MACROJOURNALS

The Journal of **Macro**Trends in Applied Science

Smart Materials: Applications and Research Trends

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Abstract

The development and use of smart materials is revolotionizing the way we design and make products.This paper reports on the applications,research trends in these important materials,and some of the challenges facing both developpers and users.

Keywords: *Smart Materials*

I. Introduction to Smart Materials, Classification of Smart Materials and Technological Trend

There has been a distinct evolution in the history of the science of materials from its conception in Paleolithic times through the Stone Age, the Bronze Age, the Iron Age, the Synthetic Material Age and to the Smart Materials Age, and the progress made during the last century has been revolutionary due to factors such tremendous technological advancements and global competition. Smart materials [1] [2], sometimes also called “intelligent” materials [3], are designed materials with unique properties that can be changed in the presence of an external stimuli to adopt optimally to their surroundings. Therefore, understanding and controlling the composition of microstructure is crucial in designing and producing high quality smart materials. External conditions that cause smart materials to react and adapt covers all domains including mechanical, electrical, magnetic, chemical, nuclear, optical, and thermal. Materials and alloys that are classified as smart materials have to satisfy a number of fundamental specifications [4] related to technical properties, technological properties, economic criteria, environmental characteristics, sustainable development criteria, sensing and actuation.

Based on the capability to transduce energy smart materials can be classified as [5] passive (e.g. fiber optics) or active. The global smart material market [6] is segmented by products and application. By application it is segmented into: sensors; transducers; actuators & motors; structural materials; energy harvesting [7] and mechanical structures. Based on the end users the smart materials are categorized as transportation, healthcare, food, leisure and sports, construction and infrastructure. Examples of most well-known smart materials are shown in Fig. 1, along with their associated stimulus-response behavior.

Stimuli	Smart material	Response
(1) Temperature, (2) Stress →	Shape memory alloy and polymers	→ Deformation
(1) Electric field , (2) Stress→	Piezoelectric material	→Electric change; mechanical strain
Magnetic field→	Magneto-strictive material	→ Mechanical strain
Change in pH→	pH sensitive polymers	→ Change in Volume
(1) Temp, (2) Pressure, (3) Mechanical Strain →	Optical fibre	→ Change in opto-electronic signals
Change in acidity →	Halochromic	→ Change in color
(1) Electrical, (2) Optical, (3) Thermal changes→	Chromogenic	→ Change in color
Light →	Photomechanical materials	→ Change shape
Light →	Photovoltaic materials	→ Electrical current
Normal usage →	Self healing materials	→ Repair damage
Chemical or biological compound→	Chemoresponsive materials	→ Change size or volume
(1) Temperature differences, (2) Electricity →	Thermoelectric materials	→ (1) Electricity, (2) Temperature differences

Figure 1 Examples of Smart Materials and their behavior associated to stimulus-response.

Piezoelectric materials [1], [8] exhibit an electromechanical coupling that produce an electrical current when a pressure or stress is applied to the material. This effect also applies in the reverse manner. Piezoelectricity was discovered on Rochelle salt in 1880 by Jaques and Pierre Curie [1]. and since then it has been increasingly used, and has become a mature technology with excellent inherent reliability [9]. Examples of piezoelectric materials [3] are : PbZr1-xTixO3, BaTiO3, PbTiO3, PbNb2O6, etc...

Shape memory materials [10] are materials that have the ability to recover their original shape from a significant plastic deformation under application of particular external conditions. There are three main groups of shape memory materials: (1) shape memory alloys; (2) shape memory polymers and (3) shape memory hybrid, and a comparison between them is made by Huang et al. [11]. Shape memory alloys [1] undergo a phase transformation under a change in temperature leading to a change in volume and shape of the sample. Titanium - Nickel alloys are the most commercially used along with other alloys [3]. Shape memory polymers [12] besides their dual-shape capability are bio functional and biodegradable. They offer advantages compared to shape memory alloys such as [10]: tailoring of material properties is easier; lower cost; lighter; higher recoverable strain; additional stimuli (light and chemical) except heat; more degrees of freedom in manipulating process to meet particular needs.

Chromogenic systems [13] , [5] change color in response to electrical, thermal, optical changes. Examples of electrically powered technologies [13] are electrochromic, electrophoretic media, phase dispersed liquid crystals and cholesteric liquid crystals. Photochromic materials are a category that change color upon exposure to ultraviolet illumination. Thermochromics materials change color with a change in temperatures, and they are based on transition metal oxides like VO_2. Thermochromics is another class of chromogenic systems, which switch optically with temperature.

Self-healing materials [14], which are a relatively new class of smart materials, have the ability to automatically recover (fully or partially) a functionality without any external diagnosis of the problem, in response to an external stimulus such as light, temperature change, etc. Types of self-healing materials are: intrinsic self-healing materials; capsule-based self-healing materials; vascular self-healing materials.

