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Smart materials - scopes and prospects

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ABSTRACT

Science and technology have made amazing developments in the design of electronics and machinery using standard materials, which do not have particularly special properties (i.e. steel, aluminum, gold). One can imagine the range of possibilities, which exist for special materials that have properties, which scientists can manipulate according to the need. Some such materials have the ability to change shape or size simply by adding a little bit of heat, or to change from a liquid to a solid almost instantly when near a magnet; these materials are called smart materials. Varieties of smart materials already exist, and are being researched extensively. These include piezoelectric materials, magneto-rheostatic materials, electro-rheostatic materials, and shape memory alloys. Some everyday items are already incorporating smart materials (coffeepots, cars, the International Space Station, eyeglasses) and the number of applications for them is growing steadily. Each individual type of smart material has a different property which can be significantly altered, such as viscosity, volume, and conductivity. The property that can be altered influences what types of applications the smart material can be used. This paper deals with the recent development of smart materials particularly piezoelectric materials and its usage for the micro machines.

Introduction

Smart materials are designed materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields (WIKI 2013). Mostly used smart materials includes Piezoelectric materials, Shape Memory Alloy materials, Magnetostriction and Electrostriction materials. This paper will give brief characteristics and idea of different smart materials for different application with scope and prospect.

History of Smart Materials

The first recorded observation of smart material transformation was made in 1932 on gold-cadmium. In addition, in 1938 the phase transformation was observed in brass (copper-zinc). It was not until 1962, however, that Beehler and co-workers found the transformation and attendant shape memory effect in Nickel-Titanium at the Naval Ordinance Laboratory. They named this family of alloy Nitinol after their lab. A few years after the discovery of Nitinol, a number of other alloy systems with the shape memory effect were found (Hodgson and Brown, 2000). Though product development using smart materials began to accelerate after the discovery of Nitinol, many of the smart materials contained expensive and exotic elements. Only the copper-based alloys came close to challenging the Nitinol family as a commercially attractive system. During the 1980s and early 1990s, a number of companies began to provide Ni-Ti materials and components, and an increasing number of products, especially medical products, were developed to market (Hodgson and Brown, 2000; Des Roches, 2002).

Transformation Mechanism of Smart Material

Smart materials exist as two stable phases under different temperatures: Austenite, the high-temperature phase, and Martensite, the low-temperature phase. In addition, there are two different forms of Martensite materials: twinned and de-twinned (Fig. 2). At a certain temperature, smart material will stay at its thermodynamically stable phase. However, when temperature changes, transformations between these two phases occur. Due to this transformation mechanism, smart materials have many special properties, such as shape memory effect and super-elasticity effect that have a wide potential use in structural applications (Lagoudas, 2002).

Smart materials

Especially due to the increasing demand in smart structures-technology, smart materials have continuously been gaining attention in the past decade, although the physical effects of many typical candidate materials are known since over 50 years. These materials

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have the characteristic that they show both sensor and actuator effects. All these materials are capable of reversibly changing their mechanical properties (viscosity, stiffness, shape) due to the influence of temperature change or an electrical or magnetical field. By some of these materials the reverse effect can be used for sensor tasks meaning that a mechanical load generates an electrical or magnetically field. Well-known are piezoelectric ceramics, magneto-strictive materials, and shape memory alloys. Key issue for smart materials is the actuator performance. The limit of the actuator authority over the structure naturally marks the performance limit of the complete smart structure. Thus, this article gives an overview of smart materials with special focus on their actuator performance (active strain, forces, dynamics, energy density) and their advantages and disadvantages for active noise and vibration reduction.

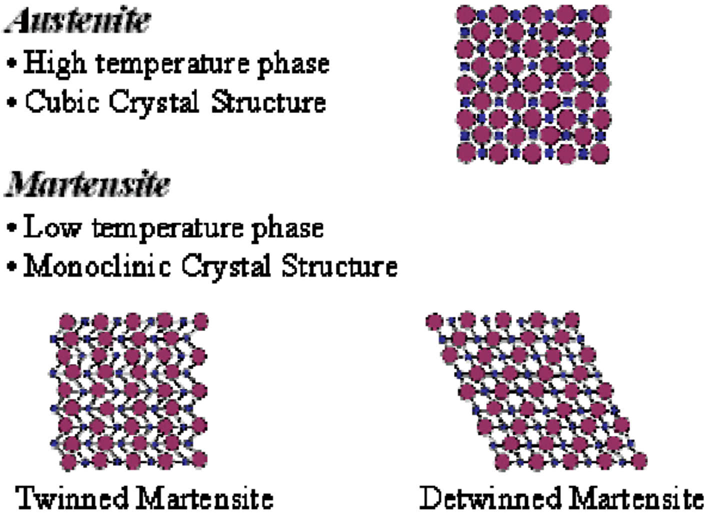

Fig.1: Different phases of smart materials ((Lagoudas, 2002)

