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Review Article

Critical Comparison of Smart Materials: Shape Memory Alloys vs Piezoelectric Materials: A Thorough Review

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Abstract

The recent increase in demand for sensors motivated development of new classes of multifunctional materials. Smart materials are recent class of multifunctional materials that undergo reversible extrinsic changes under application of external stimuli like pressure, temperature, electric/magnetic field, and stress. This ability for reversibility demonstrates the performance of these materials which in turn has led to the development of lighter, more energy-efficient innovative solutions for multipurpose applications. These multifunctional materials find application as sensors/actuators. The use of these materials and their structural characteristics up to this point has been well peer reviewed, but the relationship between sustainability considerations and the deployment of various grades of smart materials has received lesser attention. this paper attempts to draw a more significant relationship between smart materials and its notable applications through a detailed review of previous experimental, numerical, and conceptual studies, followed by an overview of their behavior and properties. Finally, some notable recent applications and influence of deployment areas of smart materials is discussed. This work lays a critical comparison between Shape Memory Alloy (SMA) and Piezoelectric (PZT) material behavior and properties.

Keywords: PZT, SMAs, SHM, Monitoring, sensors, actuators

Introduction

Smart Materials are recent class of materials that undergoes a shape transformation under application of external stimuli like stress, electric field, magnetic field and light [1-8]. The change in shape on application of external stimuli and its complete reversibility on removal of external field is a significant response of these smart materials. This reversibility is an important property to demonstrate performance matrix of these smart materials. Hence, these materials have found significant demand as actuators, sensors for aerospace, military, defense, medical and other applications. Shape Memory Alloys undergoes a solid state thermoelastic phase transformation under application of stress and temperatures. The crystallographic phase transformation takes place between a martensite (B19') phase to austenite phase (B2) and the transformation is accommodated by twin boundaries which makes it reversible. The Thermal Induced Martensite Transformation (TIMT) is an important indication of thermoelastic reversibility of SMAs. The SMAs undergo mechanical deformation in martensite phase and its reversibility on heating designated as Shape Memory Effect (SME) or its deformation and reversibility in austenite phase designated as Superelastic Behavior (SE). This behavior is depicted in a schematic format in Figure 1(a). During TIMT, the performance matrix is designated by critical transformation temperatures associated with the phase transformation designated as Ms, Mf, As, Af and the associated enthalpy values for the transformation. Differential Scanning Calorimetry (DSC) calculates these critical temperatures and enthalpy associated with the transformation pathway. For deformation in martensite phase, the critical factors are the critical deformation stresses, actuation strain, and remanent strain. For deformation in austenite phase, the critical factors are the critical deformation stresses, pseudoelastic strain, and remanent plastic strain. The stress-strain relationships have been modelled by constitutive equations. A schematic of stress-strain response of an SMA is shown in Figure 2.

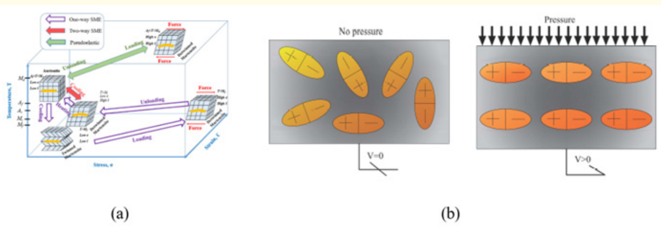

Figure 1: Behavior of (a) SMAs under application of stress and temperature[9] (b) Piezoelectric material behavior under application of stress and electric field[10].

Property	Unit	NiTi	CuZnAl	CuAlNi	Fe-SMAs
Specific heat capacity	J/kg C	450-620	390-400	373-574	540
Thermal conductivity	W/m K	8.6-18	54-120	70-75	8.4
Density	kg/m^3	6450-6500	7450-8000	7100-7200	7200-7500
Max Recoverable stress	MPa	500-900	400-700	300-600	-
Number of thermal cycles	-	10^3	10^4	$5x10^3$	-
Operation temperature range	C	-200-200	-200-150	-200-200	-
Hysteresis	C	2-50	5-20	20-40	-
Damping capacity	SDC%	15-20	30-85	10-20	-
Recoverable strain	%	5-10	-	-	2.5-13

Table 1: Critical Comparison of mechanical properties of different classes of SMAs[10

The thermomechanical constitutive relationship of Brinson for SMA wires under uniaxial loading can be simplified for isothermal conditions as [2]:

$$\epsilon_M = 0.5(1+\cos\pi(\frac{T-M_f-\sigma/C_M}{M_s-M_f}) \text{ for } A \rightarrow M \text{ transformation,for } C_M(T-M_s) < \sigma < C_M(T-M_f)$$

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Where σ is the applied stress, is the volume fraction of martensite evolved during thermal and stress cycling.

$$d\sigma = Dd\varepsilon + \Omega\epsilon_s + \Theta(T - T_{ref})$$

ε = strain, Ω=transformation vector, Θ =coefficient of thermal expansion. D= Elastic modulus of the material which is, in turn, a function of volume fraction of stress-induced martensite and austenite.

