathodoluminescent		Thermochromic (VO <sub>2</sub> )	
Mechanical	photostriction	Polymers with negative Poisson modulus	Ferro-piezoelectric Magnetostrictives Electrorheol. fluids	Conducting polymer Artificial muscle	Shape memory alloy Reversible reticulation	
Electric magnetic	Pyroelectrics photoconductors	Ferro-piezoelectrics Piezo resistives	Conductors and semiconductors		Materials with insulator-conductor trans.	
Chemical	Photoreticulation photodegradation	mechanochemistry		Degradable polymers Delivery systems	Modif. of the diffusion coefficient thermo-dereticulation	Enzymes
Thermal			Non linearly resisting materials (ZnO)			
Biochemical	photoliberation	Systems with controlled delivery	Systems with controlled delivery		Degradable polymers	Biodegradable polymers

Table I: Aspects of interphenomena coupling. From ref. (2)

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The "smartness" or 'intelligence' can be defined at three levels, each of them defining a field of research, technology development and potential applications :

- a material or a structure is said to be "sensitive" when it includes sensors providing information concerning the material itself or its environment.
- a material will be "adaptable" if integrated actuators (or "active" materials) can modify its characteristics. Such a material or structure will be adaptable only by the way of an externally determined action.'

The combination of these two above mentioned properties results in an "adaptive" or "really smart" material which collects data related to the changes in its environment or in its own evolution or damage. It processes these collected data, and reacts through its 'actuators' action. However the techniques for appropriate response functions seem until now rarely addressed.

The question is now : how works one actuator necessary to develop adaptive or smart materials?. In fact when this type of material is submitted to an optical , mechanical, electrical,..., eventually biochemical prompting, it generates a similar or different effect (Table 1).<sup>2</sup> This table gives a general view (but, of course, non exhaustive) of such interphenomena coupling, symmetric or not , with a few examples of materials able to achieve them .. The key point for the development of adaptive or smart materials and systems usable for structural or functional applications is evidently the improvement of the coupling transfer-functions. Moreover it is important for the designers of future systems to know the current level, the trends and the limits of the actuation properties as well as the using conditions linked to the physico-chemical characteristics for each type of materials. So recognising the need of a basic approach of the actuation concept the present paper sets out to perform a brief review of the physical basis of active materials behaviour . With the noticeable exception of the rheological fluids, this review is mainly focused on the electromechanical coupling and on the solid-state actuators.

## 2. ELECTROACTIVE MATERIALS

For one anisotropic, homogeneous solid, under isothermal conditions and without magnetic field, the components of the elastic strain tensor are given by the following expression:

$$\epsilon_{ij} = s_{ijkl} \sigma_{kl} + d_{ijk} \cdot E_k + M_{klij} \cdot E_k E_l + \text{higher order terms} \quad (1)$$

where the applied electric field  $\mathbf{E}$  is (as the polarisation  $\mathbf{P}$ ) a one rank tensor ;  $\sigma$  and  $\epsilon$  (respectively stress and strain) are two rank tensors and  $\mathbf{d}$  and  $\mathbf{M}$  (respectively piezoelectric and electrostrictive coefficients), are respectively third and four rank tensors. The symmetry of the crystals determine the possible values of these tensors and two types of materials can exist:

-the eleven centrosymmetric point groups in which the components of the piezoelectric tensor (and all odd-rank tensors) are equal to zero.

-the remaining 20 noncentrosymmetric point groups which are potentially piezoelectric. Among them 10 are polar and possess spontaneous electrical polarisation as well as pyroelectric effect.

For the first type of materials the electrostrictive effect described by an even rank tensor is not limited by the symmetry and is in fact present in all materials even those that are amorphous . The electrostrictive effect describes the quadratic dependence of the strain on the applied electric field. If the strain is expressed for a zero stress in terms of the components of the dielectric permittivity tensor  $\epsilon^K$ , another set commonly used of electrostrictive coefficients  $Q_{ijkl}$  can be obtained in the case of a centrosymmetric point group

$$\epsilon_{ij} = \epsilon_{km}^K \cdot \epsilon_{ln}^K \cdot Q_{ijkl} \cdot E_k \cdot E_l \quad (2)$$

Therefore, for materials with cubic symmetry and high value of the dielectric permittivity, the electrostrictive effect can be important.

