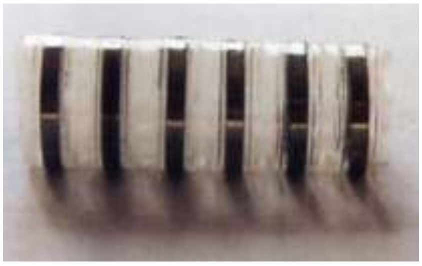
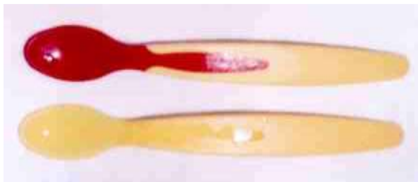
Smart Materials





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SMART MATERIALS

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CONTENTS

SMART MATERIALS

Smart materials have been around for many years and they have found a large number of applications. The use of the terms 'smart' and 'intelligent' to describe materials and systems came from the US and started in the 1980's despite the fact that some of these so-called smart materials had been around for decades. Many of the smart materials were developed by government agencies working on military and aerospace projects but in recent years their use has transferred into the civil sector for applications in the construction, transport, medical, leisure and domestic areas.

The first problem encountered with these unusual materials is defining what the word 'smart' actually means. One dictionary definition of smart describes something which is astute or 'operating as if by human intelligence' and this is what smart materials are. A smart material is one which reacts to its environment all by itself. The change is inherent to the material and not a result of some electronics. The reaction may exhibit itself as a change in volume, a change in colour or a change in viscosity and this may occur in response to a change in temperature, stress, electrical current, or magnetic field. In many cases this reaction is reversible, a common example being the coating on spectacles which reacts to the level of UV light, turning your ordinary glasses into sunglasses when you go outside and back again when you return inside. This coating is made from a smart material which is described as being photochromic.

There are many groups of smart materials, each exhibiting particular properties which can be harnessed in a variety of high-tech and everyday applications. These include shape memory alloys, piezoelectric materials, magneto-rheological and electro-rheological materials, magnetostrictive materials and chromic materials which change their colour in reaction to various stimuli.

The distinction between a smart material and a smart structure should be emphasised. A smart structure incorporates some form of actuator and sensor (which may be made from smart materials) with control hardware and software to form a *system* which reacts to its environment. Such a structure might be an aircraft wing which continuously alters its profile during flight to give the optimum shape for the operating conditions at the time.

The aim of this booklet is to describe the different types of smart materials in terms of how they work, what types of materials are used and where they are used.

SHAPE MEMORY ALLOYS

Shape memory alloys (SMAs) are one of the most well known types of smart material and they have found extensive uses in the 70 years since their discovery.

What are SMAs?

A shape memory transformation was first observed in 1932 in an alloy of gold and cadmium, and then later in brass in 1938. The shape memory effect (SME) was seen in the gold-cadmium alloy in 1951, but this was of little use. Some ten years later in 1962 an equiatomic alloy of titanium and nickel was found to exhibit a significant SME and Nitinol (so named because it is made from *ni*ckel and *ti*tanium and its properties were discovered at the *N*aval *O*rdinance *L*aboratories) has become the most common SMA. Other SMAs include those based on copper (in particular CuZnAl), NiAl and FeMnSi, though it should be noted that the NiTi alloy has by far the most superior properties.

How do SMAs work?

The SME describes the process of a material changing shape or remembering a particular shape at a specific temperature (i.e. its transformation or memory temperature). Materials which can only exhibit the shape change or memory effect once are known as one-way SMAs. However some alloys can be trained to show a two-way effect in which they remember two shapes, one below and one above the memory temperature. At the memory temperature the alloy undergoes a solid state phase transformation. That is, the crystal structure of the material changes resulting in a volume or shape change and this change in structure is called a 'thermoelastic martensitic transformation'. This effect occurs as the material has a martensitic microstructure below the transformation temperature, which is characterised by a zig-zag arrangement of the atoms, known as twins. The martensitic structure is relatively soft and is easily deformed by removing the twinned structure. The material has an austenitic structure above the memory temperature, which is much stronger. To change from the martensitic or deformed structure to the austenitic shape the material is simply heated through the memory temperature. Cooling down again reverts the alloy to the martensitic state as shown in Figure 1.

