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A Review of Smart Materials: Researches and Applications

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Abstract: Smart materials are a family of materials that are listed in advanced materials. These groups of materials have self-accommodation with environment and they are classified according to their responses, such as physical (pressure, temperature, humidity, light, electric field, magnetic field), chemical (pH, CO2, etc.), or biological stimuli. The smart materials can convert the absorbed energy or their characteristics may undergo a change. Smart materials are getting high attentions due to their commercial applications in either actuator or sensor form. This work demonstrates an exclusive review of different types of smart materials with their specific characteristics, and some related investigations that improved smart material properties. In addition, the applications of smart materials are categorized according to the different application areas, such as medical implantation, reducing waste, and nano engineered systems.

Keywords: Smart material; Shape memory alloy; Piezoelectric; Robotic; Biomedical.

Akıllı Malzemeler Üzerine Derleme: Araştırmalar ve Uygulamaları

Öz: Akıllı malzemeler, ileri malzemeler grubunda yeralan, bir malzeme grubudur. Bu malzeme grupları, çevresi ile kendi kendine uyum içindedir ve bazı fiziksel (basınç, sıcaklık, nem, ışık, elektrik alan, manyetik alan), kimyasal (pH, CO2 vb.) veya biyolojik uyarılara verdikleri tepkilere göre sınıflandırılırlar. Akıllı malzemeler, soğurulan enerjiyi, karakteristik özelliklerini değiştirmek için dönüştürürler. Akıllı malzemeler, aktüatör veya sensör şeklindeki ticari uygulamaları nedeniyle yüksek oranda dikkat çeker. Bu çalışma, farklı türdeki akıllı malzemelerin spesifik özellikleriyle birlikte özel bir incelemesini ve akıllı malzemelerin özelliklerini iyileştiren bazı ilgili araştırmaları göstermektedir. Ayrıca, akıllı malzemelerin uygulamaları, tıbbi implantasyon, atıkları azaltma ve nano mühendislik sistemleri gibi farklı uygulama alanlarına göre kategorilere ayrılmaktadır.

Anahtar kelimeler: Akıllı malzeme; Şekil hatırlamalı alaşım; Piezoelektrik; Robotik; Biomedikal

1. Introduction

Human being from thousand years ago used material for different purposes, which enhanced their life styles, even civilization was classified by different ages that started by discovering a new effective material. According to archaeologists, the first age belongs to Stone Age, and a most revolutionary fall out with discovery of bronze, because it was harder and durable than the other on hand materials. The Bronze Age was the beginning of metallurgy, which civilization steps further to extract different materials that occupied every part of our life [1].

In the last two centuries, dense researches have been done to synthesize new types of functional materials, which are classified to several groups and families. There are four main group of

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Bu makaleye atıf yapmak için
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materials which are metals, ceramics, polymers, and recently advanced materials [2]. Among them, advanced materials become more attractive one because they have more technological applications.

Since, some physical properties of advanced materials can be controlled; they are the building block of most advanced hybrid devices around us. Semiconductors revolve generation of computers from vacuum tubes to a more compacted electronic chips [3]. On the other hand, biomaterials opened the way of interaction with biological organs, likewise nano-engineered materials are more efficient than their bulky counterparts [4, 5]. Consequently, *smart* or *intelligent* materials will boom civil engineering, industrial appliances, medical instruments, automation systems and more.

Nowadays, the necessity of using smart materials (SMs) for various constructions are due to their ability to change properties when exposed to external stimuli. Their reversibility makes them to be one of the matchless materials and can be specified by their sensing, healing and adaptable in response to environmental conditions. Factors like, temperature, mechanical stress, strain, hydrostatic pressure, magnetic field, electric current, pH or chemical effect, can lead to a change in size, color, moisture, scent, and viscosity of flow [6]. Thus, the smart material's applications such as sensors [7-9], actuators [10-14], and drug delivery [15, 16] can be satisfied by using the aforementioned parameters.

In this review, we have concentrated on an introduction to different types of SMs and their potential applications in various areas. This article has been arranged such that the SMs defined in chapter two and from a historical point of view; the most important investigations and discoveries were illustrated. Since, SMs have different types, then their groups were counted and some important physical properties have been explained in chapter three. In addition, for showing their important situation in modern society, some of recent applications were represented in chapter four. Finally, some active field of research and open gates were clarified that may give opportunity to the researchers in this area.

2. What are Smart Materials

There is not a unique definition for smart materials [17-20], e.g. NASA defined them as materials that can remember different forms and able to reconcile with particular stimuli, or it can be defined as a highly engineered materials which can react smartly to their environment [21, 22]. Smart materials belong to advanced material that can sense some particular signals from outside and actuating themselves to doing a determined task. Smart, intelligent, or even adaptive are the words that are used for those materials, which are including sensors and actuators. In addition, they have some features that make them to be distinguished from the other materials, such as [21-25]:

- Transiency: they can respond to different stimuli and can be situated in varies states;
- Immediacy: they response to the external effects without wasting time;
- Self-actuation (intelligence): this ability is inside the mater;
- Selectivity: the response is distinguished and predictable;
- Directness: both act and react are accrued in the same place.

Smart materials are divided into two main categories, passive and active [26, 27]. Passive SMs are those materials that able to transfer some types of energy, e.g. they are used as fiber optic that can transfer electromagnetic wave. Furthermore, active SMs are also divided into two types. The first type are those that can alter their characteristics, when they are exposure to external effects, such as Photochromic glasses that can change its color when it presented in sunshine [28]. The other types can change energy from one form –thermal, chemical, nuclear, mechanical, electrical, and optical- to another form. Solar cells (Photovoltaic cell) and LEDs are two examples that can convert solar energy to electricity and electricity of light, respectively [29, 30]. Likewise, each pyro-electric, piezoelectric and ferroelectric are photovoltaic materials that can generate electricity by energy conversion [31]. Furthermore, since, the second type of SMs verifying the first law of thermodynamics, then they may called ‘First Law’ [32].

By using the mentioned energy fields one can determine physical properties of SMs, and the mechanism of converted energies by SMs. To specify the type of a SM is, when a given typical energy is do change in structure or even microstructure from one phase to another phase, then that SM is the first type (property change), however, if the structure of that SM stay constant, but the given energy is converted, so the SM listed as second type (energy change) [33]. Both types of SMs have reversible property and can return back the same energy to their environment. Furthermore, they can absorb signals from ambient and can perform a directional process in an intelligent way.

3. Types of Smart Materials

Due to different responses to environmental stimuli, smart materials are classified to several types, including shape memory alloys (response to thermal and pressure), piezoelectric material (response to electricity and pressure), electrostrictive materials (response to electric field), magnetostrictive materials (response to magnetic field), chromic materials (react with different type of stimuli), electrorheological fluid (react with electric field) and magnetorheological fluids (react with magnetic field). In the following sections all types of smart material shortly have been illustrated.

3.1. Shape Memory Alloys

Shape Memory Alloys (SMAs) are smart materials that have to have at least two different basic phases, which can be transformed from one phase to the other by changing temperature or stress. They able to memorize their shape in austenite phase, and thus when they are deformed, their primary shape can be recovered to the same morph. During this process the atomic structure and microstructure of solid altered, which is known as shape memory transformation [34].

Historically, Ölander discovered shape recovery in gold cadmium, Ag-Cd, at 1932 by [35]. After that, lots of researchers detected this phenomenon in many other alloys [36, 37]. But none of them were not as importance as nitinol alloy system, NiTi, which has a powerful functionality and a wide utility in commercial purposes [38]. Since, application of SMAs depend on the temperature range and many other physical parameters, then the determination and enhancing these features has made this field to be an active research area among material scientists.

Table 1. Some common SMA systems [39-41].

Alloy	Composition	Transformation temperature, A_s, Range (^oC)	Transformation Hysteresis
Ag-Cd	44/49 at. Cd	-190 to -50	~15
Au-Cd	46.5/50 at Cd	30 to 100	~15
Cu-Al-Ni	14/14.5 wt.% Al 3/4.5 wt.% Ni	-140 to 100	~35
Cu-Al-Ni polycrystalline	Cu 82.4 wt.%- Al 13.5wt.%- Ni 4.1wt.%	149	~21
Cu-Al-Ni single crystal	Cu 82.4 wt.%- Al 13.5wt.%- Ni 4.1wt.%	157	~12
Cu-Sn	15 at.% Sn	-120 to 30	~10
Cu-Zn	38.5/41.5 wt.% Zn	-180 to -10	~10
Cu-Zn-X X=Si, Sn, Al	small wt. % X	-180 to 200	~10

Metallurgists and researchers have being investigated the effect of many parameters on physical properties of SMAs, such as adding new materials to the binary SMAs [42-48], heat treatment [49-56], mechanical treatment [56, 57], different cooling methods [58-62], improving surface [63, 64], and various techniques for preparation samples [65-67]. There are several methods to prepare SMAs that give different property to the product (Table 2).

These types of smart materials can exhibit several features such as thermoelasticity, superelasticity, and damping capacity, which illustrates why these types of materials are unique.

Table 2. Different available techniques to produce SMAs.

			Advantages
Casting		Vacuum Arc Remelting	• High homogeneity and purity [68]
Casting		Vacuum Induction Melting	• Single batch melting and low cost [69]
Casting		Electron Beam Melting	• Flexibility in the surface and bulk geometry [70]
Powder Metallurgy	**Conventional Processes**	Conventional Sintering	• Low dense and high voids in microstructure [71]
Powder Metallurgy	**Conventional Processes**	Self-propagating High Temperature Synthesis (combustion)	• High porous, and make SMA for biomedical applications [72, 73]
Powder Metallurgy	**Conventional Processes**	Hot Isostatic Pressing	• Possible to be used for elementary powder mixtures [74]
Powder Metallurgy	**Conventional Processes**	Spark Plasma Sintering	• fine grains and dense structures [75] • standard carbon content [76]
Powder Metallurgy	**Conventional Processes**	Metal Injection Molding	• Generating high porous SMAs [77]
Powder Metallurgy	**Additive Manufacturing**	Selective Laser Sintering	• Producing complex structures without the need for machining [78]
Powder Metallurgy	**Additive Manufacturing**	Selective Laser Melting	• Fabricating approximately full density functional parts [79]
Powder Metallurgy	**Additive Manufacturing**	Laser Engineered Net Shaping	• Controlling shape, size, and porosity [80] • alloys with novel microstructures and high purity [81]
Powder Metallurgy	**Additive Manufacturing**	Electron Beam Melting	• Intricate geometries and low cost [82] • Comparably low carbon content [83]

3.1.1. Thermoelasticity

Due to reducing temperature the, the phase of SMAs transfer from the high temperature (austenite) to the lower temperature phase, which is known as martensite phase (also sometimes this process is called sheer or displacive transformation) [84]. This important functionality is the key point in which gives an ability to SMAs in order to recover their earlier shape [51]. However, the time of cooling is straightly influenced on this transformation [54, 85]. Among them, ferrous alloy systems are nucleation dependent (non-thermoelastic) during austenite to martensite transformation, while the other alloys are independent (thermoelastic) [86].

These kinds of materials, usually, are formed in a high temperature, and then rapidly they cooled down to the martensite phase. If a deformation occurred in an SMA due to an external stress it can be refined by some basic procedure. In a conventional material, the shape only can be recoverable by cold or worm working, however, the case is different in SMAs, somehow that, when it is warmed up to austenite phase the prior given shape can return back. This basic property is called shape memory effect (SME) [87-89].