### 2.1 Piezoelectric materials

Most inorganic piezoelectric actuators are based on the lead titanate zirconate (PZT) with the perovskite structure. For these ferroelectrics materials a large spontaneous polarisation appears at the Curie temperature due to a displacive transformation with atomic displacements of about 0.01nm. This phase change results in a complex structure of ferroelectric domains in randomly axed grains of the classical polycrystalline ceramics. Therefore the poling process is required to partly align the polar vectors of the domains conferring to the polycrystalline sample the global symmetry (6, mm) and inducing the piezoelectricity. Poling occurs under intense electric fields at elevated temperatures near the ferroelectric Curie point where

the domains are easily aligned. This poling process is markedly aided by the nearness of a morphotropic phase boundary (MPB) between tetragonal (titanium rich) and rhomboedral (zirconium rich) phases. For these compositions there are 14 possible poling directions over a wide temperature range. This can explain partly why the piezoelectric coefficients are largest near this morphotropic boundary.<sup>3</sup> Typical values are  $d_{33} = 400$  pC/N and  $\epsilon_{MAX} = 1.5 \cdot 10^{-3}$ .

An intriguing and complex effect exists also in inorganic piezoelectric crystals. The so-called photostrictive effect is a phenomenon in which a strain is induced in illuminated doped samples of PLZT type ferroelectric materials. Although the origin has not been really clarified this effect arises from the superposition of a photovoltaic effect, generating locally mobile defects and internal electric field, and the classical inverse piezoelectric effect.<sup>4,5</sup>

The PVF<sub>2</sub> corresponding to the  $(-CH_2CF_2)_n$  polymer, is the typical example of organic semi-crystalline piezoelectric material. The electronegativity of the fluor atoms confers to the CF<sub>2</sub> group one important dipole moment. Among the four possible crystalline phases, the orthorhombic  $\beta$  phase, directly obtained by crystallisation from the melt with the copolymer P(VF<sub>2</sub>/TrFE), presents the best ferroelectric properties. It is the reason why this statistic copolymer is the most widely used. It is interesting to note that if the piezoelectric constant  $d$  of PVDF is smaller than that of the PZT ceramics (20 pC/N), the piezoelectric constant  $g$  which indicates the voltage per applied unit stress, is on the contrary larger by an order of magnitude ( $160 \cdot 10^{-6}$  V/N). So the PVDF is particularly well suited for sensor applications.<sup>6</sup>

## 2.2 Electrostrictive materials

In the conventional materials as well as for many ferroelectrics, the electrostrictive effect is too small for potential applications as actuators. However the expression (2) expressed for a zero stress indicates that the electrostrictive strain is equal to  $QP^2$  where  $Q$  is a set of electrostrictive coefficients,  $P = \kappa \epsilon_0 E$  the induced polarisation,  $\kappa$  the dielectric constant and  $\epsilon_0$  the permittivity of free space. Thus materials with a very large dielectric constant can exhibit large electrostrictive strain, even though their electrostrictive coefficients are relatively small<sup>7</sup>. It is the case for some ceramics with a complex distribution of the  $B_1$  and  $B_2$  cations in the B sites of the  $A(B_1B_2)O_3$  perovskite structure. For instance the lead magnesium niobate (PMN) and its solid solutions with the lead titanate (PT) are probably the most studied. All compositions on the PMN rich side of a morphotropic phase boundary (at 35 mole% PT) exhibit a diffuse phase transition without a well defined Curie temperature and a very high dielectric constant peak dropping off rapidly with the frequency. In this type of 'relaxors' the diffuse phase transition would be linked to a chemical disorder responsible for the formation of nanodomains having different Curie temperatures. Such of chemical fluctuations have been recently evidenced on a PMN by EDX spectroscopy nanoanalyses<sup>7</sup>. Some nanonodules (10 nm) enriched with lead and magnesium are embedded in the paraelectric matrix. Consequently some polar nanoregions, evidently dependent on the electric bias field and measurement frequency, seem coexist with the paraelectric matrix in a wide range of temperature. So the thermal evolution could be described in the following frame:

- Nucleation of polar regions ( $T \# 600^\circ\text{K}$ )
- Growth of these nanodomains (1 to 10 nm) near the maximum value of the dielectric constant ( $T_{max} \# 270^\circ\text{K}$ )
- Freezing of the evolution at  $T_g \# 160^\circ\text{K}$

Nevertheless the matrix keeps 'on average' the cubic structure. Moreover it seems possible to induce a phase transition under an electric bias field by percolation of the nanodomains of rhomboedric symmetry. But, in spite of many theoretical approaches, our knowledge of this complex behaviour very dependent of the chemical composition has to be improved.

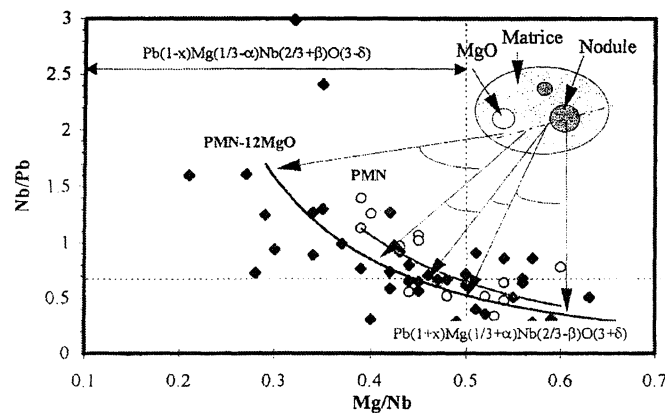


Figure 1 : Chemical fluctuation in PMN. From ref 7.

Finally it is interesting to note first, that the non linearity between strain and electric field can be in this case used to tune the apparent piezoelectric coefficient by electric polarisation of a few MV/m and second that the development of electrostrictive ceramics single crystals allows to obtain reversible strains higher than 1 %<sup>8</sup>.

Concerning the organic materials, a new class of electrostrictive polymers was recently developed by using the ferroelectric copolymers of polyvinylidene fluoride and trifluoroethylene P(VDF-TrFE). After electron irradiation the copolymers exhibit important dielectric constant and high electrostrictive strain levels (4 % at a biased electric field of 150 MV/m measured at 1Hz)<sup>9,10</sup>. Moreover, both the strain and the polarisation hysteresis are negligibly small. The reasons of this evolution are probably linked to the breakup of the coherent macro-polar regions into micropolar regions and reducing the energy barrier of switching the polarisation direction from to another. Moreover in a attempt to introduce the crystal defects likely responsible for this behaviour in a more simple manner some complex alloys have been recently processed: blends of P(VDF/TrFE) and P(VDF/HFP) copolymers<sup>11</sup> and semi crystalline terpolymers of the P(VDF/TrFE/CTFE) type<sup>12</sup>.

### 2.3 Classical polymer films : dielectric elastomers

A more simple type of 'electrostrictive' actuation has been demonstrated on classical polymer films (silicone, polyurethane..) without taking in account the polarisation effect. When a voltage difference is applied on an elastomeric polymer film sandwiched between two compliant electrodes the polymer is squeezed in thickness and stretched in length and width by the electrostatic forces generated between free charges. Assuming that the electrodes are much more compliant than the polymer film itself, then the effective pressure  $p$  generated on the film is proportional to the square of the electric field. According to the authors these electrostrictives devices can produce strains of up to 30%<sup>13</sup>.

### 2.4 Diffusion based electroactive polymers

The actuation mechanism is based in the case of the majority of polymers actuators on the diffusion of ionic species either in or out of a polymer network. The different types can be characterised as gels, conductive polymers, or ionic polymer-metal based composites (IPMC)<sup>14</sup>.