Polycaprolactone [15] belongs to a group of aliphatic polyester polymers and is synthesized in a ring opening polymerization from ε-caprolactone. Due to its advantages, polycaprolactone [16] has been used especially on medical devices, drug delivery and tissue engineering over the last two decades.

Smart Materials Market Trends: The segment that dominated the market with around 44% share in 2015 was the actuator and motor segment [19] owning to innovation and continuous improvements in variety of industrial applications. Therefore among key users, the industrial segment led the market followed by defense and aerospace, which both collectively accounted for around 62% of the market revenue in 2015 [18]. In 2016, [17] North America was the leading region in the global market followed by Europe and Asia Pacific. According to a market research report published by Grand View Research, Inc. [17], the global smart materials market size in 2016 was valued at $32.77 billion, and it is expected a robust growth at a compound annual growth rate (CAGR) of 13.5% from 2017 to 2025. Piezoelectric materials have the highest percentage in smart materials (Figure 2). The sensor segment is projected to expand at the highest CAGR of around 18% during the forecast period by 2022 [18].

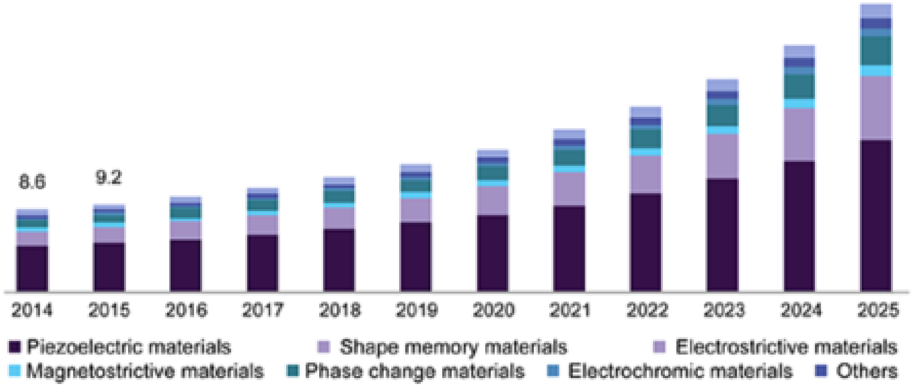
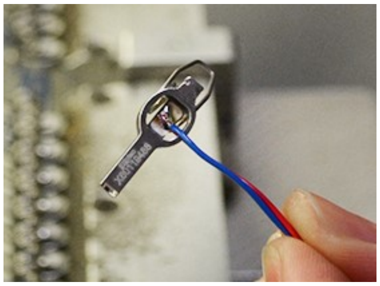


Figure 2 U.S. smart materials market revenue, by application, 2014-2025 ($ Billion) [17].

The market of smart materials is driven by [19] major driving forces related continuous technological advancements; rise in smart materials adapting products among various end-user industries such as automotive, aerospace and defense, consumer electronics; increase in research and development; evolution in Internet of Things (IoTs), and potential growth in emerging economies.

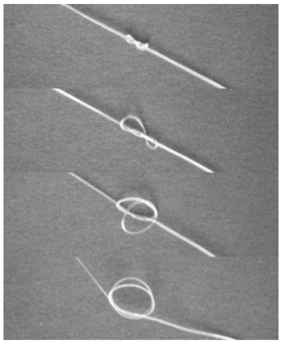
II. Applications of Smart Materials, Management Issues for both Developers and Users

Piezoelectric materials have become the most attractive functional materials as they can directly convert mechanical energy to electrical energy and vice versa. Piezoelectric materials can be both natural such as bones SiO2, sucrose, silk, DNA etc and synthetic such as ZnO, KnbO3 (potassium Niobate), LiNbO3 (Lithium Niobate), Bismuth Ferrite etc. Due to its intrinsic characteristic, piezoelectric materials have wide application in sensors, actuators, crystal oscillators, piezo motors and sonic-ultrasonic applications etc. Talking about sensors and actuators, this smart material is used in (a) Piezoelectric microphones (b) Electronic Drum Pad (c) Pressure sensors (d)Accelerometer etc. If we think about piezoelectric motors, then it is used in precision rotation and linear movement as well. Some other applications are as follows: (a) Movement of camera lenses (b) Rotation of Radar (c) Very small scale valve control (d) Laser movement and so on.



The electric boundary condition along crack faces remains a debating issue when studying crack problems in piezoelectric materials. This drew attention for research and scientists have been quite successful.

Shape Memory Polymers possess the ability to memorize a permanent shape that can substantially differ from their initial temporary shape. Large bulky devices could thus potentially be introduced into the body in a compressed temporary shape. The most popular application of SMPs is used as biodegradable implant materials as well as minimally invasive surgical procedures in medicine which has substantially improved health care within past few decades. Some other applications intend to:



a) Smart Fabrics
b) Heat-shrinkable tubes for electronics or films for packaging
c) Self-deployable sun sails in spacecraft
d) Self-disassembling mobile phones
e) Intelligent medical devices

While welding polymeric materials there are concerns that these welding gases might cause diseases, such as metal fume fever, to long-term lung damage and neurological disorders, (i.e., lung cancer and Parkinson’s disease).