The shape change may exhibit itself as either an expansion or contraction. The transformation temperature can be tuned to within a couple of degrees by changing the alloy composition. Nitinol can be made with a transformation temperature anywhere between –100ºC and +100ºC which makes it very versatile.

Where are SMAs used?

Shape memory alloys have found a large number of uses in aerospace, medicine and the leisure industry. A few of these applications are described below.

Medical applications

Quite fortunately Nitinol is biocompatible, that is, it can be used in the body without an adverse reaction, so it has found a number of medical uses. These include stents in which rings of SMA wire hold open a polymer tube to open up a blocked vein (Figure 2), blood filters, and bone plates which contract upon transformation to pull the two ends of the broken bone in to closer contact and encourage more rapid healing (Figure 3).

It is possible that SMAs could also find use in dentistry for orthodontic braces which straighten teeth. The memory shape of the material is made to be the desired shape of the teeth. This is then deformed to fit the teeth as they are and the memory is activated by the temperature of the mouth. The SMA exerts enough force as it contracts to move the teeth slowly and gradually (Figure 4). Surgical tools, particularly those used in key hole surgery may also be made from SMAs. These tools are

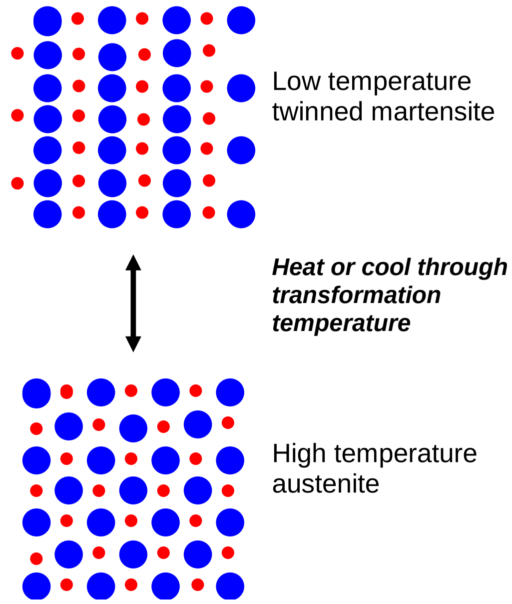

Figure 1 – Change in structure associated with the shape memory effect.

Figure 2 – This reinforced vascular graft contains rings of SMA wire which open out the polyester tube on warming with warm saline solution once in-situ. (Courtesy of Tony Anson, Anson Medical Ltd)

Figure 3 – This NiTi bone plated has been heat treated such that the central part changes from its deformed shape (top) to its memory shape (bottom) when warmed with saline solution, thus drawing the two ends of the fracture closer together. The modulus of this material has also been closely matched to that of human bone. (Courtesy of Tony Anson, Anson Medical Ltd)

often bent to fit the geometry of a particular patient, however, in order for them to be used again they return to a default shape upon sterilisation in an autoclave.

Figure 4 – SMA wire has been used here to close the gap between two teeth. Two parallelograms of NiTi wire are attached to the teeth using stainless steel brackets which are glued to the teeth (left). After six months the gap between the teeth has decreased noticeably (right). (Courtesy of Tony Anson, Anson Medical Ltd)

Still many years away is the use of SMAs as artificial muscles, i.e. simulating the expansion and contraction of human muscles. This process will utilise a piece of SMA wire in place of a muscle on the finger of a robotic hand. When it is heated, by passing an electrical current through it, the material expands and straightens the joint, on cooling the wire contracts again bending the finger again. In reality this is incredibly difficult to achieve since complex software and surrounding systems are also required. NASA have been researching the use of SMA muscles in robots which walk, fly and swim!