Gels are crosslinked polymer networks in a solvent A gel actuator is activated by different forms of stimuli (pH, heat, light, electric potential) which can cause ions to move into or out of the polymer structure, thus leading it to swell or contract. This phenomenon is associated to very large volume changes (till 1000). The amount of volume change that can be generated in a gel is evidently related to his crosslink density. Gels with a low crosslinking density display large volume change, but the low crosslinking produces a low-modulus material. So the gels actuators have three drawbacks: first, the actuation mechanism is based on ion diffusion with a low speed of reaction, second, the amount of work that can be generated is low due to the low-modulus, and third; these systems require aqueous solutions for operation.

Conducting polymers are similar in principle to the gels in that ion diffusion causes the dimensional change in the material, but the size of the actuator can be small, thereby reducing the response time. Moreover, conducting polymers are stiffer than gel actuators and a significant amount of work can be generated in this case. Conduction in these polymers is based on inserting a dopant species into the polymer network. Furthermore by applying an electric potential to the polymer, dopant insertion and deinsertion can occur. This displacement of ions in and out of the polymer network leads to dimensional change and actuation. Evidently as in the previous system, conducting polymers require an anode, a cathode and an electrolyte for operation. Fortunately the electrolyte can be solid and the electrodes fabricated out of the conducting polymer making the actuator component chemically and mechanically compatible.

Ionic membrane polymers or IPMC also rely on transport of ions with the same limitation in the response time. These systems are realised with one ion conducting membrane material, such as Nafion or Flemion plated with metal electrodes (Au, Pt, )<sup>15</sup>. By applying an electric field to this membrane, ions moving from one electrode to the other can drag water molecules through narrow hydrophilic channels in the resin. The difference in water content in the membrane swells or shrinks the membrane near the electrodes. For instance the swollen cathode and the shrunk anode deflect the composite to anode. These materials can be sealed because the ions are moving only within the membrane and the response time can be improved by controlling the diffusion length. These IPMC actuators are slightly stiffer than gel actuators but the components demonstrated to date are very soft and have limitations in work performing capability.

### 2.5 Carbon nanotubes

Just behind the extensive research on C<sub>60</sub> fullerene came the discovery of the carbon nanotubes. First reported in 1991, their structures consist of rolled-up graphites sheets. Various degrees of helicity can exist, and it is predicted that these fibres can behave as either semi-conductors or conductors, depending on the tube diameter or degree of helicity.

These carbon nanotubes have the largest known stiffness ( $\sim 1$  Tpa) along the axial direction and exceptional bending flexibility<sup>16</sup>. So such nanotubes can be bent and buckled but they will spring back to their original shape without any damage even if simulations of strain induced defects have been performed in which a bond-rotation defect could be induced in the network by the accumulation of elastic stresses<sup>17</sup>. This is likely due to the stability linked to the graphitic nature of the tube. These tubes may be opened at the ends with the nitric acid and filled with metals or probably other type of materials, possibly leading to hybrid materials with novel electrical or mechanical properties.

Recently Baughman, De Rossi, and al.<sup>18</sup> have demonstrated that carbon nanotubes can function as actuators akin to artificial muscles. Two films of bundled single-walled nanotubes are stuck to a double-sided Scotch tape and immersed into a one mole NaCl electrolyte. A dc voltage of only a few volts is applied between the two strips and charge transfer occurs; the injection of positive charges leads to an expansion of the tubes causing the strip to bend because of quantum chemical and electrostatic effect (not totally understood). Such bundled structures of nanotubes could be, in the future, used in the field of robotics and synthetic actuators. Nevertheless strength limitations involve the large-scale production of defect-free aligned nanotubes but some works are now in progress<sup>19</sup>.

### 3. MAGNETOSTRICTIVE ACTUATORS

Magnetostriction phenomenon has been discovered by Joule in 1842. He observed that an iron rod lengthens under the effect of a magnetic field directed following its axis... This is important for actuator device application because electrical (magnetic) energy can be converted into mechanical (elastic) energy via magnetostrictive materials. This magnetostrictive effect is also reversible and change in stress applied to a material generates magnetic energy (Villari effect)

The relative deformation associated to the Joule effect is a square function of the magnetic induction but as in the case of electrostrictive materials a reversible and quasi linear effect can be obtained by a static polarisation.

