FUTURE'S SMART MATERIALS

Abstract

The term "smart materials" refers to a class of materials that have the ability to modify their properties in response to external inputs. Smart materials provide several desirable characteristics that make them highly appealing. These include their lightweight nature, sensing capabilities, reduced component size, and complexity.

Furthermore, smart materials offer design freedom, enhanced usefulness, and increased reliability. A smart material is an entity that has the ability to undergo a change in its material properties and manifests a discernible and palpable response to external stimuli. The effective use of smart materials offers a degree of environmental resilience that is challenging to attain with conventional technologies, which are vulnerable to natural forces. The potential application of smart materials, such as shape-memory alloys and piezoelectricity, in the transportation sector represents a significant advancement in futuristic technology. The aforementioned modification renders smart materials increasingly crucial in several technological domains, particularly in the fields of health and information technology.

Despite the extensive range of applications for smart materials, their increased reliance is hindered by several limitations that must be resolved in order to effectively utilise these materials. These limitations include issues related to system compatibility, availability, cost, fragility, diminished performance over time, challenges in integration, and potential toxicity concerns. The future prospects of smart materials are expected to be shaped by interdisciplinary collaborations among scientists spanning various fields, including electronic engineering, chemistry, and cell biology.

Keywords: Smart Materials, Classification, Application, Shape-Memory Alloys.

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I. INTRODUCTION

The significance of advancements in materials and gadgets cannot be overstated in their contribution towards enhancing individuals' well-being and overall standard of living. Smart materials are not exempt from this observation. Due to their distinctive attributes of reactivity to stimuli and autonomous functionalities, smart materials have emerged as the fundamental building blocks for numerous innovative technological advancements. The subject of smart materials has witnessed significant advancements in recent years, with notable examples including piezoelectric materials and shape-memory materials. These innovative materials have revolutionized conventional design principles and significantly broadened their range of applications. An illustration of this can be observed in the field of robotics, where there has been a notable progression from the utilization of inflexible structures to the development of soft robots constructed using pliable materials. The potential development of future robotic systems includes the capacity for growth, regeneration, and morphological and functional adaptation in response to various physical and chemical conditions. This advancement necessitates the integration of multiple disciplines, such as chemistry, mechanical engineering, materials engineering, and bioengineering, to effectively address the associated challenges and opportunities. Smart materials are utilized in many applications to establish man-made systems that seamlessly interact with live beings, hence potentially blurring the boundaries between the two entities. Smart materials play a crucial role in various fields, including environmental sensors and actuators. Moreover, they are of utmost importance in the advancement of soft robotics and bioelectronics. Notably, smart materials have achieved significant accomplishments in medical technologies, particularly in the domains of physiological sensing, minimally invasive surgery, drug delivery, human-computer interaction, and rehabilitation. Future smart materials are anticipated to provide a broader range of functionalities, heightened controllability, and higher biocompatibility, hence offering the potential to significantly contribute to the advancement of human well-being.

II. CLASSIFICATION OF SMART MATERIALS

1. **Piezoelectric:** Piezoelectric materials exhibit a phenomenon wherein they experience mechanical deformation when exposed to an electric charge or voltage variation, and conversely, they generate an electric charge or voltage variation when subjected to mechanical stress. The aforementioned occurrences are commonly referred to as the direct and converse consequences.

2. **Electrostrictive:** The electrostrictive material exhibits similar characteristics to piezoelectric materials, with the exception that the magnitude of its mechanical deformation is directly proportional to the square of the electric field. This particular attribute will consistently result in displacements occurring in a uniform direction.

3. **Magnetostrictive:** The magnetostrictive phenomenon refers to the induced mechanical strain experienced by a material when it is exposed to a magnetic field, and vice versa, known as the direct and converse effects, respectively. Therefore, it has the potential to serve as both sensors and actuators. One such example is Terfenol-D.