In shape memory materials, the bulk form of the substance is not changed during phase transformation process, however, the crystal structure is sustained a Bain strain. Thus the cubic crystal structure distorted and make a twining structure, which are either hexagonal close packed, monoclinic, or orthorhombic [50].

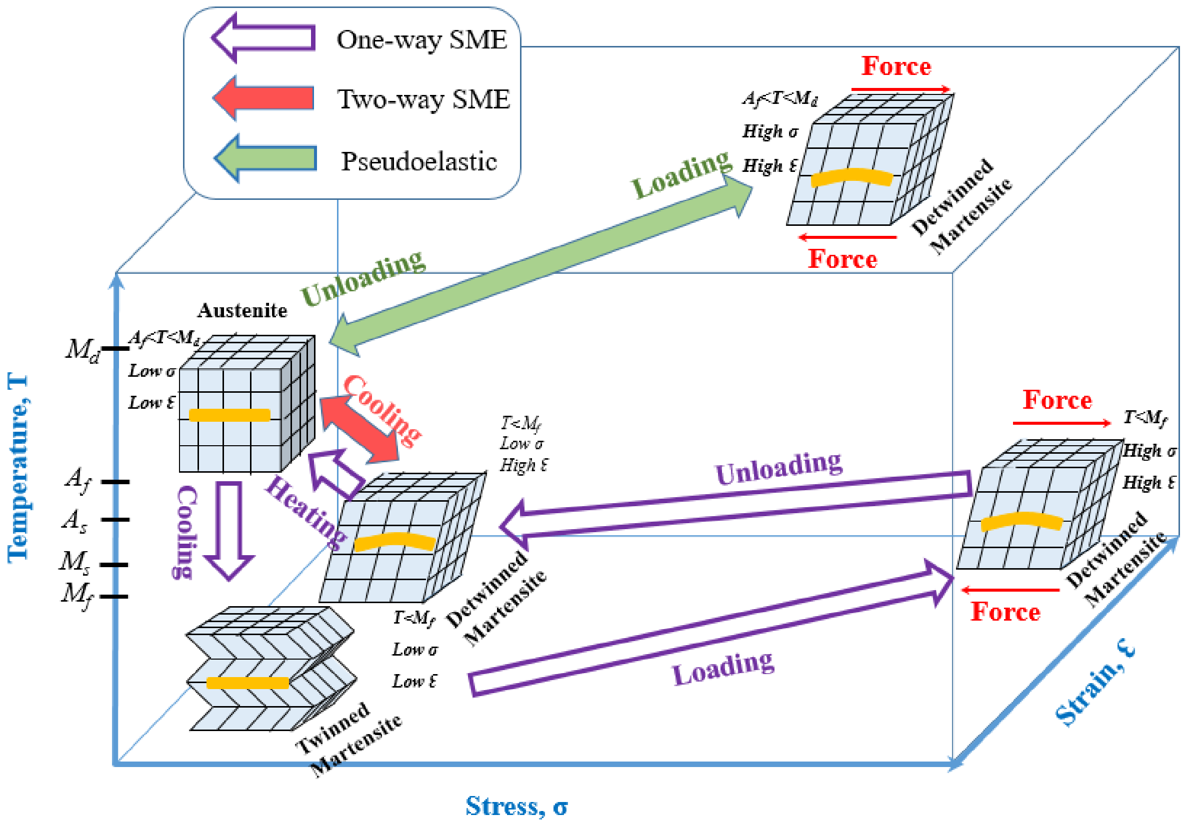


Figure 1. Schematic diagram of several SME for stress, strain and temperature parameters [90].

Schematic diagram of SMA for different physical environmental conditions is shown in Figure 1. The crystal structure of austenite phase is changed with a super cooling process, to a twinned martensite. This process is starting from martensite start temperature, M_s, and will completed bellow martensite finish temperature, M_f. When a mechanical stress distorts the twinned martensite to detwinned structure, the original shape memorized inside the SMA. To recover its original shape, it has to go through two more steps. Firstly, the external load has to be removed, it has to be heated to a complete austenite phase transformation occurred. This high temperature phase starts from austenite start, A_s, and get evolution at austenite finish temperature, A_f. All of these steps make a cycle; thus, the strain recovery is depending on the direction of process. The materials that confirm these steps are called one-way SMAs. While, the final process, which has a significant property, is called two ways SME. One-way SMAs have only a single original shape, in higher temperature, however two recoverable shapes can be given to two-way SMAs; one in the austenite and the other in the martensite phase. In addition, one-way SME is an intrinsic feature of materials, but, the two ways has to be trained in a scientific manner.

In addition, there is a gap between phase transitions. The austenite and martensite have different start and final temperatures, thus the temperature differences from 50% martensite to 50% of austenite phase is known as temperature hysteresis. Figure 2 displays the hysteresis that is one of important characteristic property of SMAs.

3.1.2. Pseudoelasticity

Pseudoelasticity or superelasticity is a nonlinear stress/strain behavior that can be appeared for a domain boundary motion or in a particular case (which is called Bain Correspondence), a transformation between different crystal structures. Figure 3 shows the diagram of superelasticity for a temperature above A_f.

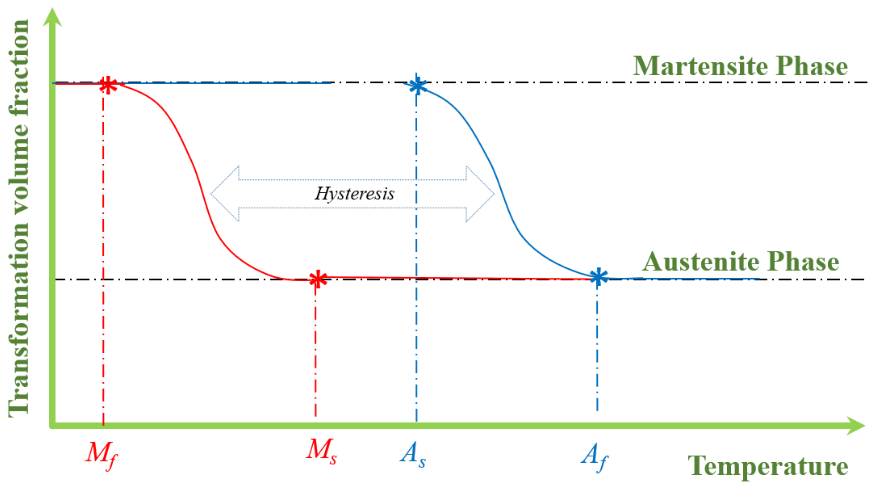


Figure 2. Phase transformation of SMAs. The difference in transformation temperature is called temperature hysteresis [91].

Furthermore, in the Figure 3a, the process is clearly illustrated. In region no. 1, when a load applied to a SMA, it undergoes an elastic deformation. For a specific pressure, the SMA absorb maximum elastic energy without any change in the crystal structure. With an approximately constant stress, the austenite phase transforms to martensite with a dramatic increase in strain and makes a plateau (region no. 2). After phase transformation completed, another elastic deformation starts for metastable martensite phase (region no. 3). Since the strain recovery is limited for every SMAs, so for a specific value of stress and strain SMAs reach a maximum superelastic capacity, which is known as yield point. The martensitic phase is not a stable phase in this range of temperature so when the load is getting away, the strain linearly decreased with reducing of stress (region no. 4). The SMAs undergo a reverse phase transformation from martensite to austenite under a constant stress (region no. 5), but during phase transformation a fraction of energy will consumed, thus the reverse phase transformation does not occur at the same stress. For a full recovery and when the martensite phase completely transformed to its parent phase, the SMA can return back to its pre-determined shape. On the other hand, the SME has not such ability to recover strain without heating (Figure 3b). In addition, above M_d temperature the stress induced martensite is not able to recover the deformation [92].

3.1.3. Damping capacity

The ability of material to dissipate vibrational energy, such as impact energy or sound wave, to internal energy is called damping capacity. Due to martensitic transformation SMAs have a huge strain recovery, and can dissipate energy more than steel and concrete [90, 95]. The damping capacity depends on the amplitude of vibration, whereby, they are more efficient for strain amplitude higher than 10^{-5} [96]. Also, the constituent and microstructure can effect on the damping capacity, e.g. Wang et al. [35] found that the damping capacity in CuAlMn enhanced by reducing the pores diameter or by increase in volume fraction of the existence pores in the alloy.

3.2. Piezoelectric Materials

Curie brothers from 1880 to 1881, were the first researchers how could found an interesting phenomenon, known as “piezoelectricity” [97]. At the beginning they just realized the role of mechanical pressure to induce electricity in some special crystals, but after some mathematical proofs based on the fundamental of thermodynamics (by Lippmann at 1881), Curies realized the reverse effect of electric field on the size of the same crystals.

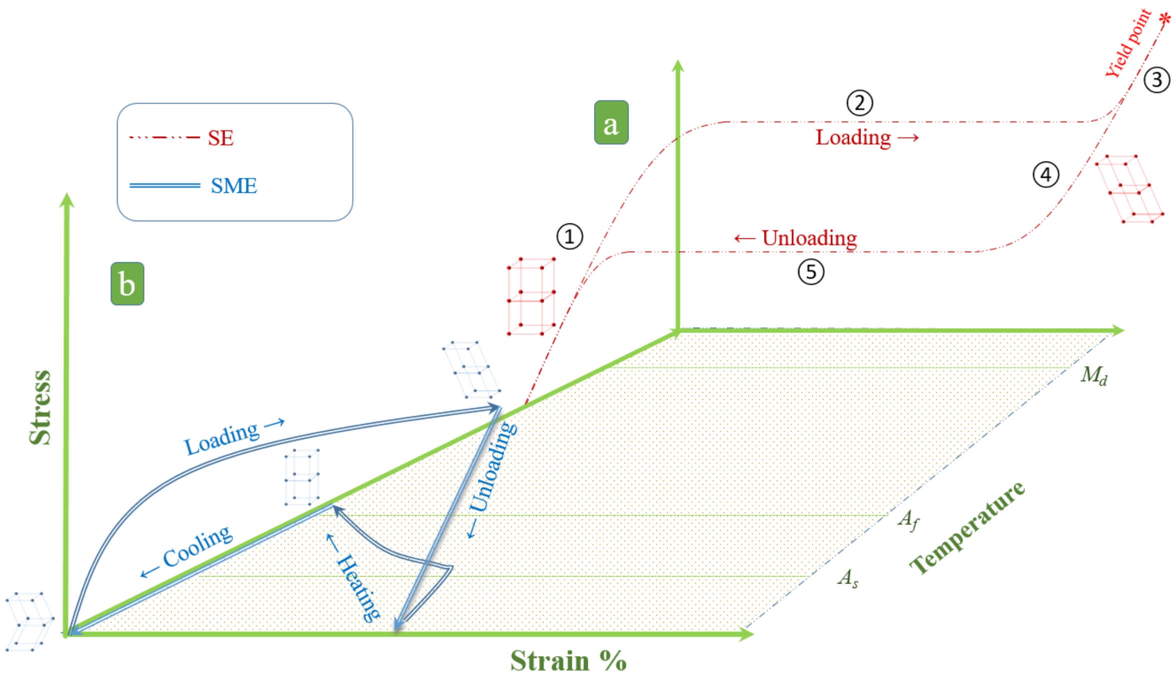


Figure 3. Stress/strain relationship for (a) Superelasticity effect, that can be seen between M_d and A_f. (b) Shape memory effect, SME [93, 94].