Domestic applications

SMAs can be used as actuators which exert a force associated with the shape change, and this can be repeated over many thousands of cycles. Applications include springs which are incorporated in to greenhouse windows such that they open and close themselves at a given temperature. Along a similar theme are pan lids which incorporate an SMA spring in the steam vent. When the spring is heated by the boiling water in the pan it changes shape and opens the vent, thus preventing the pan from boiling over and maintaining efficient cooking. The springs are similar to those shown in Figure 5.

(a) *(b)*

Figure 5 – Showing the two memory shapes of a memory metal wire coil or 'spring'. In (a) the spring is at room temperature and in (b) the higher temperature state has been activated by pouring on boiling water.

SMAs can be used to replace bimetallic strips in many domestic applications. SMAs offer the advantage of giving a larger deflection and exerting a stronger force for a given change in temperature. They can be used in cut out switches for kettles and other devices, security door locks, fire protection devices such as smoke alarms and cooking safety indicators (for example for checking the temperature of a roast joint).

Aerospace applications

A more high tech application is the use of SMA wire to control the flaps on the trailing edge of aircraft wings. The flaps are currently controlled by extensive hydraulic systems but these could be replaced by wires which are resistance heated, by passing a current along them, to produce the desired shape change. Such a system would be considerably simpler than the conventional hydraulics, thus reducing maintenance and it would also decrease the weight of the system.

Manufacturing applications

SMA tubes can be used as couplings for connecting two tubes. The coupling diameter is made slightly smaller than the tubes it is to join. The coupling is deformed such that it slips over the tube ends and the temperature changed to activate the memory. The coupling tube shrinks to hold the two ends together but can never fully transform so it exerts a constant force on the joined tubes.

Why are SMAs so flexible?

In addition to the shape memory effect, SMAs are also known to be very flexible or superelastic, which arises from the structure of the martensite. This property of SMAs has also been exploited for example in mobile phone aerials, spectacle frames and the underwires in bras. The kink resistance of the wires makes them useful in surgical tools which need to remain straight as they are passed through the body. Nitinol can be bent significantly further than stainless steel without suffering permanent deformation.

Another rather novel application of SMAs which combines both the thermal memory and superelastic properties of these materials is in intelligent fabrics. Very fine wires are woven in to ordinary polyester / cotton fabric. Since the material is superelastic the wires spring back to being straight even if the fabric is screwed up in a heap at the bottom of the washing basket! So creases fall out of the fabric, giving you a true non-iron garment!

In addition the wires in the sleeves have a memory which is activated at a given temperature (for example 38°C) causing the sleeves to roll themselves up and keeping the wearer cool.

Summary

These are just a few of the possible uses for shape memory alloys. However it is likely that as more research is carried out and these materials are better understood, more applications will be developed.

PIEZOELECTRIC MATERIALS

The piezoelectric effect was discovered in 1880 by Jaques and Pierre Curie who conducted a number of experiments using quartz crystals. This probably makes piezoelectric materials the oldest type of smart material. These materials, which are mainly ceramics, have since found a number of uses.

What is the piezoelectric effect?

The piezoelectric effect and electrostriction are opposite phenomena and both relate a shape change with voltage. As with SMAs the shape change is associated with a change in the crystal structure of the material and piezoelectric materials also exhibit two crystalline forms. One form is ordered and this relates to the polarisation of the molecules. The second state is non-polarised and this is disordered.

If a voltage is applied to the non-polarised material a shape change occurs as the molecules reorganise to align in the electrical field. This is known as electrostriction.

Conversely, an electrical field is generated if a mechanical force is applied to the material to change its shape. This is the piezoelectric effect.

The main advantage of these materials is the almost instantaneous change in the shape of the material or the generation of an electrical field.

What materials exhibit this effect?

The piezoelectric effect was first observed in quartz and various other crystals such as tourmaline. Barium titanate and cadmium sulphate have also been shown to demonstrate the effect but by far the most commonly used piezoelectric ceramic today is lead zirconium titanate (PZT). The physical properties of PZT can be controlled by changing the chemistry of the material and how it is processed. There are limitations associated with PZT; like all ceramics it is brittle giving rise to mechanical durability issues and there are also problems associated with joining it with other components in a system.