4. **Shape Memory Alloys:** When exposed to a thermal field, the material in question will experience phase transitions that result in alterations in its shape. The material undergoes a phase transformation to its martensitic state at low temperatures, and reverts back to its

original shape in its austenitic state upon heating to high temperatures. One example of a shape memory alloy is Nitinol, which is composed of a combination of nickel (Ni) and titanium (Ti). Shape memory alloys (SMAs) are a distinct category of materials that possess exceptional characteristics, notably their capacity to regain their initial form subsequent to experiencing deformation.. These alloys have attracted Upon exposure to a thermal field, the aforementioned material will experience phase transitions that result in alterations in its shape. The material undergoes a transformation to its martensitic state at low temperatures, and reverts back to its original shape in its austenitic state upon heating to high temperatures. One example of a shape memory alloy is Nitinol, which is composed of a combination of nickel (Ni) and titanium (Ti).

5. **Piezoelectric Materials:** Piezoelectric materials are substances that generate an electric charge when subjected to mechanical stress. The most fundamental description of piezoelectric materials can be obtained by separating "piezo" and "electric." "Piezo" is derived from the Greek term "piezein," which means "to press tightly or squeeze." By combining "piezein" and "electric," the meaning "squeeze electricity" is communicated. The history of piezoelectric materials is comparatively uncomplicated, and only the major milestones will be described. In 1880, Pierre and Paul-Jean Curie demonstrated the piezoelectric effect in crystals of quartz and salt of Rochelle. The initial investigations involved the attachment of weights to specific surfaces.

Crystal incisions, such as the X-cut quartz plate, were used to detect charges on the crystal's surfaces. These experiments demonstrated that the quantity of charge was directly proportional to the applied weight. The aforementioned phenomenon is now known as the direct-pressure piezoelectric effect. In the year 1881, G. Lippmann made a prediction regarding the development of mechanical strain in a crystal, such as quartz, when subjected to the application of an electric field. The Curies recorded the reciprocal pressure-induced piezoelectric phenomenon in quartz and Rochelle salt in the same year. The researchers demonstrated that when particular crystals were subjected to mechanical strain, they exhibited electrical polarisation, the extent of which was directly proportional to the magnitude of the applied strain.. The initial development of SONAR utilising quartz crystals was attributed to the French inventor Langevin in the year 1920. In the 1940s, scholars made significant advancements in the field of materials science by uncovering and refining the initial polycrystalline form of barium titanate, a ceramic material with piezoelectric properties.

One notable advantage of piezoelectric ceramics in comparison to piezoelectric crystals is in its capacity to be fabricated into many shapes and dimensions. In the year 1960, a group of researchers made a significant finding regarding the presence of a very modest piezoelectric effect in whalebone and tendon. This discovery subsequently sparked a fervent pursuit for further organic materials that exhibit piezoelectric properties. In 1969, Kawai made a significant discovery about the piezoelectric properties of polarised polyvinylidene fluoride (PVDF), revealing exceptionally elevated levels of piezoelectric activity. [7, 8]

6. **Electrostrictive:** Piezoelectric materials are characterised by their ability to demonstrate a direct and proportional correlation between electrical and mechanical parameters. Piezoelectricity is characterised by a third-rank tensor. Electrostrictive materials also

exhibit a correlation between these two variables. Nevertheless, in the present scenario, there exists a quadratic correlation between mechanical stress and the square of electrical polarisation. Electrostriction is a phenomenon that can manifest in various materials, regardless of their composition, and is characterised by its very modest magnitude. One notable characteristic of electrostrictive materials is their capacity to exhibit a more pronounced impact in close proximity to their Curie temperature, in comparison to piezoelectric materials. Electrostriction is a feature that can be observed in both centric and acentric insulators, and it is characterised by a fourth rank tensor. This assertion holds particular significance in the context of ferroelectric materials, particularly those belonging to the perovskite family. Ferroelectrics are a type of ferroic materials characterised by the capacity of their domain walls to undergo displacement in response to external pressures or fields. Besides ferroelectrics, additional significant instances of ferroic solids encompass ferromagnetics and ferroelastics, both of which exhibit promise as intelligent materials. Additional instances of electrostrictive materials encompass lead manganese niobate-lead titanate (PMN–PT) and lead lanthanium zirconate titanate (PLZT).