Figure 4a shows how an electrical potential difference can be produced (ΔV) in a piezoelectric, when it is subjected to an external mechanical stress. The polarization of ΔV depends on the direction of applied stress [100]. In contrast, when ΔV is applied to these type of smart materials, they can change their size, thus the energy can be release as a mechanical forms (see Figure 4b) [101]. This reversible process, could also be found in either "contact electricity", which electricity could be produced with a friction process, or "pyro-electricity", that heat can generate electricity and contrariwise [102]. In the other hand, when the biasing voltage is applied orthogonal to the polarization of piezoelectric material the sample will bend, which the direction of bending depends on the orientation of material (see Figure 4c).

Based on the geometrical shape, piezoelectric actuators are specified in some categories with one dimension of freedom, 1-DOF. The first one is piezoelectric actuators that are made of Lead-Zirconate- Titanate, also known as PZT Stacks. They can move a device with accuracy of nanometer [103]. These types of actuators are consisting of several piece of piezoelectric that arranged in a line. Next are tube piezo actuators, which offer each radial and axial motion. Also, shear piezo actuators are orthogonally connected to voltage source. In addition, they are a constituent part of walking piezo motors. Finally, bender piezo actuators that are produced by multilayer or basically bimorph that could bend for several millimeters.

3.2.1. Piezoelectric sensors

Measurements are the best tool in our hand to understand all physical phenomena quantitatively. Thus, some quantities can be measured directly by comparing with a corresponding standard. However, there are many quantities that have to be converted to a meaningful quantity by a default definition such as electricity. Electrical circuits are the base for several detectors and measurement tools. Likewise, piezoelectric materials can directly measure the value of mechanical quantities such as torque, acoustic sound, acceleration, force, and stress. They are classified as part of active smart materials, which their conversion do not need an external power sources [104].

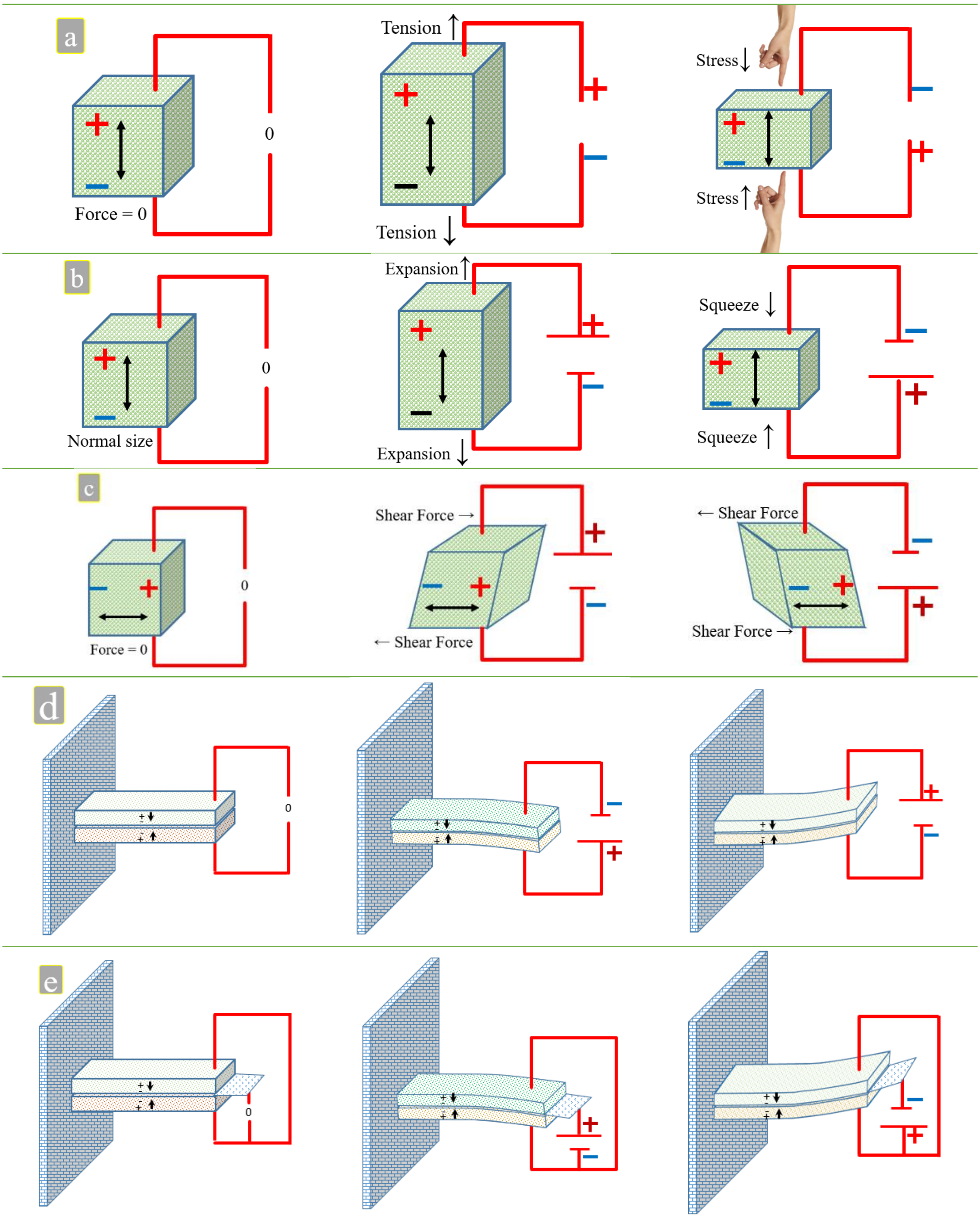
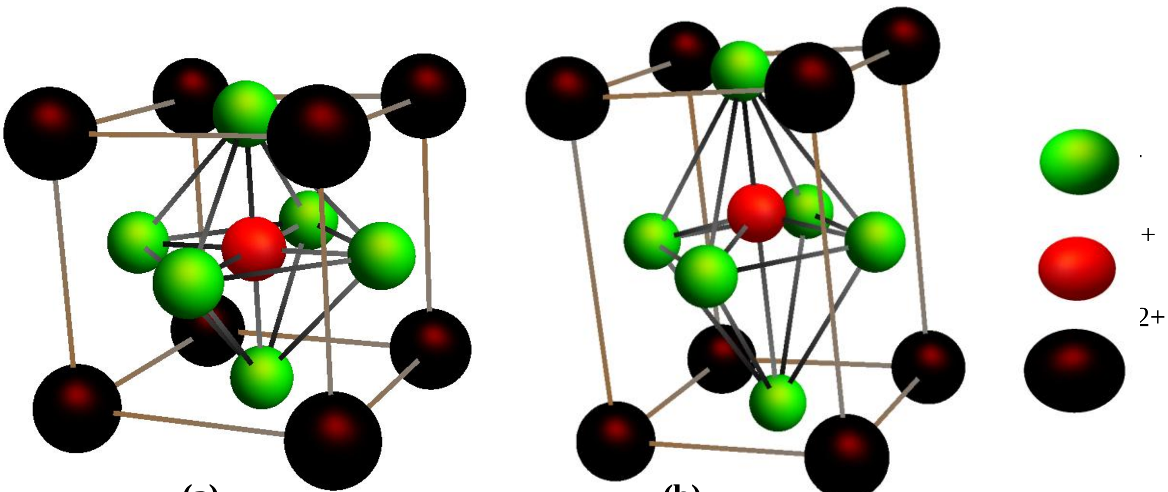


Figure 4. Schematic illustration of the piezoelectric effects. (a) Mechanical force producing electric field, (b) in contrast, by supplying electric field the shape is changed in the direction of polarization, and (c) when the electrical field is perpendicular to the polarization of crystal, the sheer force produced. Also by connecting two piezoelectric, with an opposite polarity, a bending system can be made in either (d) series, or (e) parallel form [98, 99].

Since piezoelectric materials are only being used for instantaneous measurements, then for those measurements that need a longer time they are useless. While, they have many features that make them a superiority over the others, such as isolated to electric and magnetic fields or electromagnetic radiations, work in a wide range of temperature [105], very sensitive [106], operating for an incredibly wide range [107], and working in high frequency events [108-110]. Also, piezo-sensors can convert mechanical energy to electrical power, so they can be classified as a type of generators [111].

There are many organic and inorganic materials that have piezoelectricity. Dentine of teeth and bones are organic materials with two constituent minerals, which are protein collagen and HAp (Hydroxyapatite) [112]. In addition, some inorganic ceramic materials can show piezoelectricity such as zinc oxide, ZnO [113], aluminum nitride, AlN [114], lead-zinc-zirconite-titanium oxides, $Pb(Zn, Al)O_3$ [115], and quartz (i.e. SiO_2) [116].

From microscopic point of view, the distribution of cations and anions in crystal structure is the key point that gives piezoelectricity feature to these types of materials. In a normal condition, the crystal shows a symmetrical configuration thus the dipole moment is zero. While, due to a mechanical force the crystal from a cubic crystal is reformed to a tetragonal or orthorhombic crystal structure. Therefore, an unstable asymmetrical crystal produced, which make an electrical dipole moment (see Figure 5a-b).



(a) (b)

Figure 5. (a) Three different atoms participated in the crystal structure of perovskite ($CaTiO_3$) [117]. The Ca^{2+} atoms locate in corners, which represent cations, likewise, O^{2-} atoms represent the second cations located in the faces. A single anion is in the center of crystal, which makes the crystal be electrically symmetry. (b) However, during an external force the anion shifts to one side and thus gives a polarity to the crystal.

3.2.2. Piezoelectric Actuators

As it has been clarified, electric charge can produce a motion, which its direction depends on the orientation of crystal with respect to the applying electric charge. Since, conversion of electrical energy to mechanical energy is the fundamental principal of electrical motors, so they often indicated as motors, however, the “actuator” is commonly used for this particular material.

3.3. Magnetostrictive Materials

Magnetostriction is a phenomenon that the size of a ferromagnetic material is change by applying a magnetic field. These materials could classify to positive or negative magnetostrictive materials (MS). They can either stretched or contracted as a response to biasing magnetic field. Figure **6** demonstrates an MS material that is located in a magnetic field. With a magnetic field free, the orientations of magnetic domains are random (Figure **6**a), but, when a low magnetic field is applied, a few number of domains reoriented in the direction of magnetic field (in positive magnetostriction case), thus a small elongation is occurred in the sample (Figure **6**b). By increasing magnetic field, the number of similar orientated magnetic grains is increased regularly, which make the sample more expanded (Figure **6**c). At the end, all magnetic domains reached the same direction, therefore, the elongation will get a saturation (Figure **6**d).