Where are piezoelectric materials used?

The main use of piezoelectric ceramics is in actuators. An actuator can be described as a component or material which converts energy (in this case electrical) in to mechanical form. When a electric field is applied to the piezoelectric material it changes its shape very rapidly and very precisely in accordance with the magnitude of the field.

Applications exploiting the electrostrictive effect of piezoelectric materials include actuators in the semiconductor industry in the systems used for handling silicon wafers, in the microbiology field in microscopic cell handling systems, in fibre optics and acoustics, in ink-jet printers where fine movement control is necessary and for vibration damping.

The piezoelectric effect can also be used in sensors which generate an electrical field in response to a mechanical force. This is useful in damping systems and earthquake detection systems in buildings. But the most well known application is in the sensors which deploy car airbags. The material changes in shape with the impact thus generating a field which deploys the airbag.

A novel use of these materials, which exploits both the piezoelectric and electrostrictive effects, is in smart skis which have been designed to perform well on both soft and hard snow. Piezoelectric sensors detect vibrations (i.e. the shape of the ceramic detector is changed resulting in the generation of a field) and the electrostrictive property of the material is then exploited by generating an opposing shape change to cancel out the vibration. The system uses three piezoelectric elements which detect and cancel out large vibrations in real time since the reaction time of the ceramics is very small.

By passing an alternating voltage across these materials a vibration is produced. This process is very efficient and almost all of the electrical energy is converted into motion. Possible uses of this property are silent alarms for pagers which fit into a wristwatch. The vibration is silent at low frequencies but at high frequencies an audible sound is also produced. This leads to the concept of solid state speakers based on piezoelectric materials which could also be miniaturised.

Do polymers exhibit these effects?

Ionic polymers work in a similar way to piezoelectric ceramics, however they need to be wet to function. An electrical current is passed through the polymer when it is wet to produce a change in its crystal structure and thus its shape. Muscle fibres are essentially polymeric and operate in a similar way, so research in this field has focussed on potential uses in medicine.

Summary

It is clear the scope for applications of piezoelectric materials is more limited than that of shape memory alloys. However, those applications where they are used rely on the very precise and controllable nature of the piezoelectric effect making them invaluable for the niche applications which they occupy.

MAGNETOSTRICTIVE MATERIALS

Magnetostrictive materials are similar to piezoelectric and electrostrictive materials except the change in shape is related to a magnetic field rather than an electrical field.

What are magnetostrictive materials?

Magnetostrictive materials convert magnetic to mechanical energy or vice versa. The magnetostrictive effect was first observed in 1842 by James Joule who noticed that a sample of nickel exhibited a change in length when it was magnetised. The other ferromagnetic elements (cobalt and iron) were also found to demonstrate the effect as were alloys of these materials. During the 1960s terbium and dysprosium were also found to be magnetostrictive but only at low temperatures which limited their use, despite the fact that the size change was many times greater than that of nickel.

The most common magnetostrictive material today is called TERFENOL-D (terbium (TER), iron (FE), Naval Ordanance Laboratory (NOL) and dysprosium (D)). This alloy of terbium, iron and dysprosium shows a large magnetostrictive effect and is used in transducers and actuators.

The original observation of the magnetostrictive effect became known as the Joule effect, but other effects have also been observed. The Villari effect is the opposite of the Joule effect, that is applying a stress to the material causes a change in its magnetization.

Applying a torsional force to a magnetostrictive material generates a helical magnetic field and this is known as the Matteuci effect. Its inverse is the Wiedemann effect in which the material twists in the presence of a helical magnet field.

How do magnetostrictive materials work?

Magnetic materials contain domains which can be likened to tiny magnets within the material. When an external magnetic field is applied the domains rotate to align with this field and this results in a shape change as shown in Figure 6. Conversely if the material is squashed or stretched by means of an external force the domains are forced to move and this causes a change in the magnetisation.