One intriguing utilisation of electrostrictive materials is in the realm of active optical applications. During the historical period known as the Cold War, satellites deployed over the Soviet Union were equipped with active optical systems in order to mitigate the adverse impacts of atmospheric turbulence. Electrostrictive materials provide a notable advantage over piezoelectric materials in terms of their capability to modify the position of optical components. This advantage stems from the less hysteresis linked to the motion of electrostrictive materials. Ongoing research and development efforts have been dedicated to the advancement of active optical systems. The Hubble telescope employed comparable multilayer actuators for the purpose of adjusting the positioning of its optical components. Actuators and flexible mirrors are utilised by supermarket scanners to optically decipher bar codes [9].

7. **Magnetorestrictive Materials:** Magnetorestrictive materials refer to a class of substances that exhibit a phenomenon known as magnetostriction. Magnetorestrictive materials are characterised by their ability to undergo mechanical deformation in response to the application of a magnetic field. The most significant alterations in shape occur in materials that exhibit ferromagnetic properties. The phenomenon of domain wall repositioning, which arises when certain solid materials are subjected to a magnetic field, gives rise to hysteresis in the relationship between magnetization and the applied magnetic field. point, it undergoes a phase transition and loses its magnetic properties.

When the temperature is altered, these effects cease to exist. The microscopic characteristics of a ferromagnetic solid exhibit distinctions when compared to those of a paramagnetic solid. The magnetic dipoles of a material exhibiting ferromagnetism are oriented in a parallel manner. The orientation of dipoles within a ferromagnetic solid can exhibit parallel alignment or alternative orientations (10, 11, 12). Magnetorestrictive materials, typically composed of inorganic compounds, consist of iron and nickel alloys that are doped with rare earth elements. One of the most efficient magnetorestrictive materials is TERFENOL-D, an alloy composed of terbium, dysprosium, and iron, which was created at the Naval Ordinance Laboratory. The complete manifestation of magnetorestriction is observed exclusively in crystalline materials. The cost aspect has been a hindrance to the commercial viability of magnetorestrictive materials. In the last

thirty years, significant advancements have been made in the field of enormous magnetorestrictive materials, colossal magnetorestrictive materials, as well as organic and organometallic magnets (10, 13).

8. **Shape Memory Alloys:** After being deformed, shape memory alloys (SMAs) possess the unique ability to regain their original form. Observed in metals, the phenomenon of the form memory effect is a topic of considerable interest and fascination. Consider the hypothetical scenario of subjecting a metal to complete deformation, followed by its restoration through the use of thermal energy. Using a shape-memory alloy spring and suspending a weight from one end of the spring, it is possible to effectively demonstrate the concept. Once the spring has undergone elongation, heat it with a hot-air cannon and observe its subsequent return to its original length while the weight is still attached to it. These substances undergo a thermomechanical transformation during the transition between phases. The user's text is already scholarly.

When the temperature of nickel-titanium alloys is lowered below a specific critical temperature, the crystalline structure endures a phase transformation into the martensitic phase. During this stage, the material displays a high degree of deformability, allowing for the induction of significant strains with minimal changes in stress levels. When the material's temperature exceeds its critical temperature, it endures a phase transition and enters the austenitic phase. During this phase, the material regains its high strength and high modulus, reverting to its characteristic behaviour. During the transition from the martensitic to austenitic phase, the observed phenomenon entails a decrease in the size of the material [10, 11, 12].

In numerous applications, nickel-titanium alloys have become the material of choice for shape memory applications. The group of nickel-titanium alloys known as Nitinol gets its name from the laboratory where it was first discovered, the Nickel Titanium Naval Ordinance Laboratory. Nitinol has found widespread application in numerous fields, including the military, medical, safety, and robotics industries. Specific applications include hydraulic lines on F-14 fighter jets, medical instruments such as tweezers and sutures, anchors used for attaching tendons to bones, stents designed for cardiac arteries, eyeglass frames, and antiscalding valves built into water faucets and showerheads.[10,14,15]

In addition to the nickel-titanium alloy family, other alloys exhibit the shape-memory effect. Silver–cadmium, gold–cadmium, copper–aluminum–nickel, copper–tin, copper–zinc, copper–zinc alloys with silicon, tin, or aluminium, indium–thallium, nickel–aluminum, iron–platinum, manganese–copper, and iron–manganese–silicon are among the alloys under consideration. The user's text contains no information that requires academic rewriting.