Tremendous variation in data, concerning the mechanical and active properties of smart materials can be observed in literature and is provided by the different manufacturers. Partially the values differ between 100-200% or sometimes even more. This is mainly due to the large amount of possible compositions of the different smart materials. But also the variations within the manufacturing process itself are remarkable, e.g. experiments with shape memory alloys and piezoelectric ceramics have shown that the mechanical and active performance of the same material from the same manufacturer can differ 10-20%.

Piezoelectric Materials

Simply stated, piezoelectric materials produce a voltage in response to an applied force, usually a uni-axial compressive force. Similarly, a change in dimensions can be induced by the application of a voltage to a piezoelectric material. In this way they are very similar to electro-strictive materials. These materials are usually ceramics with a perovskite structure (Fig.2). The perovskite structure exists in two crystallographic forms. Below the Curie temperature they have a tetragonal structure and above the Curie temperature they transform into a cubic structure. In the tetragonal state, each unit cell has an electric dipole, i.e. there is a small charge differential between each end of the unit cell (SMART1, 2013).

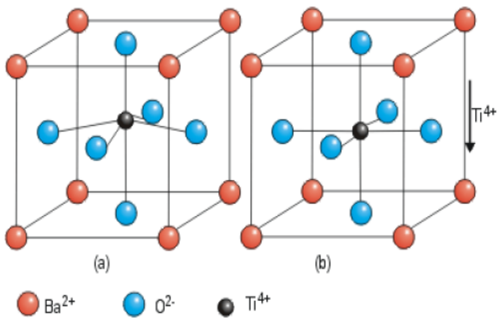

Fig.2: a) The pervoskite structure below the Curie temperature and b) cubic structure above the Curie temperature

A mechanical deformation (such as a compressive force) can decrease the separation between the cations and anions which produces an internal field or voltage. Some examples of piezoelectric materials are given in Table 1.

Table 1: Piezoelectric constants of materials

Materials	Piezoelectric Constant
Quartz	2.3
Barium Titanate	100-149
Lead Niobate	80-85
Lead Zirconate Titanate	250-365

Key Properties

There are two key properties of smart materials such as the ability to produce a voltage output in response to an applied stress and the ability to produce a strain output (or deformation) in response to an applied voltage. The generation of an electric charge occurs in certain non-conducting materials, such as quartz crystals and ceramics, when they are subjected to mechanical stress (such as pressure or vibration), or the generation of vibrations in such materials when they are subjected to an electric field. Piezoelectric materials exposed to a fairly constant electric field, tend to vibrate at a precise frequency with very little variation, making them useful as time-keeping devices in electronic clocks, as used in wristwatches and computers.

Piezoelectricity is the charge which accumulates in certain solid materials (notably crystals, certain ceramics, and biological matter such as bone, DNA and various proteins) in response to applied mechanical stress (Jordan and Ounaies, 2001). The word piezoelectricity means electricity resulting from pressure. It is derived from the Greek piezo or piezein, which means to squeeze or press, and electric or electron, which stands for amber, an ancient source of electric charge (Schönecker et al., 1994). Piezoelectricity is the direct result of the piezoelectric effet.

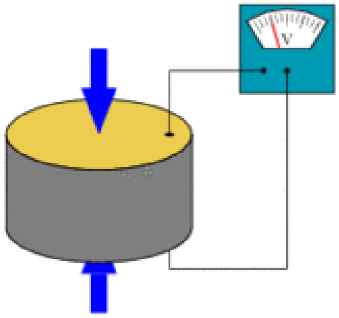

Fig. 3: A piezoelectric disk generates a voltage when deformed

The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials with no inversion symmetry (SMART2, 2013). The piezoelectric effect is a reversible process in that materials exhibiting the direct piezoelectric effect as shown in Fig.3 (the internal generation of electrical charge resulting from an applied mechanical force) also exhibit the reverse piezoelectric effect (the internal generation of a mechanical strain resulting from an applied electrical field). For example, lead zirconate titanate crystals will generate measurable piezoelectricity when their static structure is deformed by about 0.1% of the original dimension. Conversely, those same crystals will change about 0.1% of their static dimension when an external electric field is applied to the material.

