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A Review on Smart Materials: Classifications, Applications

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Abstract : Smart materials are common name for a wide group of different materials. The general feature of all of them is the fact that one or more properties might be significantly altered under controlled condition. The present trend is considered to be the smart materials era. Earlier, smart material was defined as the material, which responds to its environments in a timely manner. Smart materials are multi-functional, transitional materials that can undergo changes in properties in response to an external stimulus. Another important criterion for a material to be considered smart is that the action of receiving and responding to stimuli to produce a useful effect must be reversible.This review focuses on the introduction of smart materials and their classifications and applications. Different applications of smart materials in various fields are also being discussed starting from engineering to the present environmentapplications.
Keywords : Smart materials, Piezoelectric Materials, Electrostrictive Materials, Magnetostrictive Materials

I. INTRODUCTION

The world has undergone two materials ages, the plastics age and the composite age, during the past centuries. In the midst of these two ages a new era has developed. This is the smart materials era. According to early definitions, smart materials are materials that respond to their environments in a timely manner. Technology is becoming increasingly prominent in present daily lives, in many ways alleviating and in other ways fueling the demands of modern living. The effect can be caused by absorption of a proton, a chemical reaction, integration of a series of events, translation or rotation of segments within the molecular structure, creation and motion of crystallographic defects or other localized conformations, alteration of localized stress and strain fields, and others. The effects produced can be a color change, a change in index of refraction, a change in the distribution of stresses and strains, or a volume change. Also, it should be pointed out that the word ‘‘intelligent’’ is used to describe smart materials. The notation ‘‘smart’’ has been overused as a means to market materials and products. From the purist point of view, materials are smart if at some point within their performance history their reaction to a stimulus is reversible. Materials that formally have the label of being smart include piezoelectric materials, electrostrictive materials, electrorheological materials, magnetorheological materials, thermoresponsive materials, pH-sensitive materials, UV-sensitive materials, smart polymers, smart gels (hydrogels), smart catalysts, and shape memory alloys. In this treatment of the subject we will be using some of these classifications; in some cases, however, the classification of a particular material may appear to be in error. This will be done to illustrate the rapid growth of the field of smart materials and the rediscovery of the smart behavior of materials known for centuries. As we continue to better understand smart materials, our definitions will change. In each material section there will be discussions pertaining to the material definition, types of materials that belong to that class, properties of the members, and applications of the materials. In some cases a more detailed discussion of application will be given to both illustrate the benefit of these materials and simulate the use of these materials in new applications. Smart materials are new generation materials surpassing the conventional structural and functional materials. These materials possess adaptive capabilities to external stimuli, such as loads or environment, with inherent intelligence. (Rogers, 1988; Rogers et al., 1988) defined smart materials as materials, which possess the ability to change their physical properties in a specific manner in response to specific stimulus input. The stimuli could be pressure, temperature, electric and magnetic fields, chemicals, hydrostatic pressure or nuclear radiation. The associated changeable physical properties could be shape, stiffness, viscosity or damping. Takagi (1990) explained it as intelligent materials that respond to environmental changes at the most optimum conditions and reveal their own functions according to the environment.

II. TYPES OF SMART MATERIALS

Thus this material has built-in or intrinsic sensor, actuator and control mechanism by which it is capable of sensing a stimulus, responding to it in a predetermined manner and extent, in a short or appropriate time and reverting to its original state as soon as the stimulus is removed. The following are the different types of smart materials.

- Piezoelectric Materials
- Electrostrictive Materials
- Magnetostrictive Materials
- Electrorheological Materials
- Magnetorheological Materials
- Thermoresponsive Materials
- Ph-Sensitive Materials
- Light-Sensitive Materials
- Smart Polymers
- Smart (Intelligent) Gels (Hydrogels)
- Smart Catalysts
- Shape Memory Alloys

Piezoelectric materials are very common example of such materials where they produce a voltage when stress is applied. Since this effect also applies in the reverse manner, a voltage across the sample will produce stress within the sample. Suitably designed structures made from these materials can therefore be made that bend, expand or contract when a voltage is applied. They can also be used in optical-tracking devices, magnetic heads, dot-matrix printers, computer keyboards, high-frequency stereo speakers, accelerometers, micro-phones, pressure sensors, transducers and igniters for gas grills.

