Journal of Material Sciences & Engineering

Review
Volume 10:9, 2021

ISSN: 2169-0022
Open Access

New and Emerging Smart Materials and Their Applications: A Review

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Abstract

Smart materials are materials that have intrinsic sensing, controlling, actuation or information processing capabilities in their microstructures. These materials are used to create smart systems containing multifunctional parts that can perform sensing, control, and actuation. Smart systems often exhibit high functionality such as self-diagnosis and self-restoration. Smart materials are being developed for applications in numerous manufacturing sectors such as in the aerospace industry, biomedical industry, and general manufacturing industries. This review paper covers some of the recent advances in the area of smart materials and the enhanced functional capabilities these materials provide for a range of smart applications.

Keywords: Emerging smart materials • PTC sensors • Platinum

Introduction

The “I.Q.” of smart materials is based on their responsiveness and agility. A comparison of positive temperature coefficient (PTC)-resistance materials illustrates the difference between a regular and “smart” material. Platinum is a commonly used metal for PTC sensors, and its change in resistance is very small (<0.03 μ Ω*cm/K) over a temperature range of 20 K-1,500 K. In contrast, donor doped BaTiO3 exhibits a change in resistivity of nearly six orders of magnitude over a temperature range of 350 K-450 K. This property of BaTiO3 enables the PTC material to form a self-protection circuit through control temperature without any additional electronics [1,2].

Some materials are naturally “smart” such as piezoelectric, electrostrictive, and magnetostrictive materials. These natural materials, however, are often limited in terms of the temperatures they can operate in or in their response amplitude. By appropriate engineering, these smart materials can be made more intelligent and can be tailored for particular applications [1]. Smart materials can be passive, active, or very smart materials [3]. Passive smart materials respond without thought or signal processing. Active smart materials analyze the sensed signal and then respond accordingly. Very smart materials have the same abilities as active smart materials and can also adapt to their environment through tuning and learning. Microelectromechanical Systems (MEMS) which can integrate the control system with sensors and actuators are currently being developed and can be classified as intelligent systems. Many smart materials and smart systems are already available in the market while others are undergoing research and development for future applications.

Major Types of Smart Materials and Their Known and Emerging Applications

Piezoelectric materials

Figure 1 shows a piezoelectric transducer. Piezoelectric materials are physically defomed exposure to electric fields, and they produce energy when undergoing mechanical strain [4]. Piezoelectric actuators have many advantages because they are compact in size, have high response velocity, high accuracy, and they require little energy to react. They produce elongation with loaded voltage [2]. Piezoelectric applications include loudspeakers, acoustic imaging, energy harvesting, actuation, health monitoring, and tissue regeneration [5].

Figure 1. Piezoelectric transducer

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Received: 02 September, 2021; **Accepted:** 16 September, 2021; **Published:** 23 September, 2021

Figure 2 shows piezoceramic materials which are favorable piezoelectric materials because of their low cost and lightweight [6]. They are preferred materials for active control of structural vibration. Piezoceramics are available in various forms such as rigid patch, flexible patch, stack, Macro-Fiber Composite (MFC) actuators, and piezoceramic friction dampers [7].

Figure 2. Piezoceramics

Shape memory materials

Figure 3 shows shape memeory materials which posess unusual properties such as the Shape Memory Effect (SME), pseudo elasticity, high damping capacity, and adaptive properties which stem from their reversible phase transition behavior. These materials are capable of sensing thermal, mechanical, magnetic, or electric stimulus, and they exhibit actuation [8].

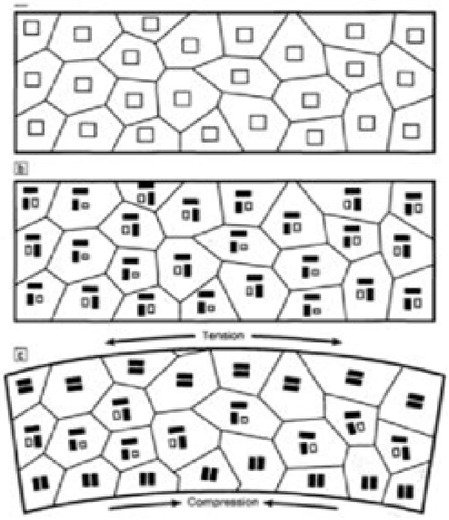

Figure 3. Top: Partially ordered high-temperature austenitic phase; Middle: Partially transformed mixed austenite-martensitic phase; Bottom: Phase changes and domain-wall movements from mechanical stress