Mathematical description

Piezoelectricity is the combined effect of the electrical behavior of the material (WIKI, 2013):

$D = \varepsilon E$ Where *D* is the electric displacement, ε is permittivity and *E* is electric field strength, and

Hooke's Law:

$S = sT$ where *S* is strain, *s* is compliance and *T* is stress.

These may be combined into so-called *coupled equations*, of which the strain-charge form is:

$$\{S\} = \left[s^E\right]\{T\} + [d^t]\{E\}$$

$$\{D\} = [d]\{T\} + \left[\varepsilon^T\right]\{E\},$$

Where [*d*] is the matrix for the direct piezoelectric effect and [d^t] is the matrix for the converse piezoelectric effect. The superscript *E* indicates a zero, or constant, electric field; the superscript *T* indicates a zero, or constant, stress field; and the superscript *t* stands for transposition of a matrix.

The strain-charge for a material of the 4mm (C_{4v}) crystal class (such as a poled piezoelectric ceramic such as tetragonal PZT or $BaTiO_3$) as well as the 6mm crystal class may also be written as (ANSI IEEE 176):

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{21}^E & s_{22}^E & s_{23}^E & 0 & 0 & 0 \\ s_{31}^E & s_{32}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66}^E = 2\left(s_{11}^E - s_{12}^E\right) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

where the first equation represents the relationship for the converse piezoelectric effect and the latter for the direct piezoelectric effect (Kawai, 1969).

Although the above equations are the most used form in literature, some comments about the notation are necessary. Generally *D* and *E* are vectors, that is, Cartesian tensor of rank-1; and permittivity ε is Cartesian tensor of rank 2. Strain and stress are, in principle, also rank-2 tensors. But conventionally, because strain and stress are all symmetric tensors, the subscript of strain and stress can be re-labeled in the following fashion: 11 → 1; 22 → 2; 33 → 3; 23 → 4; 13 → 5; 12 → 6. (Different convention may be used by different authors in literature. Say, some use 12 → 4; 23 → 5; 31 → 6 instead.) That is why *S* and *T* appear to have the "vector form" of 6 components. Consequently, *s* appears to be a 6 by 6 matrix instead of rank-4 tensor. Such a re-labeled notation is often called Voigt notation.

In total, there are 4 piezoelectric coefficients, d_{ij}, e_{ij}, g_{ij}, and h_{ij} defined as follows:

$$d_{ij} = \left(\frac{\partial D_i}{\partial T_j}\right)^E = \left(\frac{\partial S_j}{\partial E_i}\right)^T$$

$$e_{ij} = \left(\frac{\partial D_i}{\partial S_j}\right)^E = -\left(\frac{\partial T_j}{\partial E_i}\right)^S$$

$$g_{ij} = -\left(\frac{\partial E_i}{\partial T_j}\right)^D = \left(\frac{\partial S_j}{\partial D_i}\right)^T$$

$$h_{ij} = -\left(\frac{\partial E_i}{\partial S_j}\right)^D = -\left(\frac{\partial T_j}{\partial D_i}\right)^S$$

Where the first set of 4 terms correspond to the direct piezoelectric effect and the second set of 4 terms corresponds to the converse piezoelectric effect (Harrison and Ounaies, 2001). Formalism has been worked out for those piezoelectric crystals, for which the polarization is of the crystal-field induced type, that allows for the calculation of piezoelectrical coefficients d_{ij} from electrostatic lattice constants or higher-order Madelung constants (SMART3, 2013).

Applications of smart materials

A variety of smart materials already exist, and are being used extensively. These include piezoelectric materials, magneto-rheostatic materials, electro-rheostatic materials, and shape memory alloys. Some everyday items are already incorporating smart materials (coffeepots, cars, the International Space Station, eyeglasses) and the number of applications for them is growing steadily.

Transducers

Piezoelectric materials are used in electromechanical devices. In the case of a microphone transducer, sound of a particular frequency results in a strain in the material, this in turn induces an electric field. Similarly in speakers, a voltage input into the piezoelectric material can be converted into a mechanical strain, such as in a speaker transducer.