Where are magnetostrictive materials used?

Magnetostrictive materials can be used as both actuators (where a magnetic field is applied to cause a shape change) and

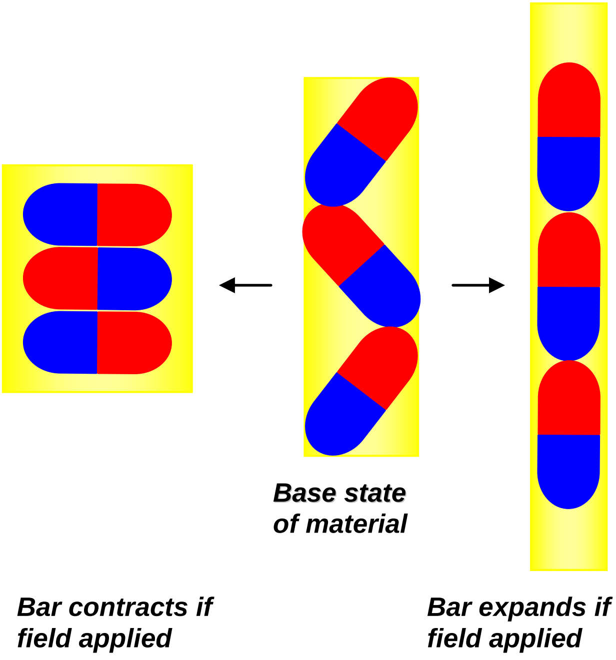

Figure 6 – Magnetostrictive materials are made up from domains (represented by red and blue bar magnets). If a magnetic field is applied the bar either decreases in length from its base state (centre to left) or increases in length (centre to right) depending on the polarisation of the applied field.

sensors (which convert a movement into a magnetic field).

In actuators the magnetic field is usually generated by passing an electrical current along a wire. Likewise the electrical current generated by the magnetic field arising from a shape change is usually measured in sensors.

Early applications of magnetostrictive materials included telephone receivers, hydrophones, oscillators and scanning sonar.

The development of alloys with better properties led to the use of these materials in a wide variety of applications. Ultrasonic magnetostrictive transducers have been used in ultrasonic cleaners and surgical tools. Other applications include hearing aids, razorblade sharpeners, linear motors, damping systems, positioning equipment, and sonar.

Summary

Although these are very specialised materials they have found niche markets in which their properties are ideal. More applications are likely to come along as the materials are developed and their performance improved.

MAGNETO- AND ELECTRO RHEOLOGICAL MATERIALS

All of the groups of smart materials discussed so far have been based on solids. However, there are also smart fluids which change their rheological properties in accordance with their environment.

What are smart fluids?

There are two types of smart fluids which were both discovered in the 1940s. Electro-rheological (ER) materials change their properties with the application of an electrical field and consist of an insulating oil such as mineral oil containing a dispersion of solid particles (early experiments used starch, stone, carbon, silica, gypsum and lime). Magneto-rheological materials (MR) are again based on a mineral or silicone oil carrier but this time the solid dispersed within the fluid is a magnetically soft material (such as iron) and the properties of the fluid are altered by applying a magnetic field. In both cases the dispersed particles are of the order of microns in size.

How do smart fluids work?

In both cases the smart fluid changes from a fluid to a solid with the application of the relevant field. The small particles in the fluid align and are attracted to each other resulting in a dramatic change in viscosity as shown in Figure 7. The effect takes milliseconds to occur and is completely reversible by the removal of the field.

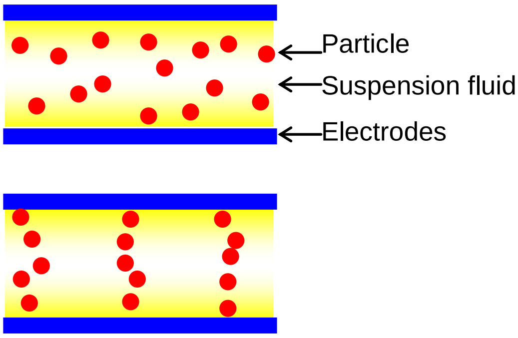

Figure 7 – Schematic diagram showing the structure of a electrorheological fluid between two electrodes. The top figure shows the structure in a low field strength where the particles are randomly distributed. When a higher field strength is applied, as in the bottom diagram, the particles align causing a change in the viscosity of the fluid.