Piezoelectric materials are materials that exhibit a linear relationship between electric and mechanical variables. Piezoelectricity is a third-rank tensor. Electrostrictive materials also show a relationship between these two variables. However, in this case, it is a quadratic relationship between mechanical stress and the square of electrical polarization. Electrostriction can occur in any material and is a small effect. One difference between piezoelectric and electrostrictive materials is the ability of the electrostrictive materials to show a larger effect in the vicinity of its Curie temperature. Elecrostriction is a fourth rank tensor property observed both in centric and acentric insulators. This is especially true for ferroelectric materials such as the members of the perovskite family. Ferroelectrics are ferroic solids whose domain walls have the capability of moving by external forces or fields. In addition to ferroelectrics, the other principal examples of ferroic solids are ferromagnetics and ferroelastics, both of which have potential as smart materials. Other examples of electrostrictive materials include lead manganese niobate–lead titanate (PMN–PT) and lead lanthaniumzirconatetitanate (PLZT).

Magnetorestrictive materials are materials that have the material response of mechanical deformation when stimulated by a magnetic field. Shape changes are the largest in ferromagnetic and ferromagnetic materials. The repositioning of domain walls that occurs when these solids are placed in a magnetic field leads to hysteresis between magnetization and an applied magnetic field. When a ferromagnetic material is heated above its Curie temperature, these effects disappear. The microscopic properties of a ferromagnetic solid are different than for a ferromagnetic solid. The magnetic dipoles of a ferromagnetic solid are aligned parallel. The alignment of dipoles in a ferromagnetic solid can be parallel or in other directions.

This class of smart materials is the mechanical equivalent to electrorestrictive and magnetorestrictive smart materials. These smart materials exhibit high hysteresis between stress and strain. The motion of ferroelastic domain walls causes the hysteresis. This motion of the ferroelastic domain walls is very complex near a martensitic-phase transformation. At this phase change, two types of crystal structural changes occur. One is induced by mechanical stress and the other by domain wall motion. Martensitic shape memory alloys have wide, diffuse phase changes and the ability to exist in both high- and low-temperature phases. The domain wall movements disappear with total change to the high-temperature phase.5,19,20 The elastorestrictive smart material family is in its infancy.

Rheological materials comprise an exciting group of smart materials. Electrorheological and magnetorheological materials can change their rheological properties instantly through the application of an electric or a magnetic field. Electrorheological materials (fluids) have been known for several centuries. The rheological or viscous properties of these fluids, which are usually uniform dispersions or suspensions of particles within a fluid, are changed with the application of an electric field. The mechanism of how these electrorheological fluids work is simple. In an applied electric field the particles orient themselves in fiberlike structures (fibrils). When the electric field is off, the fibrils disorient themselves. Another way to imagine this behavior is to consider logs in a river. If the logs are aligned, they flow down the river. If they are disordered, they will cause a log jam, clogging up the river. A typical example of an electrorheological fluid is a mixture of corn starch in silicone oil. Another fluid that has been experimented with as a replacement for silicone oil is chocolate syrup. Another feature of electrorheological systems is that their damping characteristics can be changed from flexible to rigid and vice versa. Electrorheological fluids were evaluated using a single-link flexible-beam test bed. The beam was a sandwich configuration with electrorheological fluids distributed along its length. When the beam was rapidly moved back and forth, the electrorheological fluid was used to provide flexibility during the transient response period of the maneuver for speed and made rigid at the end point of the maneuver for stability.

Magnetorheological materials (fluids) are the magnetic equivalent of electrorheologicalfluids. These fluids consist of ferromagnetic or ferromagnetic particles that are either dispersed or suspended and the applied stimulus is a magnetic field. A simple magnetorheological fluid consists of iron powder in motor oil. The Lord Corporation provided a clever demonstration of magnetorheological fluids. It supplied an interlocking two-plastic-syringe system filled with a magnetorheological fluid and two small magnets. The fluid flows freely, without the magnets placed in the middle of the two syringes. With the two magnets in place, the fluid flows completely.

Amorphous and semicrystalline thermoplastic polymeric materials are unique due to the presence of a glass transition temperature. Changes in the specific volume of polymers and their rate of change occur at their glass transition temperatures. This transition affects a multitude of physical properties. Polymers based upon the monomer vinyl methyl ether have the unique behavior of shrinking upon heating to approximately 400C. In the right design with normal behaving polymers, one can construct a device that can grasp objects like a hand.

By far, the widely known chemical classes of pH-sensitive materials are the acids, bases, and indicators. The indicators fit the definition of smart materials by changing color as a function of pH and the action is reversible. Other examples of pH-sensitive materials include some of the smart gels and smart polymers mentioned in this chapter. There are a large number of pH-sensitive polymers and gels that are used in biotechnology and medicine.