Not all combinations of two or three elements result in an alloy with shape memory. Therefore, primary sources should be consulted for a comprehensive understanding. Multiple publications by Mitsubishi Heavy Industries discuss the characteristics and properties of shape-memory polyurethanes with room-temperature functionality. From the author's perspective, these documents merely provide proof of the characteristics and properties demonstrated by a polymer during the glass transition process. Given the

reversible change in free volume, it is appropriate, when attempting to characterise the behaviour of a polymer at its glass transition temperature, to refer to it as a smart polymer, a shape memory material, or a thermo responsive material. One notable attribute of these polyurethanes is their transition phenomenon, which takes place in close proximity to ambient temperature. [17, 18]

III. APPLICATION OF SMART MATERIALS IN ENGINEERING

Smart materials are commonly employed in the roles of actuators and sensors, with their corresponding "stimulus" and "response" characteristics being illustrated in **Table 1.**

Table 1: Sensor and actuator material classes

Variables	Material Class	Stimulus	Response
Sensors	Pyroelectrics	Temperature change	Electric polarization
	Piezoelectrics	Mechanical strain	Electric polarization
	Electrostrictors	Mechanical strain	Electric polarization
	Magnetostrictors	Mechanical strain	Change in magnetic field
	Electroactive polymers	Mechanical strain	Electric polarization
	Electroluminescent	Electric field	Light emission
	Photoluminescent	Incident light	Light emission
	Electrochromic	Electric field	Color change
Actuators	Piezoelectrics	Electric current	Mechanical strain
	Electrostrictors	Electric current	Mechanical strain
	Magnetostrictors	Magnetic field	Mechanical strain
	Shape memory alloys	Temperature change	Mechanical strain
	Electroactive polymers	Electric field	Mechanical strain
	Electrorheological fluids	Electric field	Viscosity change
	Magnetorheological fluids	Magnetic field	Viscosity change

Smart materials are utilised in a diverse array of applications owing to their multifaceted ability to respond to environmental stimuli. The various domains of application encompass a wide range of sectors, including but not limited to everyday life, aerospace, civil engineering, and mechatronics. The utilisation of smart materials encompasses the resolution of technical challenges with exceptional efficacy, while also presenting prospects for the development of novel revenue-generating goods. One noteworthy characteristic associated with smart materials and structures is their comprehensive coverage across several disciplines within the realms of science and engineering [19].

1. **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. Structural Health Monitoring (SHM) is a field of study that focuses on the continuous assessment and evaluation of the structural integrity of various engineering systems. The integration of sensors into structural systems for the purpose of stress and damage monitoring has the potential to yield significant benefits, such as the reduction of maintenance expenses and the extension of the lifespan of these structures. This technology has been implemented in more than forty bridges across the globe.

2. **Self-Repair:** One technique employed in the field of development entails the integration of slender conduits containing unhardened resin within various materials. In the event of damage, the aforementioned tubes fracture, thereby exposing the resin that subsequently infiltrates and solidifies within the damaged area. The significance of self-repair becomes evident in situations that are inherently inaccessible, such as underwater or in space.

3. **In the Field of Defense and Space:** The development of smart materials has facilitated the suppression of vibrations and the ability to alter the geometry of helicopter rotor blades. Researchers are currently working on the development of shape-memory-alloy devices that have the potential to expedite the breakup of vortex waves in submarines. Additionally, adaptive control surfaces for aeroplane wings are being designed with similar objectives in mind. Moreover, ongoing research is currently centred on the development of novel control technologies for intelligent materials, as well as the design methodologies for the strategic positioning of sensors and actuators.

4. **In Nuclear Industries:** Smart technology presents novel prospects in the nuclear industrial sector for enhancing safety, reducing personal exposure, lowering life-cycle costs, and improving performance. Nonetheless, the radiation exposures linked to nuclear operations pose a distinct barrier when it comes to the testing, validation, and utilisation of smart materials. Nevertheless, the utilisation of these intelligent materials in nuclear plants necessitates a comprehensive understanding of their response to irradiation and the extent to which this response is affected by the dosage of radiation.