Figure 8 clearly shows the effect of a magnet on such an MR fluid. With ER fluids a field strength of up to 6kV/mm is needed and for MR fluids a magnetic field of less than 1Tesla is needed.

Where are smart fluids used?

Uses of these unusual materials in civil engineering, robotics and manufacturing

Figure 8 - A puddle of magnetorheological fluid stiffens in the presence of a magnetic field. (courtesy of Sandy Hill / University of Rochester)

are being explored. But the first industries to identify uses were the automotive and aerospace industries where the fluids are used in vibration damping and variable torque transmission. MR dampers are used to control the suspension in cars to allow the feel of the ride to be varied. Dampers are also used in prosthetic limbs to allow the patient to adapt to various movements for example the change from running to walking.

Summary

Despite having rather unusual properties MR and ER fluids are finding more uses as our understanding of them develops. Further uses in damping systems are likely, as are applications where the fluids are used to polish other materials. In this case the materials flow to cover the surface evenly. This technique has been used to polish lenses for high precision optics systems.

CHROMIC MATERIALS

This group of materials refers to those which change their colour in response to a change in their environment, leading to the suffix *chromic*. A variety of chromic materials exist and they are described in terms of the stimuli which initiate a change, thus:

- *Thermochromic* materials change with temperature;
- *Photochromic* materials change with the light level;
- *Piezochromic* materials change with applied pressure;
- In the case of *electrochromic*, *solvatechromic* and *carsolchromic* materials the stimulus is either an electrical potential, a liquid or an electron beam respectively.

Thermochromic, photochromic and piezochromic materials are the most popular with the first two groups finding everyday applications.

How do thermochromic materials work?

There are two types of thermochromic systems: those based on liquid crystals and those which rely on molecular rearrangement. In either case at a given temperature a change in the structure of the material occurs giving rise to an apparent change in colour. The change is reversible so as the material cools down it changes colour back to its original state.

In liquid crystals the change from coloured to transparent takes place over a small temperature range (around 1°C) and arises as the crystals in the material change their orientation (Figure 9). However, liquid crystals are relatively expensive and so where there is no need for the colour change to take place in a very narrow temperature window molecular rearrangement materials are employed.

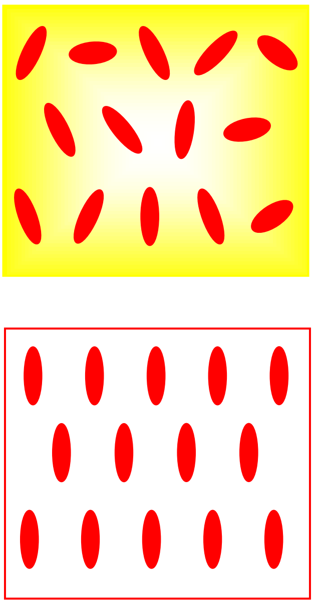

Figure 9 – A liquid crystal contains needle shaped particles which are arranged randomly below the transformation temperature (top). Above this temperature the particles are aligned, changing how the material reflects light, thus showing a change in colour (bottom)

Leucodyes change colour by molecular rearrangement and the colour and active temperature range of the dye can be controlled by changing the chemical groups on the corners and central site of the molecule. Leucodyes have a broader temperature range than liquid crystals and will usually become colourless over approximately 5ºC.

In both cases the thermochromic material is encapsulated inside microscopic spherical particles to protect it. These encapsulating molecules must themselves be transparent and able to withstand the thermal cycling which the thermochromic artefact will undergo.