There are several different material families that exhibit different behavior to a light stimulus. Electrochromism is a change in color as a function of an electrical field. Other types of behavior for light-sensitive materials are thermochromism (color change with heat), photochromism (color change with light), and photostrictism (shape changes caused by changes in electronic configuration due to light).

The term smart polymers were almost dropped as a classification for smart materials in this treatment of the subject. It is very confusing. Each field of science and engineering has its own definition of a smart polymer, each definition can fit in another classification, and its distinction in smartness can be confusing at times. The term is being included in this chapter because several excellent articles on the subject have ‘‘smart polymer’’ in the title.

The concept of smart gels is a combination of the simple concept of solvent-swollen polymer networks in conjunction

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with the material being able to respond to other types of stimuli. A partial list of these stimuli includes temperature, pH, chemicals, concentration of solvents, ionic strength, pressure, stress, light intensity, electric fields, magnetic fields, and different types of radiation.35–39 the founding father of these smart gels, Toyochi Tanaka, first observed this phenomenon in swollen clear polyacrylamide gels. Upon cooling, these gels would cloud up and become opaque. Upon warming these gels regained their clarity. Upon further investigation to explain this behavior, it was found that some gel systems could expand to hundreds of times their original volume or could collapse to expel up to 90% of its fluid content with a stimulus of only a 10C change in temperature. Similar behavior was observed with a change of 0.1 pH unit.

The shape memory effect in metals is a very interesting phenomenon. Imagine taking a piece of metal and deforming it completely and then restoring it to its original shape with the application of heat. Taking a shape memory alloy spring and hanging a weight on one end of the spring can easily illustrate this. After the spring has been stretched, heat the spring with a hot-air gun and watch it return to its original length with the weight still attached. These materials undergo a thermo mechanical change as they pass from one phase to another. The crystalline structure of such materials, such as nickel–titanium alloys, enters into the martensitic phase as the alloy is cooled below a critical temperature. In this stage the material is easily manipulated through large strains with a little change in stress. As the temperature of the material is increased above the critical temperature, it transforms into the austenitic phase. In this phase the material regains its high strength and high modulus and behaves normally. The material shrinks during the change from the martenstic to the austenitic phase.

III. CLASSIFICATIONS

Smart materials can also be classified into two categories i.e., either active or passive. Fair-weather (1998) defined active smart materials as those materials which possess the capacity to modify their geometric or material properties under the application of electric, thermal or magnetic fields, thereby acquiring an inherent capacity to transduce energy. Piezoelectric materials, SMAs, ER fluids and magneto-strictive materials are considered to be the active smart materials and therefore, they can be used as force transducers and actuators. Kumar (1991) showed that SMA has large recovery force, of the order of 700 MPa (105 psi), which can be utilized for actuation. Similarly piezoelectric materials, which convert electric energy into mechanical force, are also 'active'. On the other part, the materials, which are not active, are called passive smart materials. Although smart, they lack the inherent capability to transduce energy. Fiber optic material is a good example of a passive smart material. Such materials can act as sensors but not as actuators or transducers.

IV. APPLICATIONS

Smart materials find a wide range of applications due to their varied response to external stimuli. The different areas of application can be in our day to day life, aerospace, civil engineering applications and mechatronics to name a few. The scope of application of smart material includes solving engineering problems with unfeasible efficiency and provides an opportunity for creation of new products that generate revenue. Important feature related to smart materials and structures is that they encompass all fields of science and engineering. As far as the technical applications of smart materials is concerned, it involves composite materials embedded with fiber optics, actuators, sensors, MicroElectro Mechanical Systems (MEMSs), vibration control, sound control, shape control, product health or lifetime monitoring, cure monitoring, intelligent processing, active and passive controls, self-repair (healing), artificial organs, novel indicating devices, designed magnets, damping aeroelastic stability and stress distributions. Smart structures are found in automobiles, space systems, fixed-and rotary-wing aircrafts, naval vessels, civil structures, machine tools, recreation and medical devices. The following are the major applications of smart materials related to engineering applications to the present environment.

A.Self-Repair

One method in development involves embedding thin tubes containing uncured resin into materials. When damage occurs, these tubes break, exposing the resin which fills any damage and sets. Self-repair could be important in inaccessible environments such as underwater or in space.