Very large strains are often needed to deliver the large displacements required for smart system components and one of the shortcomings of the 3d transition metals is their low saturation strains ( $5 \cdot 10^{-5}$ ). Rare-earth are characterised by their 4f electron charge clouds which impart a non spherical shape to the atoms. This shape evolves in a regular way through the lanthanide series as electron are added. Erbium Samarium and Thulium are 'egg-shaped', Terbium and Dysprosium resemble more to flattened oblate ellipsoids. This high anisotropy combined with strong spin orbit coupling leads to large magnetostriction ( $\lambda_2 = 1.110^{-3}$ ) with saturation strains of two orders higher than Nickel ( $-3.410^{-5}$ ), Cobalt and Iron, but at a cryogenic temperature because their very low Curie temperature. However the presence of iron in the rare-earth-Fe alloys increases the Curie temperature.. Thus  $TbFe_2$  and  $SmFe_2$  exhibit important magnetostriction respectively positive and negative at ambient temperature, but their strong anisotropy disturbs the field rotation process. So in order to get a low anisotropy two rare-earth-Fe alloys having the same magnetostriction sign but opposed anisotropy have been combined and the best alloy allowing to control the shape change with small applied field is known as Terfenol-D with the composition  $Tb_{1-x} Dy_x Fe_2$  (with generally  $x = 0.7$ <sup>20</sup>). Finally it is interesting to note that this best composition of the terfenol magnetostrictor is not very far from the magnetic phase boundary between rhomboedral and tetragonal phases<sup>21</sup>. Moreover the use of magnetostrictive particles embedded in composite host materials has been the subject of several recent publications<sup>22</sup>.

### 4. SHAPE MEMORY MATERIALS

#### 4.1 Shape memory alloys

The shape memory alloys undergo by cooling, martensitic transformations similar to those observed on a lot of metallic, ceramic and even partially crystalline polymer materials, and in particular on the steels. But in the case of the commonly used SMA's (Cu-Zn-Al or Nickel Titanium) this first order transition is reversible with a small thermal hysteresis linked to a negligible volume variation. Two important characteristics of martensite phase are the absence of long-range diffusion and the appearance of a shape change. The shape memory alloys typically transform from a partially ordered cubic austenitic phase to a martensitic low temperature state. This martensite easily deforms under stress by domain-wall displacements and when reheated goes back to the original shape of the high temperature structure: this is the one-way shape memory effect<sup>23</sup>. It is also possible to obtain a reversible two way shape memory effect between high and low temperature shape by temperature cycling under applied stress or strain.. This 'training' introduces in the austenite some bundles of dislocations homogeneously distributed which direct the growth of the martensite domains. Moreover mechanical stresses can also cause phase change as well as the temperature, inducing the well know super elastic effect linked to the austenite-martensite transition.

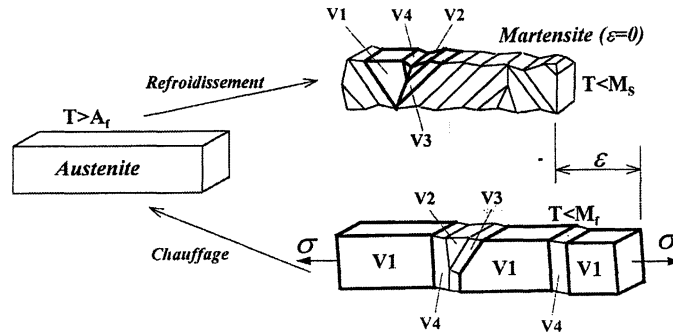


Figure2: Effect of a stress on the martensite phase. From ref 23.