Figure 4 describes Nitinol (Ti-Ni alloy) which is the most important commercial Shape Memory Alloy (SMA), and it is widely used in the biomedical field. It exhibits exclusive shape memory performance, is easily processed, and is associated with good mechanical behavior, high corrosion resistance and biocompatibility. Thin films, fibers, particles, and porous bulks of Ti-Ni have been successfully fabricated in recent years. Ti-Ni shape memory alloys are not exclusive to the biomedical field; they have demonstrated application potential in micro-electromechanical systems, intelligent systems, and structural assemblies [8]. Copper based and iron based alloys are also shape memory materials of interest due to their low cost. Copper based alloys are easily fabricated; however, most polycrystalline alloys have poor ductility and workability [9]. Adding other metals such as Al, Zn or Ni to the copper based alloys can improve the workability of these materials, but more developments must be made to improve thermal stability. Iron based alloys such as Fe-Pt and Fe-Pd alloys exhibit induced Martensite transformations when exposed to magnetic fields; they carry application potential as ferromagnetic shape memory materials. Shape memory ceramics such as mica glass exhibit clear shape memory phenomenon. These materials are viscoelastic and thermally stimulated. Pseudo elasticity and shape memory effects are exhibited if the transformations are thermoelastic or ferro-elastic or if they exhibit reversible strain or shape recovery behaviors. Shape memory ceramics have potential for high temperature applications that surpass the limits of shape memory alloys; however, they have limited capacity due to small magnitudes of recoverable strains and can exhibit microcracking. Shape memory ceramics which are ferroelectric may be better suited for certain applications over shape memory alloys. Ferromagnetic shape memory ceramics are less investigated because they only exhibit spontaneous magnetization at very low temperatures [10].

Shape Memory Polymers (SMPs) offer a number of potential technical advantages over other shape memory materials such as shape memory metallic alloys and shape memory ceramics. Shape memory polymers can recover almost all the residual transformation upon reheating to the rubbery phase, unlike ordinary polymers. Advantages include high recoverable strain (up to 400%), low density, ease of processing and the ability to tailor the recovery temperature, programmable and controllable recovery behavior, and more importantly, low cost [11]. Creation of shape memory polymer composites further enhances the performance of these materials and expands the application potential. Shape memory polymers are currently used in aerospace engineering, textiles, automotive industry, and in the medical field.

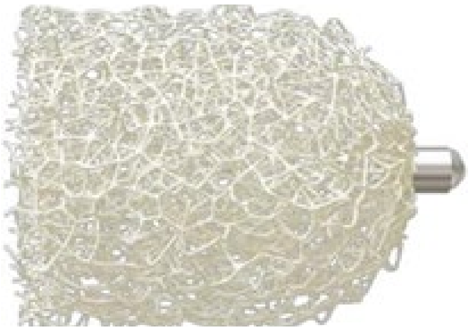

Figure 4. IMPEDE-FX, a shape memory polymer by shape memory medical for peripheral vascular embolization

Functional materials

Functional materials cover a wide range of organic and inorganic materials and are distinct from structural materials. Their physical and chemical properties are sensitive to changes in environmental parameters such as temperature, pressure, presence of electric and magnetic fields, propagation of optical waves, adsorbed gas molecules and pH changes. In addition to the materials classified as smart materials, other materials that possess certain special functionalities are considered as functional materials. Examples include the ferroelectric BaTiO3 (magnetic field sensor), La1-xCaxMnO3 (surface acoustic wave sensor), LiNbO3 (liquid petroleum gas sensor), Pd-doped SnO2 (semiconductor light detector), CdS, CdTe (high temperature piezoelectric), Ta2O5 (fast-ion conductor), and high temperature superconductors [12].

Chromogenic materials

Figure 5 is one good example of chromogeic materials which cover cover most of the visibly switchable applications such as glazing, mirrors, transparent displays, and a variety of other applications involving visual changes. Two common chromogenic effects are photochromism (color change due to ultraviolet exposure) and thermochromism (color change due to temperature). Chromogenic smart materials include electrically driven media including electrochromic materials, suspended particle electrophoresis materials, polymer dispersed liquid crystals, and electrically heated thermotropics [13]. The applications for chromogenic smart materials are mostly in automotive, architectural, aircraft, and information display fields. In the automotive industry, most major makes of cars have switchable mirror options. Several groups such as the Flabeg group and SAGE electrochroics focus on the architectural market and install electrochromic windows and skylights. Future aircraft will use switchable passenger windows; Boeing and Airbus have made such announcements. The two main areas for the information display market are cathode ray tubes and liquid crystals.