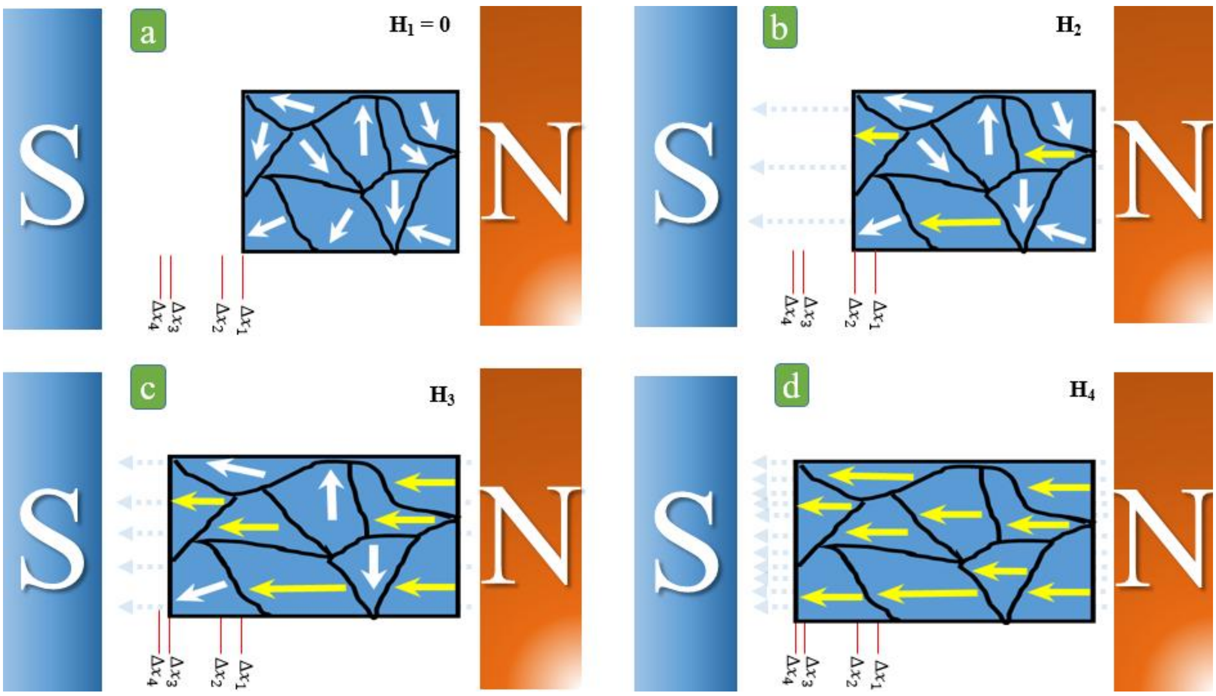


Figure 6. Schematic representation of a positive MS material that is put inside a magnetic field with different values, where $H_4 > H_3 > H_2 > H_1$. (a) When $H_1=0$, the sample get no effected. (b) For magnetic field of H_2, the sample is elongated a little bit. (c) Likewise, the expansion continues with quantitatively increasing in magnetic field, H_3. (d) Lastly the sample length gets to a maximum value, because all magnetic domains getting the same direction.

The direction of biasing magnetic field has no effecting on the stretching or contracting of MS material. Similar strategy is shown in Figure 7, for strain versus magnetic field, which briefly explained as follows:

- There is no change in size at point (1);
- In the interval between point (1) to (2), a small region of magnetic domain get the direction parallel to magnetic field;
- A linear proportionality can be seen between applying magnetic field and elongation for the range between point (2) to (3);

- Since, all magnetic domains get the same direction, so the sample do not change in size anymore (point 4).

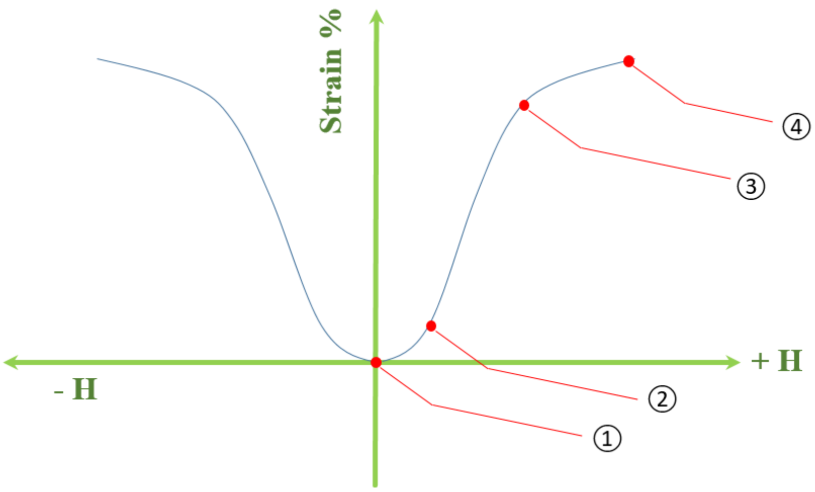
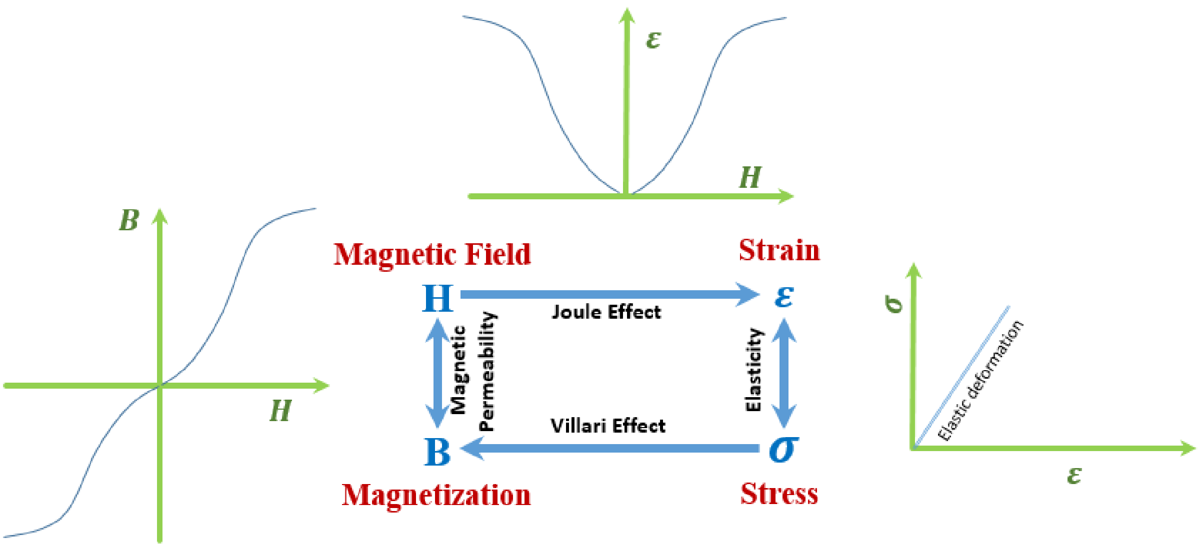


Figure 7. Induced strain vs. applying magnetic field to a positive magnetostrictive materials. Each number indicates the forward biasing magnetic field to the sample. Likewise, for the magnetic field turned to the opposite direction, the same elongation is obtained.

As it could be seen in the Figure 8, the strain induced in MS materials can be happened by an applied magnetic field, which is called Joule effect [118]. To generate a magnetic field, cyclic process has to be done from those size deformed materials. The strain can make a stress (elasticity), also stress can create a magnetization (Villari effect) [119, 120]. Finally, the magnetized materials can generate magnetic field (magnetic permeability) [121]. Among these effects, Villari and Joule effect are mostly used in MS material.



$$B = d\ T + \mu^T H$$
$$\varepsilon = c^H \sigma + d\ H$$

d is magnetostrictive constant.
c^H is elastic compliance under constant magnetic field

Figure 8. Diagrams representation of four different effects (Elasticity, Magnetic permeability, Villari, and Joule effect) [122].

3.4. Electrostrictive Materials

Electrostrictive materials response to electric field by changing their size. When they are exposed to an electric field the ions are displaced from their original positions thus the size is increased. Furthermore, this property is shown by piezoelectric material, however, there are some big differences between them. In the Table 3 some main differences between electrostrictive and piezoelectric materials are listed.

Table 3. Comparison between some properties of electrostrictive and piezoelectric materials.

Electrostrictive Materials	Piezoelectric Materials
Non-linear (quadratic strain) relation between changing size and strength of electric field [123].	Linear relationship between changing size and strength of electric field [116].
In both direction of applying electric field their size only increased, so they can not being used in bipolar mode applications [124].	Electric field direction can change the statues of either expansion or contraction of these materials [125].
In room temperature, their hysteresis is less than piezoelectric materials, and its quantitatively strongly depends on temperature [124].	Their hysteresis is more than 10%. in room temperature, while this value approximately are not big changing with varying temperature [126].
They have electrical capacitance more than piezoelectric materials.	The strain of these materials are as more stable as electrostrictive materials for varying of temperature.

3.5. Chromic Materials

Among smart materials, a family of materials can be found that change their color as a response to the variation in the environmental conditions. They can return back to their first color after that effect is disappeared. Since, changing the skin color is a camouflage technique among chameleon animals, then these type of materials that could show this ability are sometimes known as chameleon materials [127]. For each family, the reversibility of changing color depends on particular physical parameters. Table 4 gives some groups of chromic materials.

Table 4. Classification of chromic materials and their stimuli.

Chromic group	Stimuli type
Photochromic	Absorbing Electromagnetic light
Thermochromic	Changing of temperature
Electrochromic	Appling electric Field
Magnetochromic	Appling magnetic field
Piezochromic	Mechanical Loading
Solvatechromic	Contact with some liquid
Carsolchromic	Bombarding with electron beam

3.5.1. Photochromic

Generally, these groups of chromic materials are sensitive to visible and ultraviolet radiation, and they can give some colors which depend on the intensity of that particular range of radiation. Photochromic materials can be found in either organic or inorganic. Photochromic eyeglasses are one of the popular application that can reduce transparency when they are exposed to sunlight [41, 128]. Furthermore, photochromic materials are used in some textile fabrications and military protective clothes [129].

3.5.2. Thermochromic

The color in thermochromic materials altered by increasing temperature to some predetermined values. They can be produced from some compounds of semiconductor, metals, and liquid crystals. Temperature can change crystal structure, change in three-dimensional position of atoms, or rearranging atoms in molecule without changing chemical compound. These types of materials, also, have a wide application within different areas, e.g. thermostrips can be used for temperature indicators especially for determining fever.

3.5.3. Electrochromic

Electrochromic materials are fabricated in either transparent or reflective type [130, 131]. The composition of these materials, are sensitive to electrical voltage. In some particular polymers the electrochromic (EC) effect, is due to the transition of metal oxides [132]. Also, inorganic materials can exhibit electrochromic behavior by separating positive charge and electrons. There are lots of applications based on EC effect, e.g. the transparency of an electrochromic glass is decreased when a voltage is applied to it. Electrochromic window have used in Boeing 787 Dreamliner [133], ICE-3 high speed train [134], electrochromic-based display device [132], and switchable mirrors [135].