Industrial applications

Currently, industrial and manufacturing is the largest application market for piezoelectric devices, followed by the automotive industry. Strong demand also comes from medical instruments as well as information and telecommunications. The global demand for piezoelectric devices was valued at approximately US$14.8 billion in 2010. The largest material group for piezoelectric devices is piezo-crystal, and piezo polymer is experiencing the fastest growth due to its lightweight and small size (Jonocha, 2000).

High voltage and power sources

Direct piezoelectricity of some substances like quartz, as mentioned above, can generate potential differences of thousands of volts. The best-known application is the electric cigarette lighter: pressing the button causes a spring-loaded hammer to hit a piezoelectric crystal, producing a sufficiently high voltage electric current that flows across a small spark gap, thus heating and igniting the gas. The portable sparkers used to light gas grills or stoves work the same way, and many types of gas burners now have built-in piezo-based ignition systems. Other energy harvesting ideas include harvesting the energy from human movements in train stations or other public places (Claeyssen, 2002; Otsuka and Wayman, 1998) and converting a dance floor to generate electricity (Buehler et al., 1965). Vibrations from industrial machinery can also be harvested by piezoelectric materials to charge batteries for backup supplies or to power low power microprocessors and wireless radios and wireless radios (Funakubo, 1984). A piezoelectric transformer is a type of AC voltage multiplier. Unlike a conventional transformer, which uses magnetic coupling between input and output, the piezoelectric transformer uses acoustic coupling. An input voltage is applied across a short length of a bar of piezoceramic material such as PZT, creating an alternating stress in the bar by the inverse piezoelectric effect and causing the whole bar to vibrate. The vibration frequency is chosen to be the resonant frequency of the block, typically in the 100 kilohertz to 1 megahertz range. A higher output voltage is then generated across another section of the bar by the piezoelectric effect. Step-up ratios of more than 1000:1 have been demonstrated. An extra feature of this transformer is that, by operating it above its resonant frequency, it can be made to appear as an inductive load, which is useful in circuits that require a controlled soft start (SMART4, 2013). These devices can be used in DC-AC inverters to drive cold cathode fluorescent lamps. Piezo transformers are some of the most compact high voltage sources.

Sensors

The principle of operation of a piezoelectric sensor is that a physical dimension, transformed into a force, acts on two opposing faces of the sensing element. Depending on the design of a sensor, different "modes" to load the piezoelectric element can be used: longitudinal, transversal and shear.

Detection of pressure variations in the form of sound is the most common sensor application, e.g. piezoelectric microphones (sound waves bend the piezoelectric material, creating a changing voltage) and piezoelectric pickups for Acoustic-electric guitars. A piezo sensor attached to the body of an instrument is known as a contact microphone (Fig.4).

Piezoelectric sensors especially are used with high frequency sound in ultrasonic transducers for medical imaging and also industrial nondestructive testing (NDT). For many sensing techniques, the sensor can act as both a sensor and an actuator – often the term transducer is preferred when the device acts in this dual capacity, but most piezo devices have this property of reversibility whether it is used or not. Ultrasonic transducers, for example, can inject ultrasound waves into the body, receive the returned wave, and convert it to an electrical signal (a voltage). Most medical ultrasound transducers are piezoelectric (SMART5,2013).

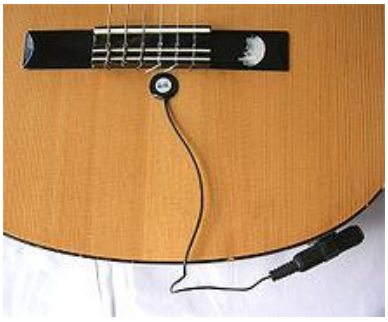

Fig.4: Piezoelectric disk used as a guitar pickup

Actuators

As very high electric fields correspond to only tiny changes in the width of the crystal, this width can be changed with better-than-µm precision, making piezo crystals the most important tool for positioning objects with extreme accuracy — thus their use in actuators.

Fig.5: Metal disk with piezo-electric disk attached

Multilayer ceramics, using layers thinner than 100 µm, allow reaching high electric fields with voltage lower than 150 V. These ceramics are used within two kinds of actuators: direct piezo actuators and Amplified piezoelectric actuators. While direct actuator's stroke is generally lower than 100 µm, amplified piezo actuators can reach millimeter strokes.

Loudspeakers- Voltage is converted to mechanical movement of a piezoelectric polymer film.