Figure 5. Switchable motorcycle helmet made by ChromoGenics

Figure 6 is an example of electrochromic materials which respond to an electric field by changing their optical properties. A reversal of the electric field will return the material to its original state. Switchable mirrors and windows use this effect. The Flabeg Group has developed a switchable glazing comprising an insulated glass unit with two panes. ChromoGenics of Sweden is developing a flexible electrochromic on plastic for use as a visor in motorcycle helmets.

Liquid crystals are being highly researched and developed for flat panel displays. The orientation of the liquid crystals alters the overall optical reflectivity properties of the window or display [13]. Thermotropic materials appear clearer at lower temperatures and become opaque at higher temperatures. Applications include skylights, inclined glazing, and upper windows. A European company named Pleotint has created a thermotropic called ThermoSEE, and its activation temperature can be set between-10°C and 50°C.

Figure 6. ThermoSEE thermotropic glazing by Pleotint. Suspended particle devices (SPDs) have applications for glasses, goggles, and windows

Ongoing Research Activities, Application Projects and Recent Advances

Civil structures

Figure 7 shows a civil structure that incorporates a smart sensor. Until now smart systems have mostly focused on mechanical engineering applications and space structures (light and flexible structures), but there is evidence of increasing interest in civil engineering. Civil engineering applications include health monitoring of building structures, self-repairing, and actuating structural members [2]. Researchers working at Takenaka Corporation Research and Development Center at University of Tokyo, and Sumitomo Heavy Industrial Research and Development Center are studying response control of shape memory alloys. Passive energy dissipation devices to improve structural safety are of great interest due to situations such as earthquakes.

Response control using piezoelectric actuators was tested in a four story steel frame. Shaking table tests were performed and the cases using piezoelectric actuators showed a maximum response time that was one eighth that of the non-controlled cases to identify maximum acceleration of each floor [2]. In another set of experiments, a shape memory wire was loaded monotonically and repeatedly in tension. Monotonic tensile load and repeated tensile load allowed the researchers to calculate the maximum strain associated with the damage of a structural member from the electrical resistance property of the shape memory alloy.

Shape Memory Alloys (SMAs) as energy dissipation devices hold potential due to their super-elastic characteristics. Nitinol SMA was used in a cyclic load experiment because it has stable hysteresis and good weatherability. Though it has the ability of energy dissipation, it has limited dissipation capacity and more developments must be made until shape memory alloys become viable and useful in civil engineering applications.

Figure 7. Test Bed-Four Story Frame

Composite polymers

Figure 8 shows SEM microgrphs of selected polymer blends. Researchers at the Université de Lyon have been focusing on conductive polymer composites. These composites are a topic of interest for their industrial applications of current limiting devices and temperature sensors. The group investigated three polymers: high density polyethylene, polybutylene terephthalate and poly (m-xylene adipamide).

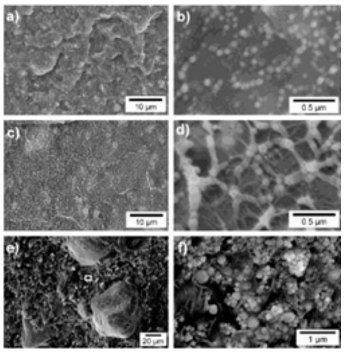

Figure 8. SEM micrographs of freeze fractured homo- and heterogeneous polymer blends of three polymers

(a and b) HDPE (80%)+20%Ag

(c and d) PBT (80%)+20%Ag

(e and f) HDPE (33%)/PBT (47%)+20%Ag

Homogeneous and heterogeneous blends were created and the filler in the homogeneous matrix exhibited a tendency to create conductive paths due to its uniform distribution. The heterogeneous matrix blend of HDPE/PBT and Ag illustrated the inhomogeneous spatial distribution of the filler that results from HDPE and PBT being immiscible. The researchers concluded that immiscible polymer blends can produce a 2 fold decrease in the percolation threshold. The HDPE/PBT-Ag composite accounted for 8.2 vol % as compared to 17.4 vol % for the individual components and this was caused by the presence of the co-continuous network. Additionally, the resistivity of the polymers was stable and low at room temperature and increased over 10 orders of magnitude as they changed from the conducting to isolating state, which could make them a multiuse alternative to conventional fuses [12].