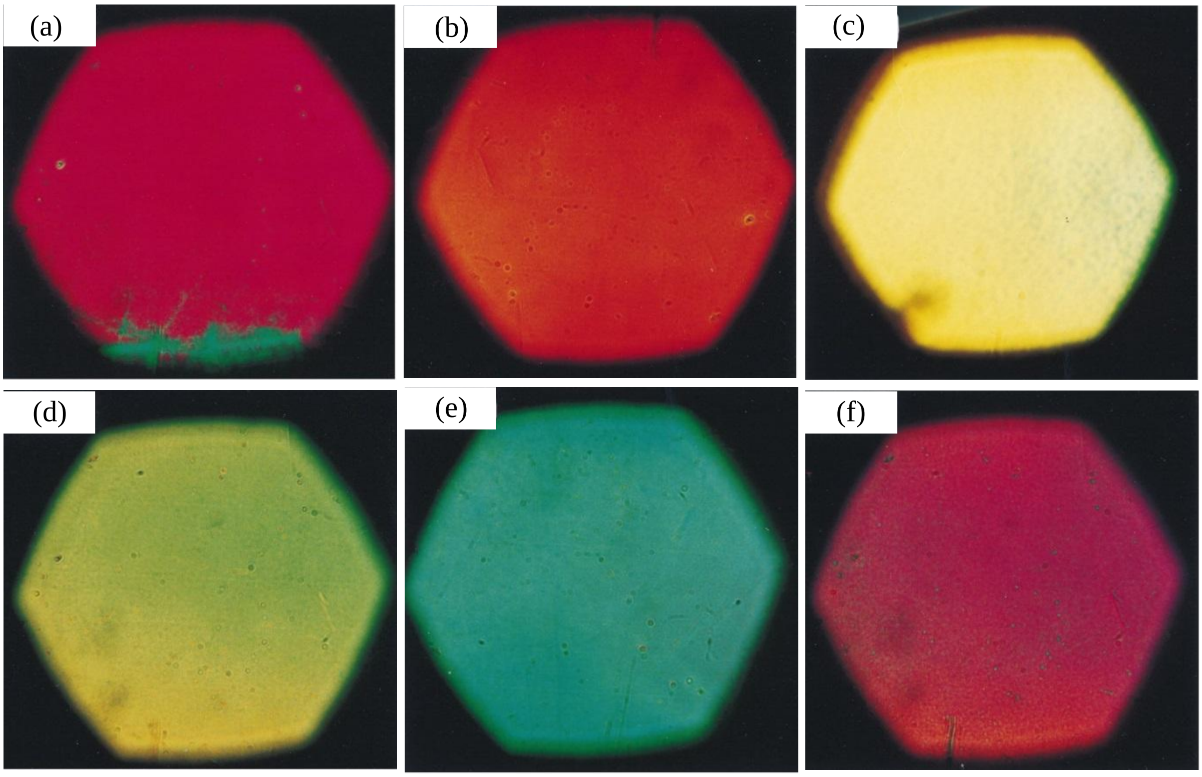


Figure 9. Diffracted light from films gives different colors due to varying magnetic field [136].

3.5.4. Magnetochromic

Magnetic field can work as a stimulus to change the color of some specific materials, which are known as magnetochromic materials. Ferrofluids are one of fluidic types of this kind of material that include magnetic particles in the range of 5-10 nm [137]. When a magnetic field is applied, the particles aligned in a regular manner, thus the incident rays are scattered from different semi-parallel planes of suspended particles. Figure **9** shows a magnetochromic film that exposed to different value of magnetic field.

3.5.5. Piezochromic

Piezochromic are materials that by applying a particular pressure and through bathochromic shift, they can change some physical properties such as absorbability, emissivity, reflectivity, or transparency. $CuMoO_4$ molecule need 2.5kbar to change its color from green to red, while Palladium (Pd) need a pressure more than 1.4 GPa [138, 139]. Many piezochromic materials, need an extremely high pressure to change the color, so they cannot be used, especially, for color pressure sensors. But some types of polymers shows bathochromic shift by exerting only 8kbar [140]. Figure 10 illustrate the schematic diagram of a typical piezochromic material, which its color is changed under an external load.

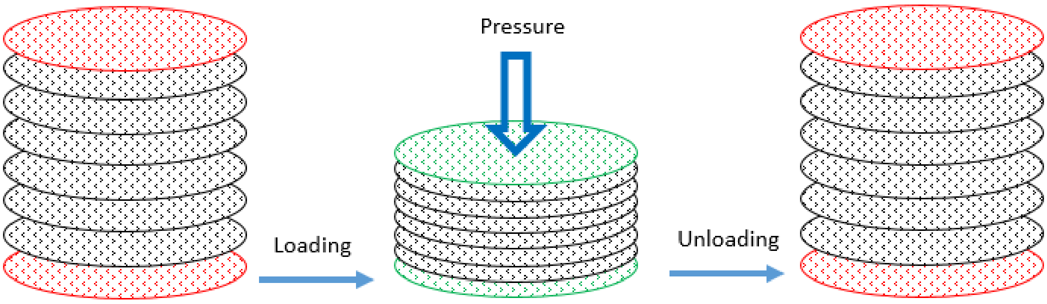


Figure 10. Schematic diagram of a Piezochromic material that can changes its color by applying a pressure [141].

3.6. pH Sensitive Materials

Smart material could react with physical, chemical, and/or biological stimuli [142]. pH sensitive polymers are one of important family in smart materials that can change their color as a response to a specific pH variation. They can be one of acidic or basic that react with their opposite counterpart. Nowadays, they are used in different areas such as medical for drug delivering [143], improving surface, and working as a filter [144].

Halochromic Materials are one of best pH indicators that are used in relevant sensors. They change their color through a chemical binding occurred between hydrogen ions and hydroxides. As an example, halochromic materials are used in bandage that can help medicine to indicate any change of burned patient. These smart textile bandages can change pH of skin during recovering period, and thus they are helpful for monitoring the level of healing [132].

3.7. Magnetorheological Fluids and Electrorheological Fluids

In general Fluids are classified to Newtonian, and non-Newtonian fluids. In Newtonian fluids, a linear relationship between their resistance of flow (viscosity) and the velocity of an object that penetrates through the fluid. However, non-Newtonian fluids exhibit different phenomena, e.g. Oobleck is made of cornstarch and water; its viscosity dramatically is changed by a fast shape disturbing [145].

Magnetorheological Fluids (MRFs) are non-Newtonian viscoelastic fluids that have suspended iron particles and can change their viscosity and thickness under applying an external magnetic field (see Figure 11). They contain micro particles, in the range of (0.1-10μm), that are bigger than nano particles in Ferrofluids, thus Brownian motion has a less effectible. MRFs can be used in three different models: sheer, valve and squeeze-flow [146].

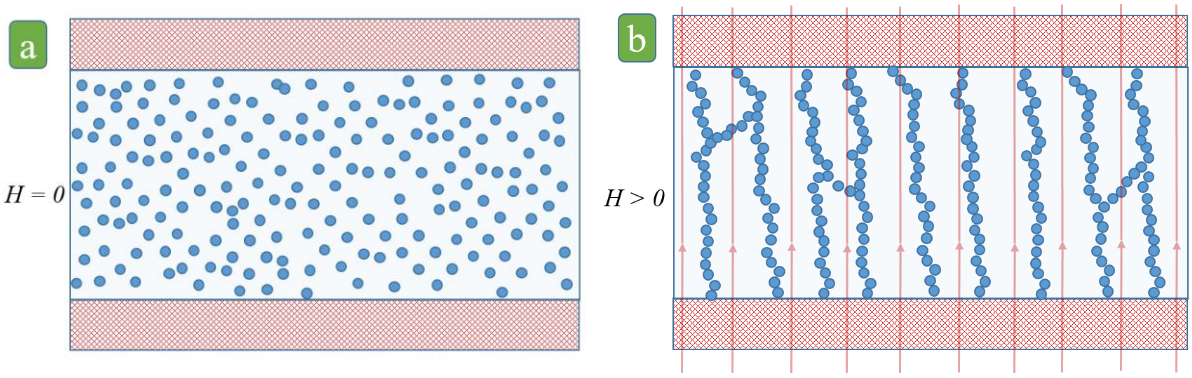


Figure 11. Schematic representation of magnetorheological fluid. (a) At a normal condition the suspended particles are randomly distributed, however (b) when a magnetic field is applied, the particles rearranged in the same direction of magnetic field and thus the thickness is increased [147].

There are a lot of amazing enhancement in engineering technological opportunities to use MRFs. They can be used in buildings to protect them during earthquake [148]. Also, shock absorber [149] can diminish boring oscillation in cars more than conventional ones with Newtonian fluids.

Likewise, electrorheological fluid (EMF) is a non-Newtonian viscoelastic fluid - like magnetorheological fluid - that have disordered suspended particles. When an electric field is applied to an EMF, the suspended particles stick together and they make chains in the same direction of applying electric field. EMF, like MRF, can be used in the same smart application systems [150-152].

4. Application of Smart Materials

Today, smart materials have significant role modern civilization, and they are appeared in most area of technology such as, civil engineering and building, medical, military, robotic machinery, aeronautical technology, industry, nuclear power plant, art, and in some active research groups. In the following sections some applications are discussed.

4.1. Walking Piezo Actuator

Walking Piezo Actuators are motors, which are constructed with of some different piece of piezoelectric materials that are used for transverse and longitudinal motion. Each motor have four legs, and the legs consist of two parts. The upper part can be used for elongation of the leg, while the foot has been designed for bending forward and backward. The walking process is shown in Figure 12. At the beginning, the longitudinal Piezo motor are elongated in axial direction. Then a voltage is applied orthogonal to the feet of all legs, to make a bend. After that, two of the bended feet, which are located on plane, change their status and bend to the opposite side. Then, these two legs are contracted, while the other two legs continuous the process [15].

Since, Walking Piezo Actuator can be controlled in the range of nanometer, so they are embedded in most precision microscopes and incredibly small robots. Moreover, encoder resolution is less than 5nm for unchanging velocities from (100 nm/s) to (1 μm/s), and are less than 400 nm for velocities more than 2 mm/s [14].

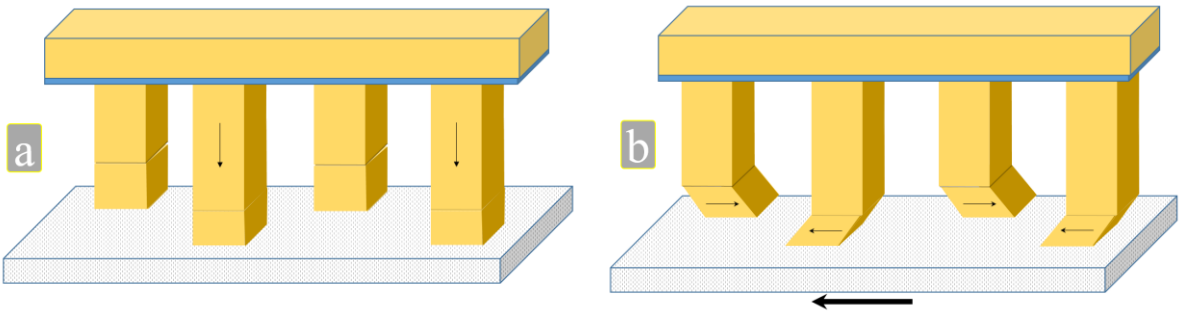


Figure 12. Schematic diagram of Walking Piezo Actuator. (a) Two drive legs is expanded to the plane, (b) then the feet of two drive legs bend in opposite direction with each other [153].

4.2. Aeronautical Technology

There are lots of advanced materials that have been utilized in different sectors of aeronautic technologies. Since their manufacturing are fulfill of these kinds of materials, so describing or even mentioning all of these materials are beyond of this review paper. In this section it has been deal with just a bunch of bangs.