Piezoelectric motors- Piezoelectric elements apply a directional force to an axle, causing it to rotate. Due to the extremely small distances involved, the piezo motor is viewed as a high-precision replacement for the stepper motor.

Piezoelectric elements can be used in laser mirror alignment, where their ability to move a large mass (the mirror mount) over microscopic distances is exploited to electronically align some laser mirrors. By precisely controlling the distance between mirrors, the laser electronics can accurately maintain optical conditions inside the laser cavity to optimize the beam output.

A related application is the acousto-optic modulator, a device that scatters light off of sound waves in a crystal, generated by piezoelectric elements. This is useful for fine-tuning a laser's frequency.

Atomic force microscopes and scanning tunneling microscopes employ converse piezoelectricity to keep the sensing needle close to the probe (Piedboeuf et al., 1998)

Inkjet printers- On many inkjet printers, piezoelectric crystals are used to drive the ejection of ink from the inkjet print head towards the paper.

Diesel engines- High-performance common rail diesel engines use piezoelectric fuel injectors, first developed by Robert Bosch GmbH, instead of the more common solenoid valve devices. Moving the patient precisely inside active CT and MRI scanners where the strong radiation or magnetism precludes electric motors (Gandhi and Wolons, 1999).

Frequency standard

The piezo-electrical properties of quartz are useful as standard of frequency. Quartz clocks employ a crystal oscillator made from a quartz crystal that uses a combination of both direct and converse piezoelectricity to generate a regularly timed series of electrical pulses that is used to mark time. The quartz crystal has a precisely defined natural frequency at which it prefers to oscillate, and this is used to stabilize the frequency of a periodic voltage applied to the crystal. The same principle is critical in all radio transmitters and receivers, and in computers where it creates a clock pulse. Both of these usually use a frequency multiplier to reach gigahertz ranges.

Piezoelectric motors

Types of piezoelectric motor includes the traveling-wave motor used for auto-focus in reflex cameras, inchworm motors for linear motion, rectangular four-quadrant motors with high power density (2.5 watt/cm^3) and speed ranging from 10 nm/s to 800 mm/s, stepping piezo motor, using stick-slip effect.

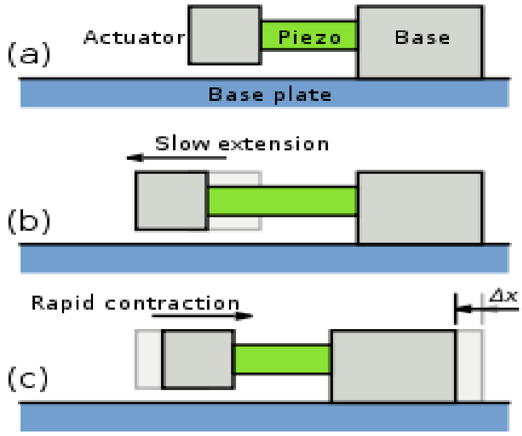

Fig.6: A slip-stick actuator

All these motors, except the stepping stick-slip motor (Fig. 6) work on the same principle. Driven by dual orthogonal vibration modes with a phase difference of 90°, the contact point between two surfaces vibrates in an elliptical path, producing a frictional force between the surfaces. Usually, one surface is fixed causing the other to move. In most piezoelectric motors the piezoelectric crystal is excited by a sine wave signal at the resonant frequency of the motor. Using the resonance effect, a much lower voltage can be used to produce a high vibration amplitude. Stick-slip motor works using the inertia of a mass and the friction of a clamp. Such motors can be very small. Some are used for camera sensor displacement, allowing anti shake function.

Reduction of vibrations and noise

Different teams of researchers have been investigating ways to reduce vibrations in materials by attaching piezo elements to the material. When the material is bent by a vibration in one direction, the vibration-reduction system responds to the bend and sends electric power to the piezo element to bend in the other direction. Future applications of this technology are expected in cars and houses to reduce noise. Piezoelectric ceramic fiber technology is being used as an electronic damping system on some HEAD tennis rackets (Tellinen et al., 2002).

Fundamental characteristics of Smart materials:

Smart materials can be described by two key parameters: free strain ε_0 and blocking stress σ_B. The linear behavior of a solid state actuator can be seen in the stress-strain diagram of Fig.7. Additionally a constant stress ($Ys \cdot \varepsilon s$) of a surrounding structure has been integrated into the diagram.

