Materials are Getting Smarter

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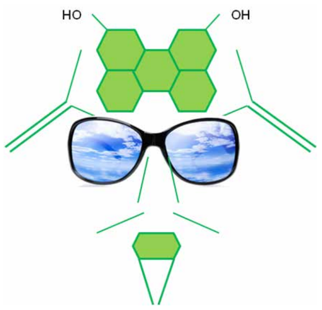
Abstract: It is not just humans evolved from 'stone age' to 'silicon age', but materials too seem to have followed humans in evolution. Now it can be categorically stated that the current advanced materials gave giant leap to humans in to next stage of civilization where we have materials which can react in response to an external stimuli. Scientific and technological exploitation of sensitivity of these materials to external stimuli such as, a pulse of light, changes in pH or temperature, reactive chemical species, has resulted in a new field of materials, which can be rightly named as 'Smart materials' or 'Intelligent materials'. Furthermore, understanding of quantum phenomena in nano sized quantum dots and other nano-structured materials has further widened the scope for the technological exploitation of materials to boost the quality of life for mankind. In this article, various smart materials are introduced with a special emphasis on application, along with a brief explanation of basic phenomena behind the material property



Materials are getting smarter

Introduction

Development and understanding of materials has been the driving force for the human civilization ever since the inquisitive ancient human started to look for better ways of living. Ancient human started with hunting and gathering and progressed to agriculture, tool making and finally to modern industrial and technical age where 'quality of life' and 'life expectation' has improved to present levels. Throughout this journey, material exploration and development has played vital role and thus civilizations were named after materials that were prominently used during that time viz., stone age, bronze age, iron age, silicon age, etc. Now we are in a transition phase to a new age which can be righty called as 'smart or intelligent materials age'. However, the term 'smart' or ' intelligent' with respect to materials doesn't refer to the logical capability that humans possesses, but these smart materials respond to a stimulus with an appropriate predictable action in contrast to a limited response displayed by conventional materials. By suitably manipulating these characteristic responses from smart materials to release a noticeable signal or to perform a predetermined action, new group of gadgets, sensors, actuators and processors are being developed by scientists and technologists. Systems that are biomimic in nature can be developed by exploiting the principles of nature that evolved through billions of years from these smart materials. Furthermore, such systems can effectively contribute to the improvement and repair of biological systems that are complex in nature. The main objective of this article to present a brief outline of working principle and proposed applications of various smart materials to encourage new researchers and technologists to innovate new devices that hold promise for many possible applications. These innovations could boost up the fields such as, but not limited to, medicine, energy, nanotechnology, green materials technology, biotechnology, food industries, process control, construction, military, information technology and communication industries. Few smart materials that have already come in to light in the recent past and potential smart applications are outlined in the following paragraphs.

Shape Memory Alloys and polymers

Shape memory materials posses ability to revert back to an original shape from deformed condition, when an external stimuli such as heat is applied. Few of the metallic alloys and polymeric compounds exhibit such memory effect. It is also reported that shape memory effect can also be triggered in shape memory polymers by applying electric and magnetic fields, light and solutions. There are two popular shape memory alloys viz., copper-Aluminum-Nickel (CuALNi), and Nickel-Titanium (NiTi), though shape memory alloys from other metallic elements are also being developed. The recoverable plastic strain in shape memory alloys is due to austenite-martensite transformation during heating and cooling of the alloy. At low temperatures the alloys is martensitic and as the material is heated to austenite transformation temperature, a pre-strained alloy remembers the original shape and recovers from the strain during the transformation to austenite. These shape memory alloys are being used in applications such as actuators, sensors, medical surgery, automobile and aerospace.

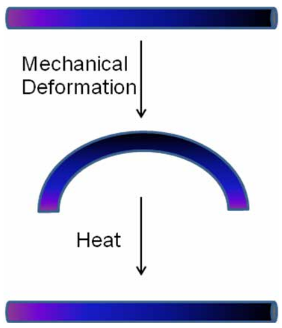


Figure 1 Shape Memory effect in materials

Shape memory polymers outrun the shape memory alloys in terms of recoverable strains reaching up to 800% in contrast to 8% for metallic alloys. These shape memory polymers consist of two phases, one with highest thermal transition, responsible for permanent shape and the other phase, termed as switching segment, which can easily softened and responsible for the temporary shape. When the pre-stressed shape memory polymer is heated above the transition temperature of the switching segment, it gets softened and allows the materials to assume original shape. Shape memory polymers are used in various applications such as, robotics, sportswear, building industry, and self repairing components. A schematic of shape memory effect is shown in figure 1.

Chromic materials

Chromic or chromogenic materials change colors with electrical, optical or thermal changes and are often reversible. This phenomenon is mainly attributed to changes in electron density of materials with the external stimuli. There are many natural compounds that exhibit this chromic behavior and many synthetic chromic materials being developed.