The first example is ultrasound fuel probe, which is an accurate indicator. An electrical stimulus piezoelectric is used to make an ultrasonic, and when the incident wave is reflected by surface of the liquid fuel, it is detected with a transducer piezoelectric sensor, thus the level of fuel can be exactly measured [154]. Second example is SMA-based wings or smart wings. These technology use SME to change the shape of wings through ascending and descending of airplane. Therefore, the hydraulic motor systems will not need anymore, also, the wings become more compatible and make a diminish in noise production [155].

4.3. Nuclear industries

Smart materials could have many superiorities for this risky and costly sector. They are more efficient with lower cost, also they can used for automation systems to avoid personal from dangerous exposure of radioactive materials. However, effectiveness to radioactive radiation and the effective rate of exposure is one of challenges in this area [156].

4.4. Intelligent textile

Textile is one of important inventions of humanity, to keep our bodies away from sun light and keep our body worm in cold days. However, in the modern society, incorporating textiles with smart material can give them further functionalities such as changing color as a response to ambient agitations. Shape memory polymers (SMPs) are able to enhance the quality of these type of intelligent clothes [157]. Intelligent textiles can be given one or more properties like self-moving, sensitiveness to emotions, intrinsic cleaning, altering color or shape.

Since, softness of polymers are changed after glass transition at a particular temperature, then they can utilized to make some textile for ventilation and regulation of body's temperature [158]. The molecular volume of polymer is extended above glass transition temperature (T_g), and hence, it opens more space to exchanging evaporated water, which is one of important factor to cool down the body's temperature in hot days. In the other hand, these breathable polymer textiles have waterproofed feature. They can be designed such, the molecules of textile have minimum volume at room temperature, so the textile prevent any penetration of moisture from surrounding to body or evaporation from body to ambient, However, in a higher temperature (T_g), the molecules extended and thus making some small holes for ventilation [157]. The water vapor permeability has been more improved by embedding multi walled carbon nanotube [159].

Furthermore, since the vertical stress of SMPs are lower than the regular textile, so it gives more flexibility to SMPs and thus they will get a compatible size with body. Likewise, using SMPs in fiber core can show SME, which its schematic is shown in
Figure **13**.

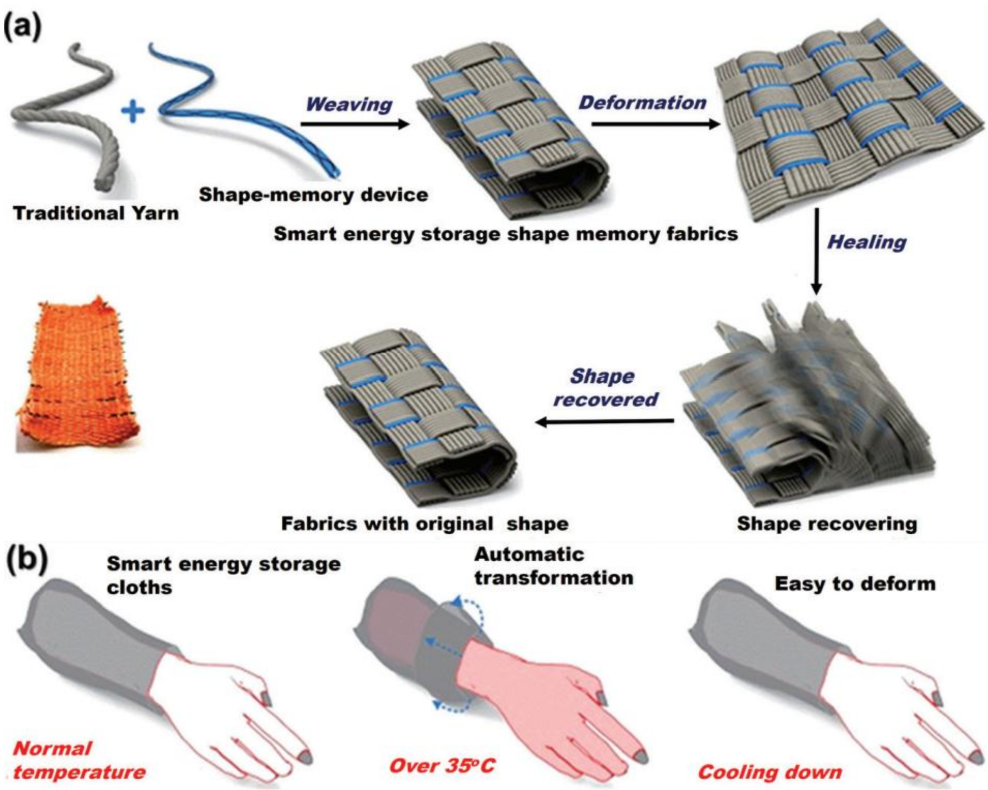


Figure 13. (a) Schematic composition of both traditional and SMP in a smart textile, which exhibits SME, and (b) it is handled in a smart garment [157].

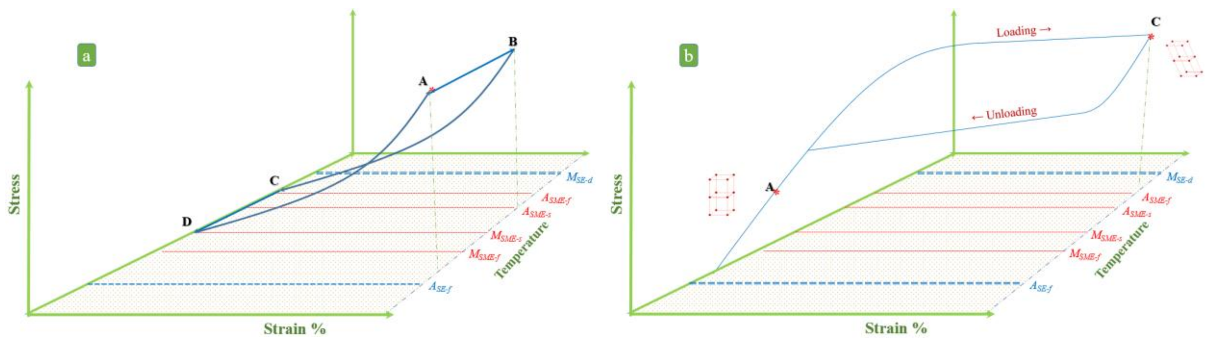


Figure 14. Stress-strain relationship for each side of Ni-Ti film in different situations. (a) The SME-layer return back to its original shape due to heated, which started from martensite phase (A) and will completely recover its predetermined shape at austenite phase (C). (b) Firstly SE-layer of

the film, is in its austenite phase (A), and when the other side show SME this layer will be deformed due to martensite transformation (C).

4.5. Micro actuator of Ni-Ti film

Combination of both superelasticity and shape memory effects in a same object is possible with fabricating Ni-Ti film [160]. To make this film, the first layers on substrate has to be sputtered with nickel-rich and continuing the process by decreasing Ni rate in the other layers. Thus, the film gets two various properties that could work as a bilayer system, which could be defined as a two-way shape memory effect.
Figure **14** shows the stress/strain status of each SME-layer and SE-layer of Ni-Ti film. In addition, SME-layer has a prior flat shaped in its austenite phase, while SE-layer has been given a bended shape in its original austenite phase.

At room temperature SE-layer has stiffer than its opposite side, so it converts the whole film to a bending form, in this statue the SME-layer deformed to a detwinned martensite. But, when the sample is heated to A_f temperature, a phase transformation occurred in SME-layer, and thus, its stiffness overcome to SE-layer. Consequently, the film is got the plan shape. The range of temperature for this flip-flopping has to be keep in mind to achieve this property. The two temperature that can be determined are $A_{SE\text{-}f} < T_{bend} < M_{SME\text{-}f}$ and $A_{SME\text{-}f} < T_{flat} < M_{SE\text{-}d}$, where $A_{SE\text{-}f}$ and $M_{SE\text{-}d}$ are austenite finish and M_d of SE-layer; $M_{SME\text{-}f}$ and $A_{SME\text{-}f}$ are martensite finish and austenite finish of SME-layer, respectively; T_{bend} and T_{flat} are temperatures of bended shape and flatted shape of the film, respectively (Figure **15**).

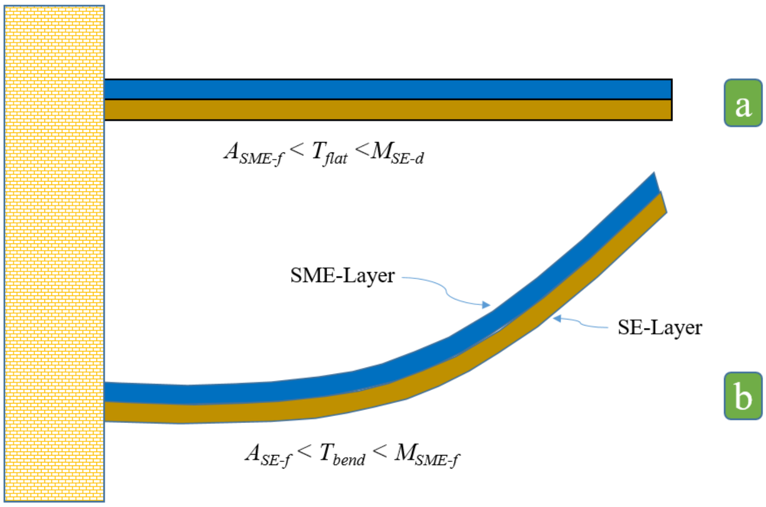


Figure 15. Operational states of a bilayer Ni-Ti film including two layers with different Ni composition. SME-layer has more Ni composition rate and its shape memory effect is used, while SE-layer has lower Ni composition rate and its superelasticity is utilized. (a) At higher temperature SME-layer change the shape of the system to its predetermined shape, and (b) at lower temperature SE-layer bring the shape to its prior morph [161].

4.6. Linear Magnetostrictive Actuator

For giant transducer actuators, a linear rod made of MS materials can create a sufficient force. It is look like a solenoid with a rod in the core and coil is surrounds the rod. A magnetic field is created by applying a DC current, which make an expansion in the rod, and hence the movement of the rod can be used for different mechanical purposes (see Figure 16). Furthermore, MS actuators have been used in many other applications such as reaction mass actuator, sonar transducers, wireless rotational motor, electro-hydraulic actuator, wireless linear micro-motor, thin film application in valves, and contactless torque sensors [122].

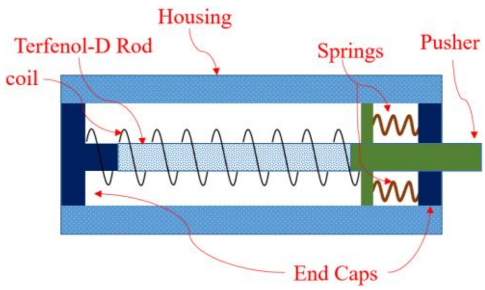


Figure 16. Schematic diagram of a linear MS actuator [162].