#### 4.2 Magnetic shape memory alloys

A drawback of the shape memory alloys is their slow response due to their thermal control mainly in cooling. A new mechanism based on the magnetic-field-induced reorientation of the twin martensite variants of a magnetic shape memory alloy has been suggested by Ullakko<sup>24</sup>. Effectively the magnetic control of the shape memory effect would lead to much more rapid response of the actuator than the thermal control. Magnetic field controls the reorientation of the twin variants in an analogous way as the twin variants are controlled by the stress in classical shape memory alloys. Magnetostrictive strains play no role in this mechanism. When they are subjected to one externally applied magnetic field, the twins in a favourable orientation grow at the expense of the others. This results in a shape change of the magnetic shape memory alloy. At the beginning Ullakko et al. reported a 0.2% reversible strain in Ni<sub>2</sub>-Mn-Ga. This strain has been improved in the case of the Fe-Pd alloy with a 1.3% free strain on a material in a stress-cooled state. The theoretical maximum limiting the achievable strain is the value of the transformation strain which is 6.6% in Ni-Mn-Ga. Recently a model describing the discontinuous actuation (~2%) of a single crystal of this alloy under stress has been developed by Murray & al.<sup>25</sup>, and detailed studies with a non-stoichiometric Ni<sub>2</sub>-Mn-Ga by Ullakko & al.<sup>26</sup> showed that with thermomechanical treatment it is possible to reach much higher magnetic-field-induced strains than without such treatment (consisting of 5% compressive deformation cycles at a temperature which is 5°K higher over A<sub>f</sub>). In these conditions the magnetic-field-induced strains of the 'trained' columnar polycrystalline alloy is over 4% at room temperature.

#### 4.3 Shape memory ceramics

The change in the spontaneous strain accompanying a phase transition can theoretically be expected to be much larger than that associated to the polarisation reorientation in the ferroelectric phase. It is the reason why some antiferroelectrics lead titanate stannate based systems (PNZST) able to switch from an antiferroelectric state to a ferroelectric one have been proposed<sup>27</sup>. The induced strain reaches up to 0.4% (longitudinal effect) which is much larger than the one expected in classical piezoelectrics. This field induced transition exhibits a shape memory effect for appropriate compositions. The material memorises its ferroelectric state even under zero-field conditions although it can be erased with the application of a small reverse bias field. It is important to note that this shape memory ceramic does not require a continuous electric field application but only a pulse drive, thereby saving a lot of energy.

#### 4.4 Shape memory polymers

The polytetrafluoroethylene (PTFE) is a thermoplastic semi crystalline polymer. The crystalline part of PTFE is complex as three crystalline phases can be found at normal pressure. The corresponding phase transitions are located at about 293°K and 308°K. In the sintered samples used in this work<sup>28</sup> the crystalline ratio of the obtained material is about 55%. The effect of a constant compressive stress during thermal cycles is illustrated by the figure 3. The temperature range of the thermal cycles is centred on the phase transformation occurring at 293°K. The amplitude of each deformation is about 2% and a similar effect is found in tensile mode experiment. Moreover it can be observed that the reversible deformation cycles due to the memory effect shift to higher deformation value. This shift can be attributed, as in classical shape memory alloys to the irreversible transformation plasticity linked to the phase change process.

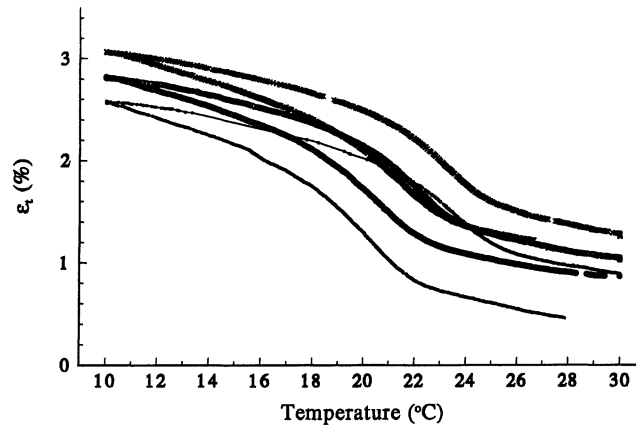


Figure 3 : Effect of a constant compressive stress during thermal cycles on PTFE. From ref. 28.