In Chromogenic Smart Materials "Chromo-" originates from the Greek language and means that something is colored. There are three categories of applications such as, - photochromic, thermochromics and electrochromic. Photochromic applications include use in glasses as they can be dark under light and light in darkness. Thermochromics materials are often used for testing. Their color changing properties can warn when something is too hot or too cold. Spoons, rubber ducks for infants are often made from thermochromic materials. Electrochromic materials are also used in smart windows. The less voltage that is applied across the window, the more transparent it is. An example of these electrochromic smart windows in application is in the 2004 Chrysler Pacifica, the driver is able to dim the rear view mirror according to his need and preference. The extremely small size scale poses serious problems in viewing and handling such materials during production and there are some potential health risks that are still under investigation.

Self-healing materials in today’s date include self-healing dyes, self-healing fiber-reinforced polymer composites, self-healing coatings, self-healing cementations materials, self-healing ceramics etc. Self-healing coatings allow the retention and improvement of bulk properties of a material. They can provide protection for a substrate from environmental exposure. Thus, when damage occurs (often in the form of micro cracks), environmental elements like water and oxygen can diffuse through the coating and may cause material damage or failure. The concept of self-healing ceramics has been proven using SiC to heal cracks in an Alumina matrix. Self-healing epoxies or dyes can be incorporated on to metals in order to prevent corrosion. For the development of one-part self-healing anticorrosive coatings, selection of the healing agent is a crucial issue.

Polycaprolactone (PCL) has been widely used in long-term implants and controlled drug release applications. PCL is highly hydrophobic and thus has longer degradation times than PLA (2–5 years), which makes it suitable for applications where long degradation times are required.ˏ Another type of reactive blending was reported by Semba et al. (2006) for PLA/PCL blends through the application of dicumyl peroxide (DCP) as a cross linker. Rapid degradation of PCL leads to loss of mechanical strength and significant local production of glycolic acid. It changes the research approach of the scientists.

III. Future Thinking

Technology advancements occur at an exponential rate, and while there is much known about various types of smart materials, society is far from understanding everything about them. The stimuli for each type of material must be monitored closely to receive the optimum output. The science of developing and operating each type of smart material can be compared to chemical reactions at an atomic level. Something to consider in the future is how to maintain stability in varying conditions.

Piezoelectric materials, for example, will produce varying amounts of electricity based on the temperature [20] of the raw material used, since materials under compression get hotter, the heat which is a by product of the compression is also a variable in the final output. Since materials have different chemical compositions, there might be certain piezoelectric materials which are more stable in the colder parts of the world or which function better when kept in climate-controlled rooms.

Something to consider about Shape Memory Polymers is the how long an object remains in the temporary state. These materials use a combination of heat and stress which can both vary with time [12]. In the future, it would be worthwhile to discover a way to make identifiable life cycles for the material which are time dependent. This might also improve material stability and might even be used to manufacture different types of parts.

The future of Chromogenic Smart Materials, which change color depending on various circumstances, could be one in which a fabric polymer could change color to match the environment. This type of clothing would have the potential to be extremely helpful in the military or hunting where camouflage is important. This might involve some type of embedded crystal/glass fragments in the clothing. Another potential option would be shields that act as camouflage. Both of these concepts would require the material to change into a specific pattern of multiple colors, which is not how this concept is used today.

Self-healing materials right now are limited to specific types of polymers under certain conditions [14]. With time, this technology could advance in such a way so that any material under any circumstance and self-heal in a continuous state. For example, tires which gradually lose tread based on wear and road conditions would possibly never lose tread if they had the ability to self-heal while still under pressure. Another application would be the ability for automobiles to heal them-selves after an accident. This would require certain types of fiberglass, steel, and aluminum (at a minimum) to be able to self-heal, or a new material which is safe to use in the construction of a vehicle. This use could lower insurance rates and potentially run body repair shops out of business.

Polycaprolactone (PCL) has the potential to replace most plastics and reduce the rate of greenhouse gas emissions. Since it is FDA approved, it could replace styrofoam and plastic food supplies and storage containers. In the future, this smart material is capable of having a huge impact in plastic recycling. Something to consider would be a way to combine existing plastics with this polymer and develop a hybrid plastic which helps break down existing plastics.

In Summary, smart materials have potential to make a huge impact in our society with proper research and testing. While this paper only discussed five of the most common smart materials, smart materials in general can cover many areas. Finding methods to combine some of these materials could have an even greater impact, such as a self healing plastic that has color changing capabilities and the strength of existing steel used in military tanks.

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