4.7. Nano Systems

Nano materials are more active than their bulk counterparts, because of higher ratio of surface per unit volume [163, 164]. Furthermore, size effect on the other physical quantities have being investigated such as thermal conductivity [165-167], lattice constant, volume per atom, melting temperature [168], Debye temperature and more [169, 170]. Nano-engineered materials are fabricated in either zero dimension (quantum dot), one dimension (nanowire), two dimensions (thin film), or even three-dimensional carbon nanotube (CNT). CNT has an electromechanical feature that could be used as an actuator in a related size [171]. Nanotweezers arm are made of CNT, which can be used for grabbing micro objects in high accurate modern microscopes. Tweezers arms are elastically bended by applying a voltage and they can back to the relaxed form when the biasing voltage get zero (see
Figure **17**) [172]. In addition, the diameter of nanotube could has a close related to the value of CNT elasticity [173]. This technology enables the users of scanning probe microscopes to perform electrical measurements and other manipulations with sample by grabbing it with those arms.

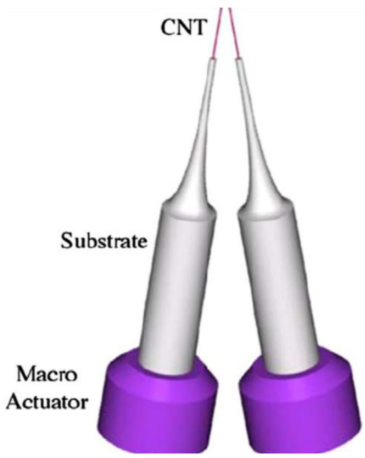


Figure 17. Schematic diagram of CNT – based actuator [172].

In a modern technology TiNi/DLC microcage with TWSME (Figure 18) has been produced. It has the similar basic idea, which is illustrated in section 4.5. The process of opening or closing can be achieved by giving thermal or electrical energy. Since it does not apply an extra force to grip micro-objects, then it gets more attentions than the conventional tweezers.

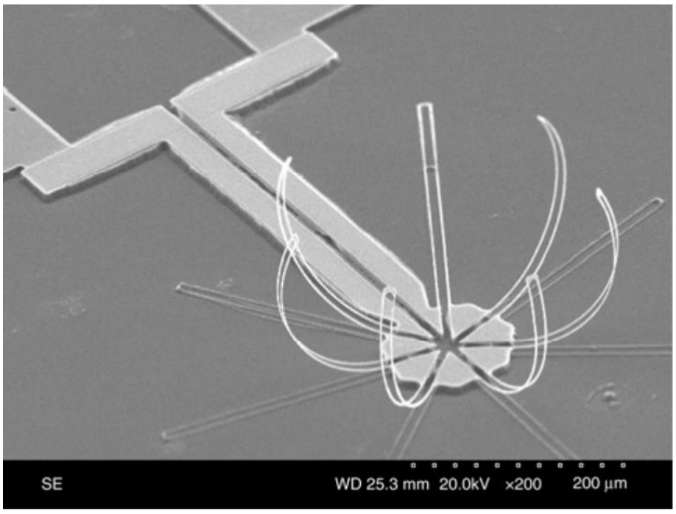


Figure 18. TiNi/DLC microcage with TWSME [160].

4.8. Power Generating Sidewalk

Harvesting clean energy from footsteps of people could be confirmed by special tiles that is made of piezoelectric materials. Since piezoelectric materials need a dynamic force to generate electricity, so using them in pedestrian can be a good deal, to feed energy to some pedestrian facilities.

Figure 19. Tiles that are based on piezoelectric material to generate electricity [174].

4.9. Medical Field

4.9.1.<u>Orthodontic arch wire</u>

In order to solve the problem of disorderness of teeth, arch wire is a good suggestion (Figure 20a). This technique is not new, but the materials that are used for arch-wire have been changed to more efficient ones. As an example gold alloy, stainless steel, beta titanium and Cr-Co-Ni alloys were commonly used for a period of time [35, 36].

Ni-Ti alloys had some properties that did not possessed in the previous traditional materials, i.e. pseudoelasticity of Ni-Ti gives a constant force for a long distance with a sufficient stiffness. From

Figure 20b it can be seen that Ni-Ti alloy has a moderate stiffness with a relatively good elastic recovery.

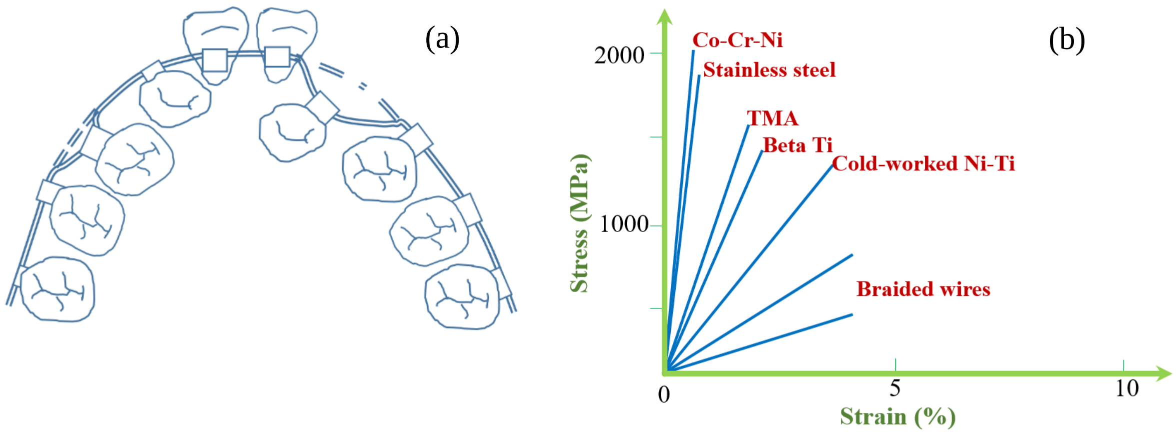


Figure 20. (a) Schematic diagram of orthodontic arch wire used for unordered teeth. (b) Elastic property of some materials that has been used for orthodontic purposes [175].

The range of acceptable stress is determined, which is called optimal range. More forces could damage tissue and less forces have less efficient, which are called excessive and suboptimal, respectively. Thus, the effective strain recovery, displacement of deformed wire, could be measured from this range. The longer the effective strain, the more efficient to utilize them.

As shown in Figure **21**, Ni-Ti has bigger effective strain (ε_{eff}) than stainless steel. In addition, martensite transformation of superelastic nitinol is located in the optimal range, therefore the value of ε_{eff} is so greater than other conventional materials. Furthermore, since a constant force is produced in the range of phase transformation, so the arch-wire can constantly pull the displaced teeth to its ordered position.

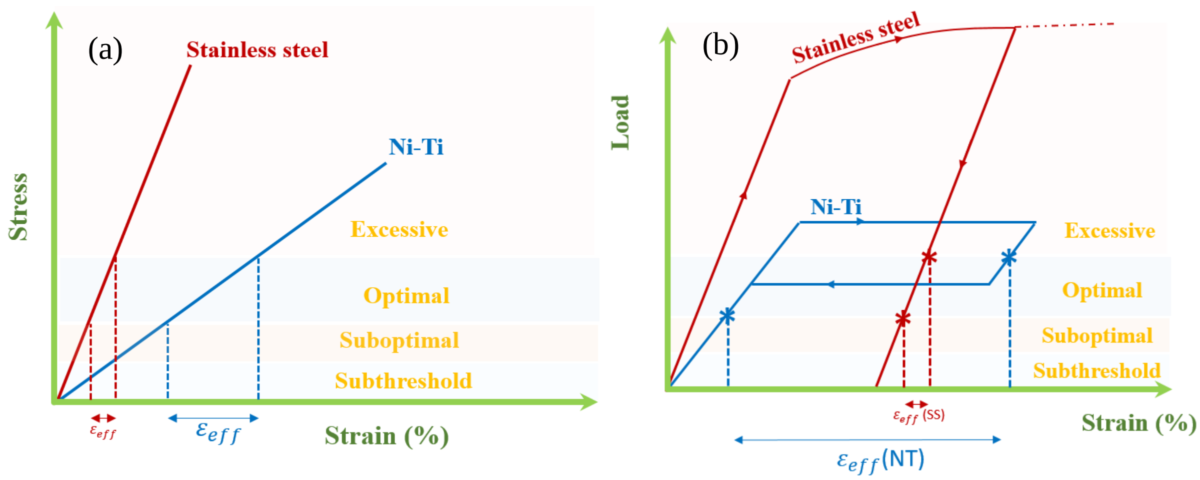


Figure 21. (a) Stress-strain comparison between effective strains when only elasticity is taken into account. (b) When elasticity of Ni-Ti is considered, the effective strain quantitatively become bigger with respect to stainless steel [175].

4.9.2. Plates for fractured bones

From ancient time people used to fix the fractured bones externally with some material e.g. wood. However, today by using operation, surgeon try to put all fractured parts in their right place and by some conformable plates, which are made of SMAs, can bond them together (see Figure 22). These kind of alloys can store potential energy when they are deformed, so they can be used for giving a comparable force to fractured bones and help to weld them in a short period of time [176].

Figure 22. (a) To heal a fractured bone, (b) a SMA-based plate by some related screws are planted [176].

4.9.3. Spinal vertebral spacer

Spinal consists of 33 vertebrate bones that are connected to each other. Since, they can reorient for different forms of body, then they have to be protected from their rub with a washer-like SMA, which is called vertebral spacer disk. The most popular problem is due to bad attitudes, which damage these disks. They can withstand the big deformations without limiting body's motion. Likewise, the superelasticity of SMA–based disk is utilized to save energy of deformation in term of elasticity and martensite transformation, and thus, by releasing this energy can force on body to come back to its original form.

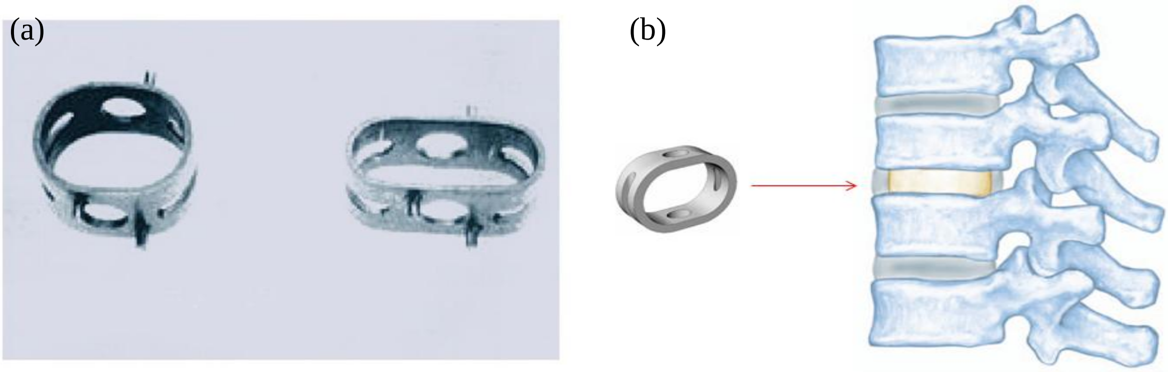


Figure 23. (a) Spinal vertebral spacer in both austenite (left) and detwinned martensite (right). (b) Planted the artificial SMA–based disk instead of damaged disk [177].