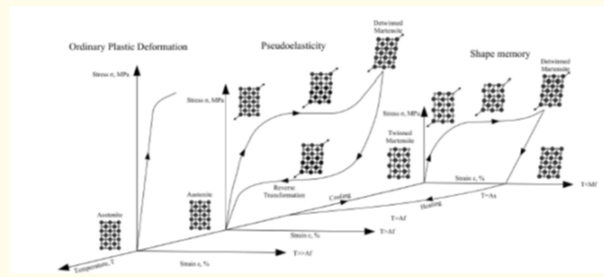

Figure 2: Mechanical response of SMA at different temperatures showing SME, SE and plastic deformation along with critical values that are estimated from stress-strain response curve [10].

The characteristic metric for the SMAs vary with composition, microstructure and underlying phases which in turn controls the thermoelastic reversibility. A critical comparison of the metric for different classes of SMAs is shown in Table 1. High stiffness, strength, and low production cost of these SMA have a led to wide range of applications in civil engineering. Fe-based SMAs are of two classes: The first group includes Fe–Pt, Fe–Pd, and Fe–Ni–Co alloys having temperature induced phase transition behavior similar to Ni-Ti along with low thermal hysteresis, but no pseudoelasticity is observed. The second class are Fe– Ni–C and Fe–Mn–Si which display higher thermal hysteresis in phase transition along with exhibition of Shape Memory Effect (SME). Low cost, excellent workability, good weldability makes Fe–Mn–Si SMAs the most demanding iron-based SMAs. Good shape recovery, feasibility of production, and excellent thermal and electricity conductivity of Cu-based SMAs with or without ternary additional components like Zn, Al, and Sn excellent candidate for applications. Further Cu-based SMAs show significant TIMT, along with an incomplete reverse martensitic transition. However low thermal stability, high brittleness, of Cu-based SMAs, have restricted their applications in certain fields and areas. The class of Piezoelectric material (PZT) refers to a class of material that shows significant electric polarization under application of stress and vice-versa. The reversible conversion of mechanical field to electric field is an important property of piezoelectric material. Primary cell misalignment due to a link between mechanical deformation and electron energy divergence results in this behavior. The behavior of Piezoelectric material is shown in Figure 1(b). For Piezoelectric materials 1D constitutive equations have been used to model the behavior of a PZT and derive material properties and parameters[2,7,11].

$\epsilon = S^{\psi \mathrm{E}}\sigma + \rho\psi\mathrm{E}$ … … (inverse effect),

$D = \rho\sigma + K^{\sigma}\psi\mathrm{E}$ … . . (direct effect)

Where ε is the strain, σ is the stress, D is the electric displacement, and ψE is the electric field. The elastic compliance, piezoelectric coupling and permittivity are denoted respectively by s, ϱ and κ. The behavior under application of stress and electric field is shown in Figure 3. The capacitance can then be calculated by the following equation that relates the dimensions and permittivity of the material. The capacitance of a PZT system is dependent on the size of the actuator. The simplified form can be expressed, when canceling the free space permittivity [1].

$C = K\epsilon 0A/t,$

Where K = relative permittivity, A is actuator area, and t is the thickness.

PZT has the capability to store electric energy; hence it can act as a capacitor. The capacitance of the system plays a role in the functionality of the piezoelectric actuator. The capacitance can be

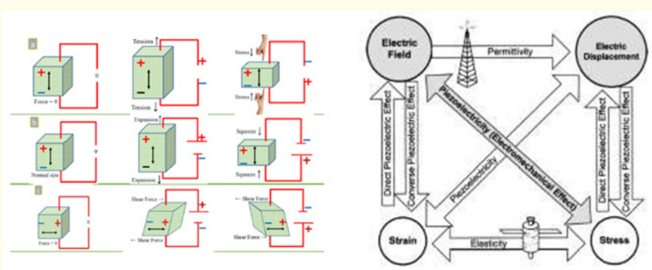

Figure 3: Schematic showing the behavior of a PZT under application of stress and voltage [3,9,11].