5. **In Structural Engineering:** These materials are utilised in structural engineering as well. Monitoring civil engineering structures to determine their durability is common practise. Smart materials and structures not only possess sensing capabilities, but also demonstrate adaptability to their surroundings, such as the ability to move, vibrate, and manifest a variety of other responses. Utilising adaptive materials entails the capacity to manipulate the aeroelastic configuration of an aircraft wing in order to reduce drag and improve operational effectiveness. In addition, these materials are used to control the vibration of lightweight satellite structures. In addition, smart structures are being developed to facilitate the monitoring of structural integrity in aircraft and space structures. A substantial amount of research has been conducted on specific piezoelectric materials for the purpose of reducing noise levels in air conditioning systems. In addition, these materials are used in the field of civil engineering to monitor the structural integrity of infrastructure elements such as bridges, dams, and offshore oil-drilling towers. In this context, fiber-optic sensors are implanted within structures to effectively identify problem areas or prospective problems.

6. **Biomedical Applications:** Biomedical applications refer to the use of scientific and technological advancements in the field of medicine and healthcare. Ongoing investigations are being conducted in the realm of biomedicine and medical diagnostics. Poly-electrolyte gels are currently being investigated for their potential applications in artificial muscle systems. These gels consist of a polymer matrix that is infused with a solvent capable of expanding or contracting in response to external stimuli, such as an electric field. Furthermore, the potential biodegradability of these materials renders them potentially advantageous for utilisation as a medication delivery mechanism.

7. **Reducing Waste:** Electronic garbage is rapidly becoming one of the most rapidly expanding components of home waste on a global scale. In the course of garbage disposal and processing, it is imperative to prioritise the removal of hazardous and recyclable materials. The process of manual disassembly is characterised by high costs and time consumption; however, the integration of smart materials has the potential to automate this process. In contemporary applications, there has been a growing utilisation of fasteners fabricated from shape memory materials, which possess the unique capability of autonomously disengaging upon exposure to heat. After the fasteners have been disengaged, the components can be easily separated by employing a shaking motion on the product. The implementation of temperature-responsive fasteners enables the hierarchical disassembly of items, facilitating the automatic sorting of materials.

8. **Reducing Food Waste:** Food constitutes the largest proportion of waste in comparison to other categories. A significant portion of food produced for human use is discarded before to consumption as a result of exceeding its expiration date. The provided dates are considered to be cautious approximations, and it is possible that the actual lifespan of the product may exceed these projections. Currently, manufacturers are actively seeking strategies to prolong the lifespan of products through the implementation of intelligent materials within packaging. As the freshness of food diminishes, chemical reactions occur within the packaging, leading to the accumulation of microorganisms. Novel smart labels have been created with the capability to undergo a colour shift, serving as an indicator for the heightened concentration of specific chemicals or microorganisms within them. The degradation of most items is mostly influenced by storage temperature rather than time. Certain firms have successfully created "time-temperature indicators" that exhibit a colour change over a period of time, with the rate of change being contingent upon the prevailing temperature.

9. **Health:** Biosensors constructed from intelligent materials possess the capability to effectively monitor glucose levels in individuals with diabetes, facilitating communication with an insulin pump for the purpose of administering insulin when necessitated. Nevertheless, it is important to note that the human body might be considered a challenging environment due to its hostile nature, which can result in the susceptibility of sensors to harm. Several studies have been conducted on barrier materials with the aim of safeguarding these sensors. Currently, various enterprises are engaged in the development of intelligent orthopaedic implants, including fracture plates, which possess the capability to detect the progress of bone healing and transmit relevant data to the surgeon. Preliminary clinical trials conducted on a limited scale have yielded positive outcomes for these implants, indicating the potential for their availability within a timeframe of around five years. Additional potential devices encompass prosthetic joints that establish communication when they experience loosening or detect the presence of an infection. The present technological capabilities of these devices restrict their functionality to data transmission only. However, future advancements hold the potential for these devices to exhibit direct responsiveness through autonomous adjustment, such as the controlled administration or cessation of antibiotic substances. This has the potential to mitigate the necessity for invasive surgical procedures.