4.9.4. Biomedical application

Physicians need to diagnose some organs in the human body, to see the real location of the disease. Nowadays, it is possible to use inchworm robot to colonoscopy, which is based on SMA actuators. Reynaerts et al. in 1999 proposed a prototype based on SMA-actuators that has three possessive degree of freedom [178]. Figure 24 shows a schematic diagram of an inchworm-like robot that has only 95mm length and 15 mm diameter. It can be easily monitored when it goes through colon. The robot elongated by expanding SMA-actuators. Also, some of these actuators are used to stick the robot to the wall. The robot can creep one step to forward or backward.

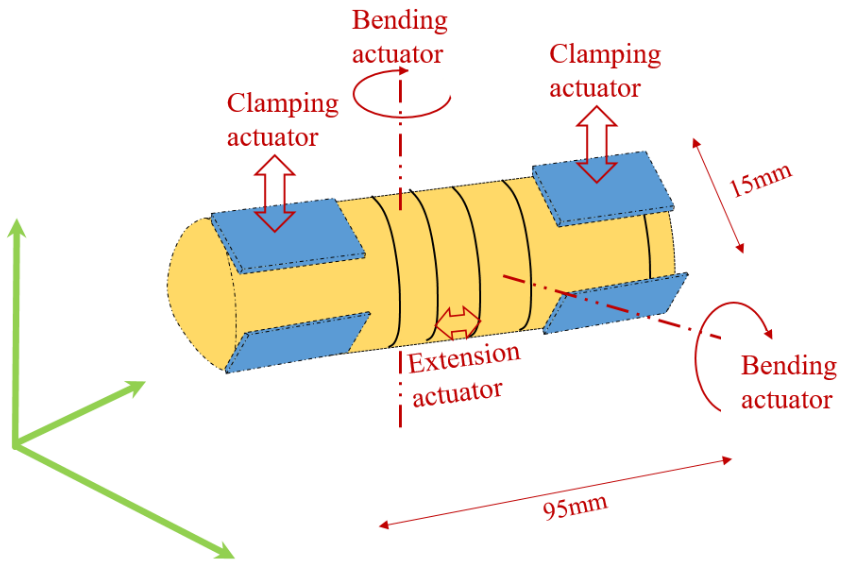


Figure 24. Schematic diagram of inchworm robot with three degree of freedom to move [178].

Then Menciassi et al. [179], got more success to propose earthworm robot with different actuators modules and a silicon shell to make it more elastic and soft (Figure 25).

Figure 25. The proposed earthworm-robot prototype by Menciassi et al. [179].

4.9.5. Bioengineered robotic hand

Recreating lost human bodies that could perform their tasks smoothly and accurately, can be practicable with smart materials. Bioengineered robotic hand [180, 181], is an example which has been manufactured by using SMAs (Figure 26). It is a compact, lightweight, and powerful technology, which can be utilized as an artificial muscle. Its fingers are made of aluminum and SMAs.

4.10. Reducing Waste

There are lots of artificial contaminations such as nuclear waste, and toxic materials that become a big problem for health and even they have changed some vital environmental conditions. Thus, to eliminate or reducing these hazardous wastes, some smart materials are good candidates and a dramatic influence for this purpose. Smart catalysts eliminate wastes in a programmable manner and they can be recovered without generate an additional contaminants [182, 183]. In addition, graphene-based nanoparticles could be used for water treatment [184-186]. Likewise, carbon nanotube (CNT), can absorb each heavy metals, metalloids, polycyclic aromatic hydrocarbons, endocrine-disrupting compounds, and pharmaceuticals in waste water [187-192].

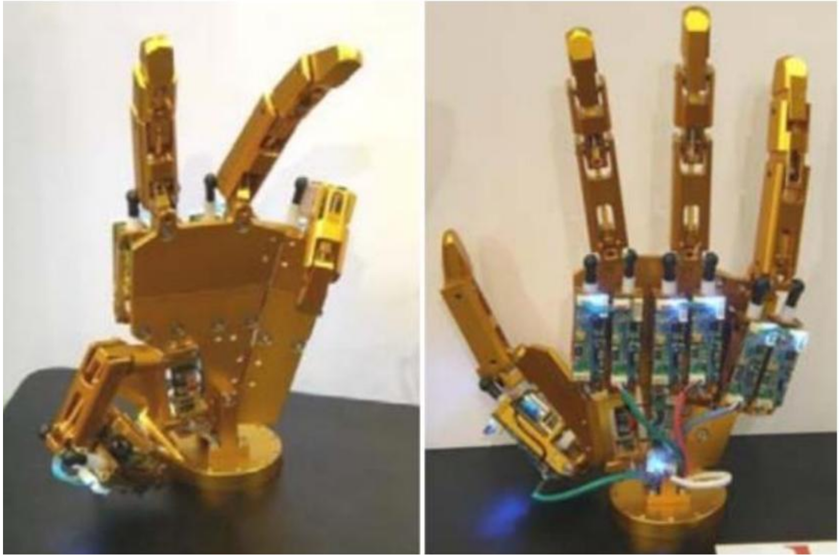


Figure 26. Robotic hand prototype based SMA [181].

4.11. Electrochromic Mirrors and Smart Windows

The reflected light of back coming cars, from mirrors, is one of driving problem in night. To tackle this problem, smart mirrors were designed that can reduce the reflected light relatively [193]. These mirrors normally fabricated in seven sputtered thin layers (see
Figure **27**), which are including a transparent glass, two transparent electrodes (anode and cathode), an ionic storage layer, an electrolyte, an electrochromic layer (e.g. WO_3), and a usual mirror. In a normal condition, the electric circuit is opened and approximately all incident light can reflected from the mirror (
Figure **27**a). However, an electric field produced between electrodes when the circuit is closed, and thus, electrons from ion storage layer start to follow through electrolyte layer and reach the electrochromic layer. Consequently, the mirrored is turned to dark and accordingly the reflected light decreased with increasing electric potential difference (
Figure **27**b).

Likewise, for create a smart window, the only thing that has to be done is replacing the backward mirror with another transparent glass. So the transparent irradiated light can be controlled [194]. Smart windows have many advantages to utilize them in the intelligent houses, such as minimizing consuming energy and giving more privacy.

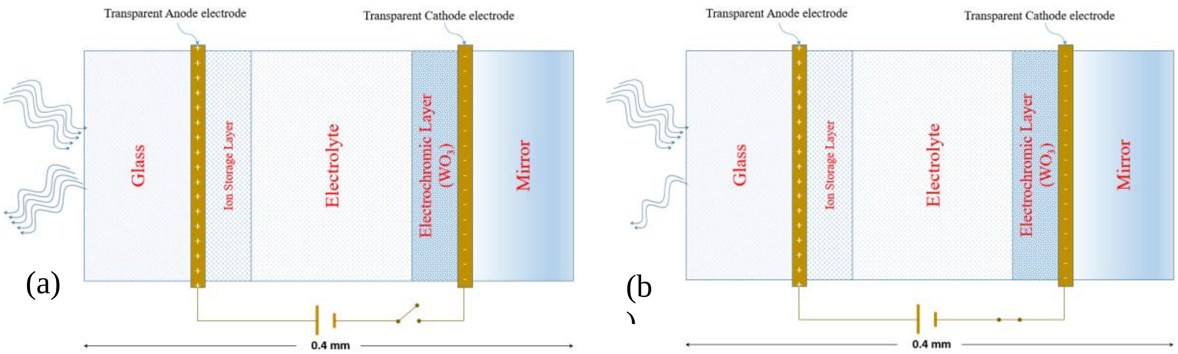


Figure 27. Schematic diagram of electrochromic mirror for (a) open circuit, which approximately all incident light is reflected by mirror, and (b) when the potential difference is applied to electrodes, some incident light will be absorbed and thus it causes to decrease reflected light.

4.12.Magnetorheological Shock Absorber

Magnetorheological Shock Absorbers are damper systems which include a spring and a shock absorber [35, 195, 196]. They are the significant part in almost all vehicles to diminish the incoming shocks. Also, they can protect all parts of car and give a comfortable sense to the driver and passengers. The shock absorbers normally are made of an oily fluid in a closed cylinder and a movable piston (see Figure 28a). The fluid inside the cylinder is divided to up and down chambers by a piston. So, the viscosity of the fluid can help to diminish the velocity of piston during up and down.

Figure 28b presents a shock absorber with MRF instead of a conventional fluid, also a coil is embedded that can be controlled with electrical current. When the MRF flow through the channels is affected by magnetic flux and can diminish the impact of the shock.

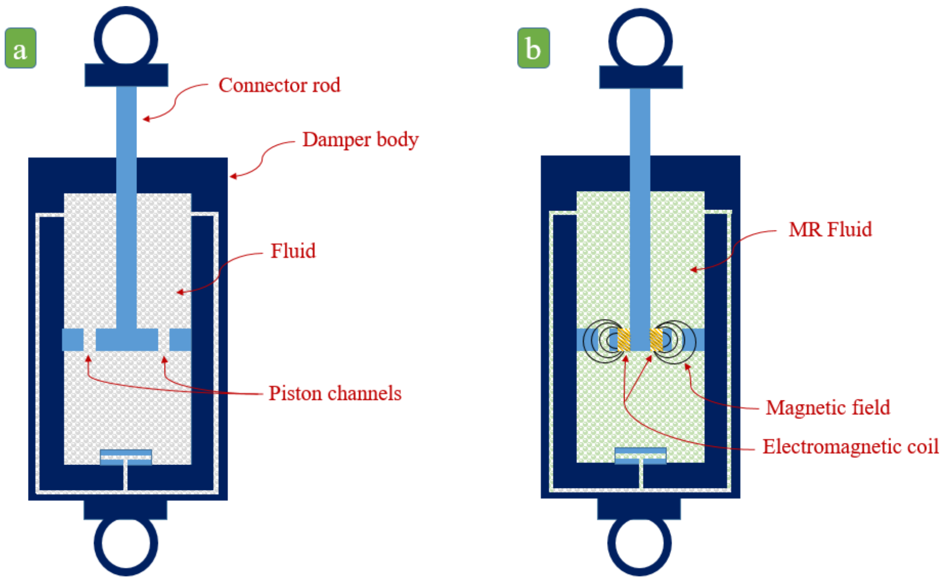


Figure 28. Schematic diagram of shock absorber (a) with a conventional fluid, and (b) with MRF that is restricted inside piston channels when magnetic field is applied [197].

5. Conclusions

All of the smart materials are important, however, some of them are getting more attention among researchers due to their applications in the sensitive sectors. The importance areas that smart materials have a crucial role are medical, automotive engines, robots and incredibly squeezed devices. Generally, piezoelectric and shape memory materials having comparably more application than the other types, especially for actuating purposes. While, their potentials are noticeable, but there are lots of restrictions and opportunities for researcher that are mentioned in the following.

Potentials and advantages

- They are self-accommodation with their environment
- High sensitivity to stimuli
- Fast response to different conditions
- They have smaller size comparable with other automotive systems.
- Less energy consumption.

Restrictions

- In some cases, the costs of preparations are comparably high.
- They cannot operate in all temperatures.
- They are strongly sensitive to compositional rate of constituents, then their preparation needs more attentions.
- Like other traditional materials, some smart materials are also suffering in fatigue, corrosion, and losing functionality.

Opportunity for researchers

- Since, for different conditions smart materials can be used, so materials can be improved to the convenient conditions.
- Smart materials can give different feature for any composition and adding new additives, thus, there are an extremely different ways for investigation in either experimental or theoretical approaches.

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