Conjugate polymers

Figure 9 illustrates how certain conjugate polymer materials can be used to detect the presence of gases. Conjugate polymers are another smart material of interest for their applications as sensors and actuators with gases. Researchers at the Linköping University in Sweden created biopolymer strips by laminating a conjugated polymer with a substrate polymer layer. The strips were fixed at one end and the other end was allowed to freely move and sense gases.

The experiments showed a PPy/Au/PE (PPy is polypyrrole) strip reversibly senses ammonia by adsorbing and desorbing it and directly changes the chemical energies into mechanical energy. Additionally, a strip using polytheophene (PT) instead of PPy can be used to sense iodine; however, it initially undergoes shrinking before swelling and this swelling greatly depends on the alkyl substituents of the polymers.

The bending beam method has provided a novel way to exploit conjugated polymers as new sensors and actuators because of their ability to convert chemical energy into mechanical energy. This method also provides a sensitive and reliable way to measure the in situ volume changes or conformational changes in conjugated polymers during its doping/undoping or other interactions with gases [14].

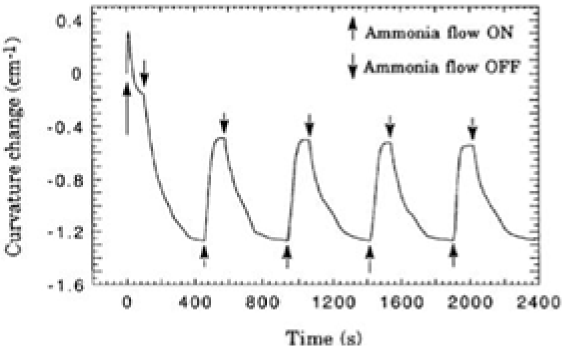

Figure 9. SEM Curvature change of a perchlorate doped PPy/Au/PE strip in response to ammonia gas flow

The occurrence of electrochromism in PDAs is illustrated in Figure 10. Polydiacetylenes (PDA) are conjugated polymers that have an assortment of sensing and detection capabilities. They are a major research area due to their interesting optical, spectral, electronic, and structural properties. The structural diversities of PDAs have heralded clear applications in several key areas and there is ongoing discovery of new PDA formulations. Polydiacetylenes have interesting structural manifestations such as liposomes, tubes, fibers, organic/inorganic incorporated hybrids, and composite structures. PDAs are currently in development as core components of efficient sensors, imaging, and display systems [15]. Looking at PDAs in the first dimension, PDA-embedded electrospun fibers show different colorimetric responses upon exposure to organic solvents such as gasoline. PDA can be used as a real time sensor for detecting gasoline quality. Researchers have also created carbon nanotube-PDA composites to examine if PDA can exhibit electrochromic behavior by exploring the coating of carbon nanotubes. Pure PDA structures have a very low conductance [15]. Applying current to the composite structures produces reversible color transitions, which is of special interest because PDA structures are well known to display irreversible thermochromic changes. The response of PDA/CNT composites to various stimuli such as heat, mechanical abrasion, and chemical organic compounds in the same study shows the potential for the use of composite as the active material for sensors and actuators [16].

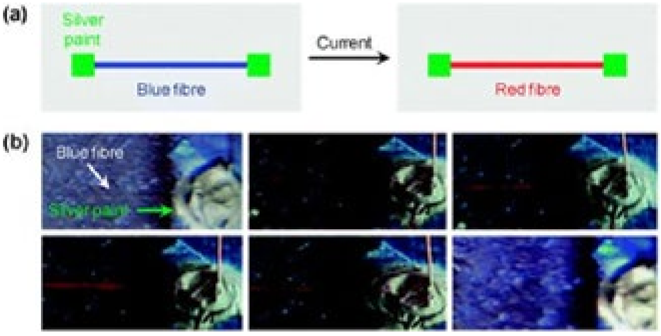

Figure 10. Illustration of electrochromism in PDA fiber connected between two electrodes. The blue fiber (top-left) turns into red (top-right) 1s after current is switched on. 2 s after current switched off (bottom-left) the red fiber returns back to blue (bottom-right). The images were acquired with sequential 1 s steps

Figure 11 shows how two dimensional PDAs can be used for visual monitoring of heat distribution. Two dimensional PDAs prove to be prove to be a simple and effective application for monitoring the thermal distribution and heat originated multi-failure points on heat dissipating operational devices such as operating semiconductor devices. Even more superior are three dimensional PDAs because of increased surface area and multipoint interaction sites for sensor application [17].