$$e = cd^T = \begin{bmatrix} 0 & 0 & e_{13} \\ 0 & 0 & e_{13} \\ 0 & 0 & e_{33} \\ 0 & e_{42} & 0 \\ e_{42} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} C/m^2 \quad ec^{-1} = \begin{bmatrix} 0 & 0 & d_{13} \\ 0 & 0 & d_{13} \\ 0 & 0 & d_{33} \\ 0 & d_{42} & 0 \\ d_{42} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \mathrm{C/N}$$

(a)

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{12} & S_{22} & S_{13} & 0 & 0 & 0 \\ S_{13} & S_{23} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix}$$

(b)

Figure 4: Metrices that denotes the anisotropy properties of the piezoelectric materials[1,7]

used to relate between the strain coefficient (d) and what is call the voltage coefficient (g). The voltage coefficient is another property that is given as basic PZT material properties and has units of volt meters/Newton (Vm/N).

Application of 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. In contrast, when ΔV is applied to these types of smart materials, they can change their size, thus the energy can be release as a mechanical form (Figure 3). 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. 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. Based on the geometrical shape, piezoelectric actuators are specified in some categories with one dimension of freedom, 1-Degree of Freedom (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. 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. The ability of these smart materials to control shapes with external stimuli and consequent reversibility find its application in multiple areas. Table 2 shows the various areas of application of SMAs and piezoelectric materials. One of the cutting-edge applications is sensors.

Areas of applications	
Sensors	Accelerometer, Pressure transducer, force transducer, acoustic transducers, microphone, impact transducer, health monitoring, modal sensors
Actuators	Precision manipulator, pressure generator, displacement actuator, vibration isolation, ultrasonic motors, passive shunt damping, self-sensing actuators
Structures	Vibration, noise, stress, strain, health monitoring
Machines/ mechanical systems	Vibration and noise monitoring, strength, optical systems, force-acceleration-pressure measurements, rotor control
Medical and Biomedical	Disposable sensors, ultrasonic devices, precision devices like STM
Robotics/ Mechatronics	Precision/micro robots, robot grippers, flexible robot control, MEMS
Smart Structures	Adaptive structures/composites, structural control, adaptive aircraft wings, helicopter blades, self-sensing and self-healing actuators, satellites

Table 2: Application of Smart materials (PZT and SMAs)[4]

(a)

(b)

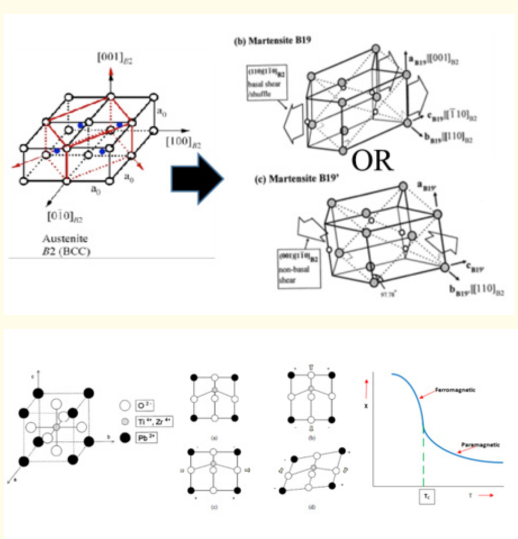

Figure 5: Example of crystallographic transformation(a) Nitinol (SMA) which undergoes transformation from B2 to B19/B19' [12], (b) Lead -Titanate/Zirconate that undergoes deformation under application of potential [13].

Case evaluation: Nitinol SMA vs lead-titanate/zirconate piezoelectric

For case evaluation two common example of smart material has been presented, Nitinol as SMAs and Lead-Titanate/Zirconate as PZTs as shown in Figure 5. Table 6 shows the comparison between the sensor properties and performance matrix between NiTi microactuator [3,5,7,9,13] and PZT based material. As compared to other SMAs, Nitinols have higher strength to weight ratio, high oxidation resistance, higher recovery stress, higher recoverable strain compared to other class of SMAs. Nitinol undergoes a thermoelastic crystallographic transformation from (B2) Austenite to (B19') monoclinic or (B19) orthorhombic crystal structure under application of stress/temperature and it reverses when the external stimuli is removed [10,14-19]. Lead Titanate/zirconate is a class of PZT that has a crystallographic symmetry about the center atom. The atoms in the crystal are in ionic form and under application of electric field a polarization takes place which in turn undergoes a mechanical deformation. The transformation takes place above a critical temperature called Curie Temperature (TC) [11,20-23]. It reverses to its original shape on removal of electric field. The degree of reversibility is a property of smart material. Direct and converse piezoelectric effect, which both are of constant macroscopic volume can be differentiated. The direct piezoelectric effect induces polarized electric field when a material is strained whereas the converse piezoelectric effect causes a material to induce local strain fields when polarized by an electric field. Piezoelectric ceramics can both be used as sensor and actuator although polycrystalline PZTs do not have piezoelectric characteristics in their original/as received state which in turn can be induced through poling beneath the Curie temperature at high dc electrical fields [15] leading to an alignment of the polar axis of unit cells parallel to the applied electric field leading to permanent mechanically deformation due to the reorientation of domains [15-17,21,23-27]. The induced strain can be differentiated into the longitudinal, transversal and shear effects, where the longitudinal effect is the strain parallel to the electric field and in the polarization direction, the transversal effect is the in-plane Poisson strain, and the shear strain is vertical to the electric field and parallel to the polarization direction [23-27].