10. **The Ageing Population:** In nearly every region of the world, the population of those aged over 60 has surpassed that of children, so giving rise to a burgeoning market for items designed to enhance the quality of life for older adults. A potential approach to enhance the

functionality of these items is through the use of smart materials and systems. An instance where shape memory materials may find application is in the realm of food packaging, specifically in the context of individuals afflicted with arthritis. In this scenario, the materials would possess the ability to automatically open upon exposure to heat. Researchers have constructed smart homes specifically designed for those with dementia, employing sensor technology to monitor their behaviour and assure their safety.

IV. THE BARRIERS TO SMART MATERIALS

Smart materials provide producers with the opportunity to create goods that possess reduced weight and the capacity to react to diverse stimuli. These technologies provide a means of decreasing the quantity of components utilised in a product and frequently enable the creation of intricate topologies through 3D printing, which would otherwise be unattainable through traditional manufacturing methods.

Smart materials are still underutilised in the industrial sector despite the many benefits they offer. Cantilevers, axial rods, linear springs, torsion springs, screw-like actuators, multi-fingered claws, and foldable structures have all been successfully built out of materials like shape memory polymers (SMPs). These resources do have some restrictions, though.

Smart materials have challenges in terms of stabilising their repeatability, as well as exhibiting slower and weaker characteristics compared to conventional actuators and sensors. Additionally, the performance of smart materials may deteriorate with time, posing difficulties in control. Moreover, the use of smart materials can incur significant costs.

Professor Andrés Daz Lantada of the Technical University of Madrid published a scholarly study in the open access journal Polymers in September 2017. Professor Lantada clarified the significance for engineers to carefully analyse numerous variables when choosing a category of intelligent materials in this publication. The actuation force, achievable displacements, response time, and bandwidth are all included in this list. The speaker went on to explain that because shape-memory polymers typically exhibit actuation forces between 1 and 100 N and actuation speeds between 0.5 and 10 s/cycle, they do not fall into the most powerful or rapid categories of "smart" materials.

Engineers must consider a number of additional characteristics when choosing a smart material in addition to force and speed, including but not limited to creep, behaviour, stress, relaxation, fatigue, physical and chemical ageing, and water absorption. Certain faults can be remedied with more ease compared to others. Consider the concept of speed, for instance. The speed of a traditional actuator can be enhanced by increasing the applied force, which is commonly achieved through the utilisation of a larger motor and a larger hydraulic or pneumatic pump. However, it should be noted that in the case of an actuator constructed using a shape memory polymer, the absence of a motor or pump necessitates the incorporation of nickel nanoparticles or a similar substance within the material. This is done to enhance the heat-based activation process, resulting in improved speed, control, and efficiency.

This observation underscores the imperative for engineers to meticulously evaluate the material properties throughout the selection process of a smart material, while also emphasising the importance of considering the entire lifecycle of the component. The ability of

manufacturers to promptly repair or replace parts will become crucial as innovative materials are progressively integrated into future designs. Collaborating with a responsive parts supplier becomes imperative in order to prevent the supply chain from becoming a vulnerable aspect of operations.

Notwithstanding the existing obstacles, it is imperative for the industry to adopt the advantages presented by smart materials and persistently engage in innovation to explore and expand the limits of what can be achieved.

V. CONCLUSION

The area of smart materials is inherently interdisciplinary in nature. The scope of this field encompasses fundamental sciences, including physics, chemistry, mechanics, computing, and electronics, as well as applied sciences and engineering disciplines, such as aeronautics and mechanical engineering. The potential of smart materials and structures for future applications is vast and expansive.

In the contemporary context, the utilisation of smart materials and constructions emerges as a highly auspicious avenue for enhancing lifespan efficiency and bolstering reliability. The primary goals of study in this field involve comprehending and managing the composition and microstructure of novel materials, which is crucial for the development of high-quality smart materials.

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