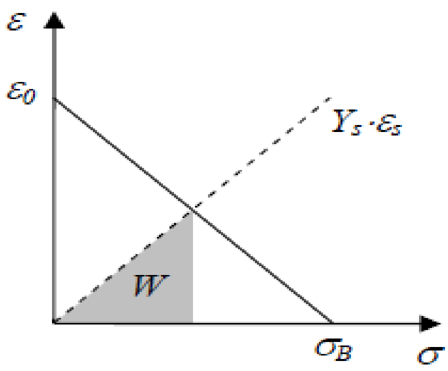

Figure 7: Stress-strain characteristic of a smart material

The working point of an actuator is characterized by the intersection point between the characteristic lines of actuator and structure.

With the Young's modulus Y_a of the actuator the blocking stress can be written as (Mopner, 2005)

$$\sigma_B = Y_a \varepsilon_0 \quad \text{-------------------------------------(1)}$$

The maximum volumetric work per cycle $W_{max,volumetric}$ then is

$$W_{max,volumetric} = \frac{1}{8}\sigma_B\varepsilon_0 = \frac{1}{8}Y_a\varepsilon_0^2 \quad \text{------------------(2)}$$

The maximum gravimetric work per cycle can be calculated with the density ρ_a of the smart material

$$W_{max,\,gravimetric} = \frac{W_{max,volumetric}}{\rho_a} = \frac{1}{8}\frac{Y_a\varepsilon_0^2}{\rho_a} \quad \text{----------(3)}$$

The volumetric work per cycle, also referred to as mechanical energy density, has to be considered to be of fundamental importance when comparing smart materials. Equation (2) represents the maximum energy that can be transferred to the mechanical structure by minimal actuator volume, which is the case when the stiffness of the smart material is identical to the stiffness of the structural material. This means the actuator stress has to be $\sigma = \sigma_B/2$ and the actuator strain $\varepsilon = \varepsilon_0/2$. Impedance matching between smart material and structure is therefore basis for an efficient design.

Shape memory alloy (SMA)

Shape Memory Alloy (SMA) is a special class of adaptive material that can convert thermal energy directly into mechanical work. When properly mixed, a variety of alloys exhibit this effect by repeated heat treatments. Ni-Ti is the most commonly used SMA (Maji and Negret, 1998).

First investigations related to the shape memory effect were reported by A. Ölander. He discovered the pseudo-elastic behaviour of the Au-Cd alloy in 1932 (Otsuka and Wayman, 1998). In 1961, the U.S. Naval Ordnance Laboratory discovered the shape memory effect in a nickel-titanium alloy which then was named Nitinol (Nickel-Titanium Naval Ordnance Laboratory). Nitinol can be considered a breakthrough in the field of shape memory materials because it exhibits much higher shape memory effects than previous materials (Buehler et al., 1965). SMAs have two stable phases - the high-temperature phase, called austenite and the low-temperature phase, called martensite. The austenite crystal structure is a simple cubic structure with only one possible parent phase, while martensite has a more complex rhombic structure with a total of 24 crystallographically equivalent habit planes. This phenomenon causes the SMAs to revert completely to the shape it had before the deformation. While NiTi is soft and easily deformable due to de-twinning in its lower temperature form (martensite), it resumes its original shape and rigidity when heated to its higher temperature form (austenite). This is called the one-way shape memory effect allowing 100% strain recovery of up to a maximum of 8% extensional pre-strain. The ability of shape memory alloys to recover a preset shape upon heating above the transformation temperatures and to return to a certain alternate shape upon cooling is known as the two-way shape memory effect (Funakubo, 1984). The usable two way strain is strongly dependent on the requirements concerning amount of cycles and the stress/strain mode. The following Table 2 presented by Memory-MetalleGmbH (SMART5, 2013) is a guideline for standard binary NiTi alloys. However, special treatment of the NiTi alloy may result in longer lifetime.

Table 2: Recoverable strain as a function of the number of cycles for NiTi

Cycles	Max. strain [%]
up to 1	8
up to 100	5
up to 100,000	3
above 100,000	2

Above the transition temperature, shape memory alloys show an extraordinary elasticity of 6-8 % reversible strain which is far beyond that of conventional materials. The restoring force is nearly independent of the strain. This effect is referred to as super elasticity and is based on stress-induced martensite formation. NiTi alloys are available as wires, rods, tubes, ribbons, and thin sheets. The Young's modulus for martensite is 21-69 GPa and austenite 70-110 GPa (SMART6, 2013) meaning austenite has a two- to fourfold larger Young's modulus in comparison to martensite. Operating frequencies in the two-way mode typically are <1 Hz because cooling of the materials is a rather slow process.