B. Nuclear Industries

Smart technology offers new opportunities in nuclear industrial sector for safety enhancement, personal exposure reduction, and life-cycle cost reduction and performance improvement. However, the radiation environments associated with nuclear operations represent a unique challenge to the testing, qualification and use of smart materials. However, the use of such smart materials in nuclear facilities requires knowledge about the materials respond to irradiation and how this response is influenced by the radiation dose.

C. Structural Health Monitoring

Embedding sensors within structures to monitor stress and damage can reduce maintenance costs and increase lifespan. This is already used in over forty bridges worldwide.

D. Structural Engineering

These materials also find application in the field of structural engineering. They are used to monitor the civil engineering structures to evaluate their durability. Not only the smart materials or structures are restricted to sensing but also they adapt to their surrounding environment such as the ability to move, vibrate and demonstrate various other responses. The applications of such adaptive materials involve the capability to control the aero elastic form of the aircraft wing to reduce the pull and improve operational efficiency, to control the vibration of satellites' lightweight structures; Smart structures are also being developed to monitor structural integrity in aircraft and space structures. Effort has been made to investigate certain piezoelectric materials to reduce noise in air conditioners. Besides, in civil engineering, these materials are used to monitor the integrity of bridges, dams, offshore oil-drilling towers where fiber-optic sensors embedded in the structures are utilized to identify the trouble areas.

E. Biomedical Applications

In the field of biomedicine and medical diagnostics, still investigations are being carried out. Certain materials like poly-electrolyte gels are being experimented for artificial-muscle applications, where a polymer matrix swollen with a solvent that can expand or contract when exposed to an electric field or other stimulation. In addition, due to biodegradability of these materials, it may make it useful as a drug-delivery system.

F. Reducing Waste

All over the world, the electronic wastes are the fastest growing components of domestic waste. During disposal and processing of such wastes, hazardous and recyclable materials should be removed first. Manual disassembly is expensive and time consuming but the use of smart materials could help to automate the process. Recently fasteners constructed from shape memory materials are used that can self release on heating. Once the fasteners have been released, components can be separated simply by shaking the product. By using fasteners that react to different temperatures, products could be disassembled hierarchically so that materials can be sorted automatically.

G. Reducing Food Waste

Food makes up maximum waste among all others. Most of the food grown for consumption is thrown away without consumption due to their reaching of expiry date. These dates are conservative estimates and actual product life may be longer. Manufacturers are now looking for ways to extend product life with packaging by utilizing smart materials. As food becomes less fresh, chemical reactions take place within the packaging and bacteria build up. Smart labels have been developed that change colour to indicate the presence of an increased level of a chemical or bacteria in it. Storage temperature has a much greater effect than time on the degradation of most products. Some companies have developed ‘time-temperature indicators’ that change colour over time at a speed dependent on temperature.

H.Health

Biosensors made from smart materials can be used to monitor blood sugar levels in diabetics and communicate with a pump that administers insulin as required. However, the human body is a hostile environment and sensors are easily damaged. Some researches on barrier materials are going to protect these sensors.

I. Defence And Space Applications

Smart materials have been developed to suppress vibrations and change shape in helicopter rotor blades. Shape-memory-alloy devices are also being developed that are capable of achieving accelerated breakup of vortex waves of submarines and similarly different adaptive control surfaces are developed for airplane wings. Besides, present research is on its way to focus on new control technologies for smart materials and design methods for placement of sensors and actuators.

V. UNUSUAL BEHAVIORS OF MATERIALS

As one researches the field of smart materials and structures, one realizes that there are many smart materials and there are many material behaviors that are reversible. The ability to develop useful products from smart materials is left up to one’s imagination. For example, water is a very unique material. It expands upon freezing. As we know, the force generated by this expansion causes sidewalks and highways to crack. Now, what if you surround water pipes with a heating system that consists of a heater and water enclosed in a piezoelectric polymer or elastomer container that is in a fixed space. As the temperature drops to the freezing point of water, it expands and generates a force against the piezoelectric container which in turns generate electricity, thus powering the heater and keeping the pipes from freezing.

VI. CONCLUSION

The technology of smart materials by its nature is a highly interdisciplinary field. Starting from the field of basic sciences such as physics, chemistry, mechanics, computing and electronics it also covers the applied sciences and engineering such as aeronautics and mechanical engineering. This may explain the slow progress of the application of smart structures in engineering systems, even if the science of smart materials is moving very fast. In the present scenario, the most promising technologies for lifetime efficiency and improved reliability include the use of smart materials and structures. Understanding and controlling the composition and microstructure of any new materials are the ultimate objectives of research in this field and is crucial to the production of good smart materials.

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