Thermochromism is the property of material that results in change in color with temperature. Temperature sensors, baby milk bottles and thermochromic dies are few of the potential applications for these materials. Photochromatic glasses are widely used as optical lenses and window screens to filter UV rays coming from the sun light. Photochromism can be defined as electromagnetic radiation assisted reversible transformation between two forms which absorb different absorption spectra. Pericyclic reactions, cis-trans isomerizations, intramolecular hydrogen transfer, intramolecular group transfers, dissociation processes and electron transfers are few of the suggested mechanisms behind the photo chromatic effect of the photochromic materials. Electrochromic materials change their color and texture with the application of charge or voltage. In electrochromic materials the color contrast can be closely controlled compared to other chromic materials and are widely used in automotive industry, building glasses as 'smart windows'. Depending on solvent polarity, solvatochromic materials change colors and find applications as environmental sensors and in molecular electronics for construction of molecular switches.

Piezoelectric Materials

Piezoelecric effect is defined as reversible conversion between strain and electrical charge by piezoelectric material. A piezoelectric material produces electric charge in response to applied stress and vice versa. There are many naturally available materials such as tendon, silk, wood, enamel, dentin and DNA in varying magnitudes of piezoelectric effect. Many synthetic piezoelectric ceramics are prepared among which most popular are Barium titanate ($BaTiO_3$), Lead titanate ($PbTiO_3$), Lead zirconate titanate ($Pb[Zr_xTi_{1-x}]O_3$, Potassium niobate ($KNbO_3$), Lithium niobate ($LiNbO_3$) and Lithium tantalate ($LiTaO_3$). Asymmetric charge distribution in the crystal lattice or molecular group charges is reported to be origin of piezoelectric effect. Off centered Ti^{4+} ion on the $BaTiO_3$ as shown in figure 2 results in electrical dipole which ultimately leads to the formation of randomly oriented electrical domain. Dipole alignment due to applied strain or applied electric field causes domain alignment and results in piezoelectric effect in the material. These piezoelectric materials are widely used as sensors, ultrasonic transducers, micro/nano manipulators, switches etc.

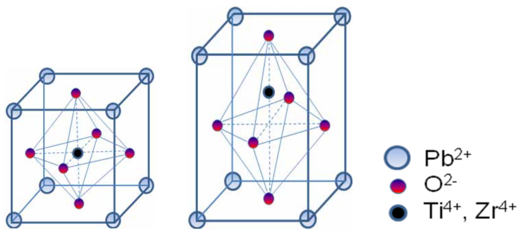


Figure 2. Mechanism behind piezoelectric response

Artificial muscles

Materials or assemblies that respond to external stimulus, such as voltage, temperature, pressure, chemical environment; with a reversible actuation viz., contraction, expansion and rotation, are called artificial muscles. Electroactive polymers (EAPs), conducting polymers, and ionic polymer metal composites (IPMC) respond to electric fields and currents. Polymeric materials that respond to applied pressure and temperature were also being researched. Shape memory alloys are also can be used as artificial muscles. These artificial muscles find wide applications in robotic arms, artificial arm replacements and bio medical devices.

Self healing and assembly

Machine components, mechanical and electrochemical systems often fail due to mechanical damage during service. Researchers and technologists took inspiration from biological systems and developed materials that can intrinsically heal the mechanical damages during service without needing to replace and extend the service life of the component. Molecular breakdown and bond cleavage due to service conditions is said to be the reason behind the mechanical failure of the polymeric materials. This kind of mechanical failure can be fatal and cause severe loss to property and human life. Many approaches were used to develop polymers that can heal the damage without any external action by humans. Sequence of actions can be divided in to three steps for self healing polymers similar to biological systems. Triggering or actuation is the first stage of healing process which happens after the damage of the polymer. Materials will be transported to the damaged area during the second stage of healing process. During the third stage a chemical reaction heals the damaged area restoring the original condition of the component before the damage. This third stage healing process display different chemical repair mechanisms in the damaged area depending on the curing agent used. In hallow tube and micro capsule healing, thermoset encapsulated monomers that are dispersed throughout the polymer matrix along with a polymerization catalyst. In the event of the mechanical damage by crack initiation and propagation, catalysts that are present in the matrix, polymerize the monomers released from the capsules in the cracked area and results in crack healing. Coating of self healing epoxies to prevent corrosion of metallic substrates are becoming popular as corrosion protection methods.

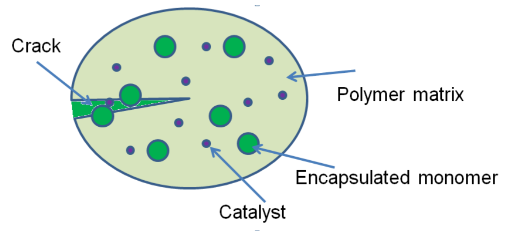


Figure 4. Self healing mechanism in a polymer

Summary

Multiferroic materials are defined as materials with more than one ferroic order in a single material which are ferromagnetic, ferroelectric and ferroelastic orders. In such material, one ferroic response can be triggered by applying the other ferroic stimuli. These materials promise high potential as sensors, transducers and dielectric materials. Molecular Machines are nanomachines that give quasi-mechanical movements in response to external stimuli. These complex nanomachines have various applications as molecular sensors, drug release agents, nano manipulators, molecular switches etc. Photomechanical materials that change shape with the application of electromagnetic energy, polymorphic materials that can be given any shape at ease are also being developed. With the development of new characterization tools and understanding the material behavior to external stimuli, new smart materials are being developed and used. There is a great potential for scientists and technologist to explore the vast field of materials and contribute to the better quality of life to the mankind.

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