The thermochromic material does not generally produce two or more colours itself. The encapsulated particles of the material are printed on to or mixed in to another material in the second colour. At room temperature the sample is the colour of the thermochromic dye but when it is heated above its transition temperature the thermochromic material becomes transparent thus showing the base colour underneath. For example if a layer of red thermochromic pigment is applied to a blue substrate at room temperature it will appear red but as if warms up it becomes blue. As the temperature decreases again the red colour will reappear.

Where are thermochromic materials used?

Since thermochromic pigments can be used in a variety of ways they have found a varied range of applications.

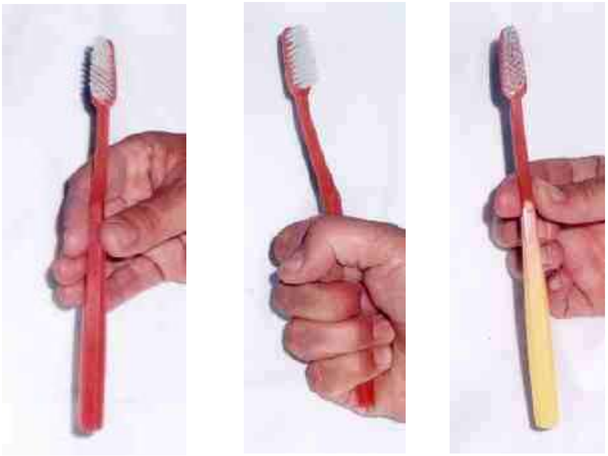

Figure 10 – A thermochromic toothbrush at room temperature, being warmed by holding in the hand and when warm.

The pigments can be incorporated in to dyes for fabric to produce clothing which changes colour with temperature. Thermochromic inks can also be used for printing on to clothing and food packaging.

Thermochromic toothbrushes have been produced that change colour as they are warmed in the hand. It takes roughly two minutes to warm the brush enough to see a change in the colour and this is the length of time dentists recommend teeth should be brushed. Such a toothbrush is shown in Figure 10.

Thermochromic thermometers have been developed as they offer significant safety advantages over traditional glass / mercury thermometers. The plastic substrate consists of stripes of different colours representing the different temperatures. This is then coated with a layer of thermochromic dye of varying thickness (it is thinner at the cool end of the thermometer than it is at the higher temperature end). As the thermometer is warmed by placing it on the forehead the thin layer of dye warms up and becomes transparent first. The higher the temperature the thicker the layer of dye which can be warmed sufficiently to change colour.

This principle is also employed in the tester strips which appear on the sides of some batteries, but this time the heat is generated by the resistance heating effect of a small electrical current flowing across the battery.

Thermochromic materials have also found safety applications in kettles and baby spoons. The body of the kettle is actually made from pink plastic, however this contains a small amount of a thermochromic dye which is blue at room temperature and becomes transparent when warm, thus showing the pink colour. A series of photographs showing the change in colour as the kettle is boiled are shown in Figure 11.

Thermochromic pigments have also been employed in baby spoons which change colour to warn if the food is too hot for feeding. Babies generally like to eat their food no hotter than one degree above body temperature, so the spoons are designed to change colour at 38°C. The room temperature and hot states of such a spoon are shown in Figure 12. The hotter

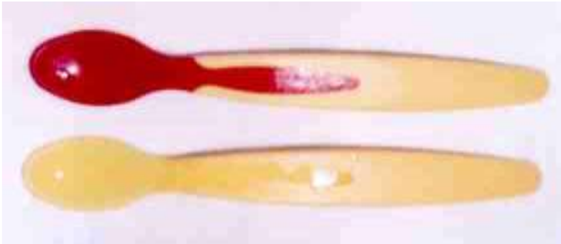

Figure 12 – Showing a thermochromic baby spoon at room temperature (top) and after immersion in boiling water (bottom)

the food the more rapidly the spoon changes from red to yellow. The bright yellow colour has been achieved by immersing the spoon in boiling water.

Thermochromic dyes with a higher temperature resistance and higher transition temperature have also been produced and incorporated in to pans. These pans have a small coloured circle in the bottom which changes colour when the pan has reached the optimum temperature for cooking.