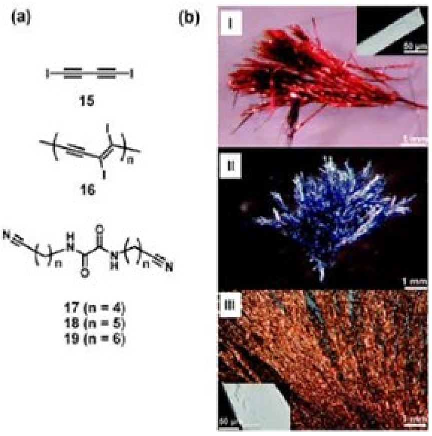

Figure 11. Illustration of multi-dimensional PDA (a) Molecular structures of PDA 16, its precursor di-idobutadiyne 15 and Lewis-basic host molecules (b) Optical microscope images of co-crystals prepared by the interactions of 15 with host molecules 17 (I), 18 (II), and 19 (III)

Another group developed a method of preparing PDA crystals and all the developed crystals initially displayed a blue color after synthesis but changed color after a week at room temperature, depending on the length of the side chains of the host materials [18]. It was observed that 3-D formations can provide a clear advantage in surface area enhancement for sensing applications while 2-D films can provide superior surface coatings for imaging and display technologies.

There still exists an apparent gap in the sensor platform and display technologies demonstrated at the laboratory level and practical PDA-based devices used in everyday applications; however, PDAs are already used in applications such as contamination detection of gasoline and Volatile Organic Compounds (VOCs), as detectors of temperature distribution, for failure analysis of electronic devices, and as ink precursors in validation/authentication applications. Studies on the electrochromism and magnetochromism of PDAs are still in their infancy, but it is believed that PDAs will find many new uses in scientific and engineering applications [16].

3D printing

Figures 12 and 13 illustrate the stretching and folding behavior of certain 3D printed materials. The School of Mechanical and Aerospace Engineering (MAE), Nanyang Technological University (NTU), and the Institute of Sports Research (NTU) are researching additive manufacturing, commonly known as 3D printing of smart materials and structures [5]. 4D printed smart materials are additive manufactured pieces with the ability to respond to applied external stimuli by changing their shape or properties over time. Additive manufacturing processes that do not exhibit behaviors such as self-sensing, self-actuating, or shape changing are regarded as non-smart. Research is being done in additive manufacturing of smart nanocomposites, shape memory materials, self-evolving structures and actuators.

There are also multiple technologies already available for additive manufacturing. Poly jet printing is similar to ink jet printing, Selective Laser Melting (SLM) technology is a powder based 3D printing method that uses a high energy density laser to melt layers of metallic powder in order to create a dense and homogeneous 3D metallic structure. Another 3D printing technique, Digital Projection Printing (DPP) offers high resolution, reproducibility, and precision. 4D printing has certain limitations at present and these can be categorized as technological, material, and design limitations. 4D printing of multiple smart materials or a combination of smart materials and conventional materials requires both design knowledge, material knowledge and process knowledge. Another trendy research in additive manufacturing is 4D bio printing. Even though there is a lack of consensus on the exact process terminology, it has the potential to physically replicate the development path of biology and bring organ printing one step closer to reality [8,19].

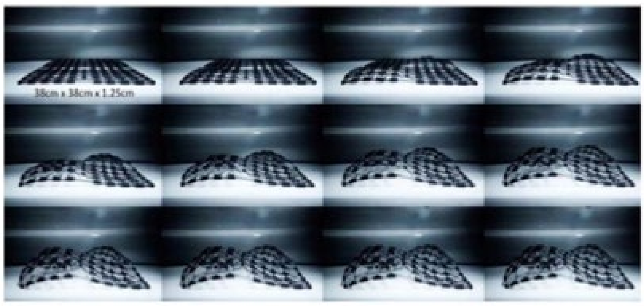

Figure 12. Complex 2D multi-material component exhibiting stretching and folding

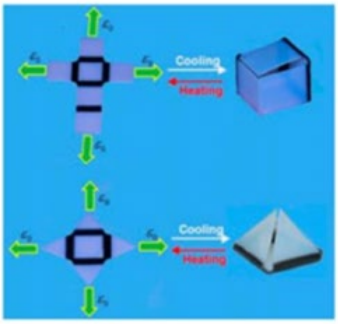

Figure 13. Active origami box and pyramid shapes before and after self-folding

Biomaterials and biotechnology

Figure 14 illustrates how molecular motion can be achieved and utilized using electric potential. Recent progress in various biotechnology fields such as in various biotechnology fields, such as microfluidics, tissue engineering, and cellular biology, has created a great demand for substrates that can undergo defined remodeling with time. As a result, the latest research on materials with dynamically controllable surface properties has led to a variety of novel smart surface designs [20]. Switching can be performed using various means: electrochemical approaches, photoinduction, changing of temperature or pH, mechanical controls, and electrically driven conformation.