## 5. TUNABLE MATERIALS : ELECTRO AND MAGNETORHEOLOGICAL SYSTEMS

Electro and magnetorheological fluids are not actuators *stricto sensu*. Nevertheless it is possible to tune within a millisecond time their rheological properties, yield stress and apparent viscosity, by using one electric or magnetic field<sup>29</sup>. Currently no model can completely describe the behaviour of the ER fluids. However a Bingham plastic model can often provide a sufficient accurate description to be used for the designing of ER material devices. Although no consensus regarding the mechanism for the observed ER effect has been reached, it is generally accepted that the phenomenon originates from particles polarisation induced by the electric field. The observed changes in mechanical properties are the result of the formation and breakdown of one induced particles chain network. So materials that exhibit more than 3 k.Pa in dynamic yield stress, less than 0.35 Pa.s in zero field viscosity; and stability over a reasonable temperature range are currently available.

The same type of comments can be made concerning the magnetorheological fluids, but the higher values of the yield stress (until 30 kPa in a 500 kA/m magnetic field) should be facilitate their development. Finally it is interesting to note the occurrence of homogeneous liquid crystals polymers based functional fluids. This kind of non yield effect material could be particularly attractive for vibration control devices.

By extension of this concept of tunable fluid it is also possible to realise elastomer based functional materials loaded with magnetic particles before crosslinking<sup>30</sup>. During the cure one magnetic field induces the formation of a particle chain network with colinear dipoles parallel to the applied field. The crosslinking process locks the embedded particles chains in place and the stress-strain curve of the composite depends of the applied magnetic field. So this processing results in a material with a 'field dependant' apparent modulus. It seems possible to use such materials for different devices as a tuned vibration absorber or a stiffness tunable suspension.

## 6. CONCLUSIONS : TOWARDS IMPROVED AND NEW MATERIALS

The improvement of the small strain capabilities as well as the hysteresis behaviour of the piezoelectric ceramics is the subject of a lot of research. One interesting way is represented by the single crystals materials. Park and Shrout<sup>8</sup> reported first strain levels up to 1.5% for single rhombohedral crystals of relaxor perovskite PZN-PT with a reduced strain hysteresis. These outstanding properties only occur for specific orientations <001> of the electric field with respect to the crystal axes and the anisotropy in response is really large. This concept of 'cristallographic engineering' resulting in stable domain configuration is applicable to other ferroelectric crystals in order to enhance their piezoelectric performances<sup>31</sup>.

Driving the shape memory effect with other 'fields' than temperature is also an interesting research direction. The advantage consists mainly in the reduction of the response time. As in the case of the electroactive ceramics the elaboration of single crystals of magnetic shape memory alloys is the best way to improve the strain capabilities. The theoretical maximum limiting the achievable strain is the value of the transformation strain, that is 6.6%.

Since the research on giant magnetostrictive materials has started, most of the work has been conducted about bulk alloys of RE-Fe in order to obtain textured polycrystals or even single crystals. But the research and development for thin films has recently been increased and can open new fields of research and applications.

The potential of the classical electrorheological fluids for practical application is limited by the problems of particle precipitation and instability outside a rather narrow temperature range. This led to renewed interest in homogeneous ER fluids since the discovery in the early 1990's of an extremely large ER effect in certain liquid-crystalline polymer fluids<sup>32</sup>. Two structural mechanisms, one high aspect ratio of liquid-crystalline molecules, and a sufficient interaction between adjacent liquid-crystalline domains, were considered as a possible basis for obtaining a large ER effect. In the case of the poly ( $\gamma$  benzoyl L- glutamate) (PBLG), the increase in shear stress at 25°C by application of a dc 2kV/mm electric field is about 3000 Pa. This effect is enough large but polymeric fluids are in fact able of more than 10.000 Pa and present advantages over particles dispersed ER fluids particularly in torque control and vibration damping.. For EAP, actuation properties have been demonstrated in small scale and in limited cases. In fact the fundamental mechanisms providing the actuation are, specially for IPMC, not fully understood. However, in spite of a severe limitation in their response time and in force generation linked to their low modulus, many applications could be reached as microrobotic actuators or even 'artificial muscles'.

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