SMAs can be activated by external heating (SMA reacts to the ambient temperature) or electrical heating (Joule heating with electrical current). By electrical heating the energy consumption carefully has to be considered since most of the input energy is transformed to heat rather than mechanical strain resulting in low efficiency (<2 %). NiTi alloys have a density of about 6.45 g/cm^3. The transformation temperature between low-temperature and high-temperature phase (-200 to+110°C) (SMART7, 2013) can be adjusted by varying the proportions between nickel and titanium within the alloy. Due to their slow response time and low efficiency active noise and vibration reduction tasks are not the domain of NiTi alloys. However, by using the hysteresis of the super elastic effect for structural damping or changing the Eigen frequencies by generating internal compressive stress in a structure for certain specialized applications SMAs can be an interesting alternative.

Performance summary of smart materials

In the following Table 3 the performance of the different smart materials are summarized. Additionally, the volumetric work per cycle and gravimetric work per cycle has been calculated according to the equations (2) and (3), respectively.

Table 3: Comparison of smart material properties

Material	Young's modulus Y_a [Gpa]	Max actuator strain ε_0 [%]	Density ρ_a [g/cm^3]	Operating frequency at ε_0 [Hz]	Blocking stress σ_B [MPa]	Volumetric work per cycle (2) [J/cm^3]	Gravimetric work per cycle (3) [J/kg]
"Classic" smart materials							
PZT	50-70	0.12-0.18	7.6	100,000	72	0.0108	1.42
Terfenol-D	25-65	0.075-0.2	9.15-9.25	10,000	82.5	0.0155	1.67
PVDF	2.1-2.5	0.1	1.47	100,000	2.3	0.000288	0.196
NiTi	70-110 (a)	2-8	6.45	1	425*	1,59*	247*
Emerging smart materials							
FSMA	0.45-0.82	2-10	8.36	100-1,000	18	0.0675	8.1
PVDF-TrFE	1	2-4	1.9	100,000	40	0.2	105
ESSP-Silicon	0.0001-0.001	117-63	1.1-1.15	100-1000	0.63	0.0496	45
ESSP-Acrylic	0.003	215	0.8	10-100	6.45	1.733	2167
Grafted Polymers	0.55	4	1.78	100-1,000	42.6	0.11	62
CP-Polyanilin	1.42	1-10	1.5	0.1-1	22	0.16	106
IPMC-Nafion	0.09-0.19	2.3-2.6	2.5-2.9	1	4.75	0.0148	5.1
SWNT theory	640	1	1.33	1-10	6400	8	6015
SWNT fiber	80	0.5-1	1.33	0.1	400	0.25	188
SWNT sheet	0.3-6	0.2	1.33	0.1	10	0.0025	1.88

* The calculated blocking stress σ_B for the shape memory alloy NiTi exceeds the ultimate tensile strength of 1900 MPa (SMART7, 2013). Therefore, the average value of 425 MPa for the plateau stress of austenite (200-650 MPa) given by Memory Metalle GmbH was taken to calculate the volumetric work per cycle and gravimetric work per cycle.

Conclusions

Smart materials have continuously been gaining attention in the past decade and are using mostly in developing smart structures or machines. There are many promising new materials from the field of the electro active polymers (EAP) are emerging as smart materials. Some everyday items are already incorporating smart materials (coffeepots, cars, the International Space Station, eyeglasses) and the number of applications for them is growing steadily. Each individual type of smart material has a different property which can be significantly altered, such as viscosity, volume, and conductivity. Smart Materials Expected to Cater to Diverse applications. The advances and improvements in smart materials allow them to cater to a diverse set of applications, especially in the defense, aerospace, healthcare, electronics, and semiconductor industries. Although very few of these applications are at present commercially viable, their potential for future acceptance is irrefutable. Smart materials are particularly useful for cellular production, observes the analyst. With future advances, smart materials are also likely to be useful for fabricating insulin pumps and drug delivery devices. The successful integration of the hardware and software based infrastructures accompanied by the application of combinatorial chemistry is set to increase technology development in the field of smart materials and systems by leaps and bounds, observes the analyst.Smart structures of the future may be so advanced that they would be able to design themselves, just as computers can be developed which can write their own software as needed.

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