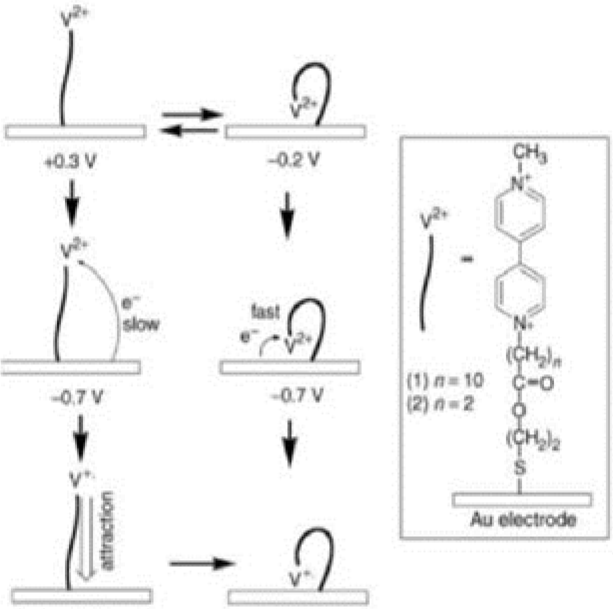

Figure 14. Potential-induced molecular motion due to the redox reaction of a bipyridinium monolayer on a gold electrode

Current "biomimetic" materials contrast with former versions of biological materials that lacked the ability to undergo defined remodeling with time. Smart surface designs will be required when imitating nature's approach of dynamically controlled tissue formation and differentiation of cells. These dynamically controllable substrates may ultimately result in novel biomaterials with unique structures and biological functions. Potential applications of smart surfaces may include substrates to study cell/cell and cell/protein interactions, rechargeable platform surfaces for biosensors with tunable dynamic ranges, functional units in microfluidic devices (e.g., valves or reservoirs), and smart scaffolds for tissue engineering [20]. One of the largest challenges in creating biomaterials is associated with accurately predicting the formation of large scale self-assembled structures. With the advent of key technological advances in imaging, peptides have recently begun to be exploited for their potential use as biomaterials, such as filaments and fibrils, hydrogels, surfactants, and peptide hybrids [21]. Peptides offer attractive features, principally because of our detailed understanding of their ability to fold into specific structures, and the rich chemistry with which their structure and function can be manipulated for environmental response [22,23].

Peptides offer many possibilities, and they possess favorable properties such as biocompatibility, immunogenicity, and biodegradability, all of which turn them into non-toxic waste products. They can be used to nucleate and guide the growth of minerals, as scaffolds for tissue regeneration including cartilage repair and promotion of nerve cell growth. They have potential for minimized solar cells, optical devices, electronic devices, and for the development of molecular machines or robots that can be turned on and off in response to a signal [21].

Discussion and Conclusion

There are numerous demands on smart materials and structures. The field of smart materials and structures is a thoroughly interdisciplinary field which borrows from science and technology and combines the knowledge of physics, mathematics, chemistry, computer science, materials science, electrical engineering, and mechanical engineering. It implements human creativity and innovative ideas to serve human society for such tasks as making a safer car, a more comfortable airplane, a self-repairable water pipe, etc. Smart structures can help us control the environment better. They can increase the energy efficiency of devices [1]. Aerospace engineers are interested in smart air foils to control drag and turbulence. People suffering from diabetics need medical systems to sense sugar level and deliver controlled amount of insulin. Architects can build smart buildings that incorporate self-adjusting windows to control the flow of energy into houses. Smart irrigation systems are needed to optimize the world's food supply [3]. Some researchers even foresee miniaturized devices such as electromechanical devices using smart structures capable of directly communicating with the human brain. Smart materials are being developed and improved; one can expect to see super smart materials and structures with an unbelievable range of functionalities and uses in the near future.

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How to cite this article: Julia, L and Radhakrishnaiah P. “New and Emerging Smart Materials and Their Applications: A Review.” *J Material Sci Eng* 10 (2021); 1-6