Figure 11 – Showing gradual change in colour as the thermochromic kettle boils.

These materials are already starting to find a large number of uses in our everyday lives and there is no doubt that as thermochromic dyes are further understood more uses will be found.

What about photochromic materials?

Photochromic materials are those which change when they are exposed to light, UV light in particular. As with thermochromic materials, the colour change arises from a change in the structure of the material allowing it to change from completely clear to dark yet still transparent.

The main application of photochromic materials is in spectacle lenses which change in to sunglasses outside. Figure 13 shows such a lens which has turned brown after sitting on a sunny window sill. If you have a pair of these glasses you will know that they are always very slightly tinted as there is always a small amount of UV present. You may also have noticed that, rather annoyingly, they do not generally change colour when you are driving as the windscreen contains a filter to cut out the UV portion of the light.

These materials could also be used to coat large office windows so that they cut out some of the light on hot days.

Figure 13 – An unground, photochromic spectacle lens sat on a sunny windowsill.

Summary

Chromic materials are here to stay! From the colour changing T-shirts of the 1980's to the new temperature sensing baby spoons, thermochromic materials are finding more and more uses in our everyday lives. Other forms of chromic materials are also growing in popularity, photochromic spectacle lenses have come down in price and become far more popular over the past decade or so. The other types of chromic materials will also become more widespread as their properties are developed and the costs come down. For example electrochromic coatings may be used for modesty panels on doors or to block out the sunshine in office block windows. Piezochromic materials are already used to measure pressure, however at the moment the colour change associated with this is not reversible so the materials can only be used once.

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Volume 9, number 3, March 2001. Pp 11 – 13.

Clifford Friend "Sense and sensibility of products around the home"

Volume 9, number 9, September 2001. Pp 12 – 14.

Roger Stanway "Smart fluids – the shock of the new"

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HOW TO USE THE RESOURCES SUPPLIED WITH THIS PACK

A number of samples have been provided to help you demonstrate Smart Materials in the classroom. They can be used as follows.

Shape memory alloy spring

This spring is infact not a spring but a coiled piece of wire. As such UNDER NO CIRCUMSTANCES should you try to extend or compress the sample by pulling or pushing the ends, as this will render it useless. This wire shows a two-way shape memory effect whereby at room temperature it is tightly coiled. To activate the high temperature of the alloy simply pour on very recently boiled water and the coil will expand to about double its length. This transformation occurs almost instantaneously. The transformation temperature of this alloy is about 97ºC. To return the coil to its original size, simply remove it from the hot water and allow it to cool. You will be able to see this happen as it occurs much more slowly.

Shape memory metal wire

A small length of Nitinol wire has been supplied as a small coil and this material shows the one-way shape memory effect. The wire can be straightened or crumpled up at room temperature and then returned to its memory shape by immersing it in boiling water or passing it through a lighter flame (again the memory temperature is around 100ºC). If you would like to change the memory shape of the wire secure it to the desired shape at room temperature (by screwing it down to a metal plate or holding it in pliers) and heat to a temperature of about 450ºC, which can be achieved using a domestic blow torch. At this temperature the wire will take on a bright orange glow. To fix the new memory shape plunge the glowing wire into cold water. This quenches the material and changes its microstructure. It is essential that the wire is held securely as it is heated, as it will try to change shape to its original memory shape.

Thermochromic spoon

The red section at the end of this spoon contains a thermochromic dye. To change the colour of the spoon simply put it in some warm water. The transformation temperature of the dye is around 38ºC at which point it changes from being red to transparent, thus exposing the yellow plastic below. The colour change will occur more rapidly the higher the temperature of the water (i.e. the colour change is quicker in water at 100ºC than water at 40ºC). The original red colour returns when the spoon is allowed to cool.

Thermochromic pen

The thermochromic dye is in this case blue and the colour change can easily be activated by holding the barrel of the pen in a warm hand. The blue dye becomes transparent showing the white plastic underneath. The blue colour returns as the pen is allowed to cool back to room temperature.