Material	Young's modulus (GPa)	Max actuator strain (%)	Density (g/cc)	Operating frequency (Hz)	Blocking stress (MPa)	Vol work/ cycle (J/cc)	Gravimetric work/ cycle (J/kg)
PZT	50-70	0.12-0.18	7.6	10^5	72	0.0108	1.42
NiTi	70-110	2-8	6.45	1	425	1.59	247

Table 6: Comparison of property of NiTi vs PZT shown by red box [28].

Cutting edge application SMAs vs PZT

A notable application of SMA is as intelligent textile. In this application, Nitinol wire is oven along with textile material which in turn can induce additional functionalities in textiles in response to ambient agitations. Shape memory polymers (SMPs) are able to enhance the quality of these type of intelligent clothes. 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 be utilized to make some textile for ventilation and regulation of body's temperature. The molecular volume of polymer is extended above glass transition temperature (Tg), 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 (Tg), the molecules extended and thus making some small holes for ventilation. The water vapor permeability can be improved by incorporating multi walled carbon nanotube. 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. This is shown in figure 6.

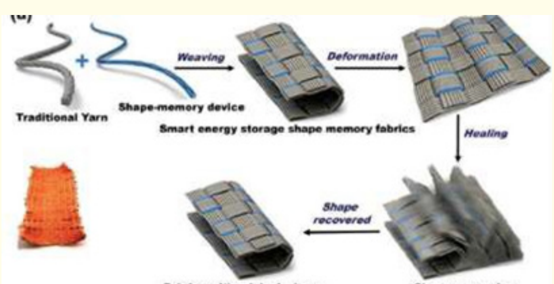

Figure 6: Schematic composition of both traditional and SMP in a smart textile, which exhibits SME [9].

A notable application of PZT material is use as transducer for Structural Health Monitoring (SHM). The SHM is a non-destructive testing (NDT), that blends high throughput sensors with algorithms for examining systemic health conditions [4,7,11,29]. Generally, SHM used in wide applications with its advanced technologies. An improvement of orthotropic and isotropic properties for piezoelectric transducers improves its properties significantly, like improvising the strength and toughness of structural material improves its performance. However, delamination in composite structures reduces rigidity and strength which in turn reduce device reliability which through incorporation of piezoelectric transducers can perform health monitoring using the SHM [9,27,30-34]. This detection can be understood by measuring transmitted wave intensity signals using PZT ceramics, where the embedded piezoelectric sensor signals are analyzed by both the global dynamic technique and the EMI technique. Incorporation of the digital image correlation (DIC) can analyze local defect/strain fields that were caused by EMI output and the DIC system in the specimens over the weakness test. Figure 7 depicts the ultimate process for SHM depending on impedance.

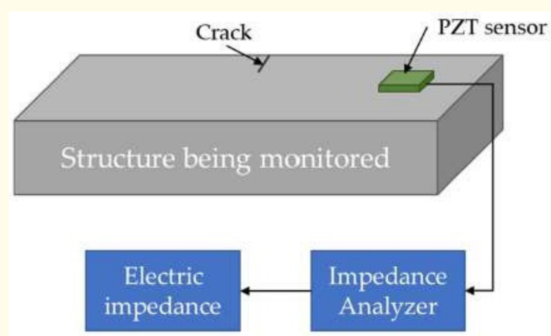

Figure 7: SHM of the cracked structure by impedance analyzer[11].

Conclusion

This work shows a detailed study to understand the working principal of two classes of multifunctional materials, SMA and PZT. These material systems have been used for sensor applications over the decade, but conjoint applications of these material systems are a prospective future in the coming decade. This paper widely covers the prospective and wide scale applications of these multifunctional materials and opens up a wider field where these materials can be used to a larger scale for sensing and actuation applications for defense, medical and structural health monitoring units through advancement in their developments and processing.

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