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A Review on Smart Materials and Additive Manufacturing

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Abstract

Due to their unique ability of changing shape based on external stimulus, smart materials are finding applications in diverse fields like electronics, medical, construction etc. Smart materials include thermochromic pigments, shape memory polymers, shape memory alloys, self-healing materials and hydrogels. Self-healing materials are man-made substances that have an integral ability to spontaneously heal damages themselves without any diagnosis and human. Additive manufacturing or 3D printing has become popular all around the globe due to benefits like reduced wastage, ease of customization, rapid prototyping and direct production. Combined use of 3D printing and concept of smart materials have led to the development of 4D printing. This paper presents an overview of the smart materials and its detailed classification. An attempt is also made to present the application of additive manufacturing on smart materials and the latest research trends in the domain.

Keywords: Smart Materials; Shape Memory Alloys; Self-Healing Materials; Additive Manufacturing; 3D Printing; 4D Printing

Abbreviations

AM: Additive Manufacturing.
ABS: Acrylonitrile Butadiene Styrene.
DED: Directed Energy Deposition.
SEBM: Selective Electron Beam Melting.
SLS: Selective Laser Sintering.
SM: Smart Materials.
SMM: Shape Memory Material.

Introduction

Smart materials (SMs) are substances that alter their behavior as a reaction to an external impetus. These stimuli could be variation in the intensity of electric and magnetic fields, stress, acoustics, temperature, radioactive radiation, or chemical characteristics. These materials aid in adapting to environmental alterations. The geometry and properties of multifunctional materials aka smart materials can be triggered via electrical inputs [1]. Additive Manufacturing [AM], (also referred as 3D printing) has a lot of promise for material, printer, and process advancements. Thus, layer-by-layer manufacturing has been around for three decades, and new advancements in smart materials have lately emerged. Technicalities and the procedures involved in the manufacturing of advanced structured and responsive materials, which are employed in multi-functional and high-performance goods have been figured out. The traditional design and production processes will be impacted by contemporary research and development initiatives. As a result, 4D printing signals a major shift in the product design and production process from static structures to dynamic structures with integrated functions, such as Shape Memory Material (SMM).

Scientific community has shown great interest in the production and development of Smart Materials. Applications of SMs include diverse sectors especially the medical and electronic applications. Development of SMs has shown 13% annual increment and has reached around 73.9 billion dollars by 2023. With the tremendous growth rate insight has led to the development of next-generation SMs which involves composites materials. This shift has been propelled for minimizing the cost, mass and the duration of the active material. These materials are also employed in additive manufacturing, a process that revolutionizes non-traditional manufacturing. As we all know, additive manufacturing is important in a variety of industries, and the application of smart materials gives rise to 4-D printing. Many academics have been concentrating on employing additive manufacturing in large-scale production, however this has proven difficult because to the slower production rates. Hence, this stands as the solution to the problem [2].

Types of Smart Materials

Smart materials can be classified into two types on the basis of 'type of smart material' and 'type of response'. The list of SMs that are in use are given below:

- Smart and Complex Materials.
- Shape Memory Materials (SMM).
- Shape Memory Polymers.
- Shape Memory Alloys.
- Shape Memory Ceramics.
- Metamaterials.
- Tunable Metamaterials.
- Self-Healing Materials.
- Microvascular Self-healing Mechanisms.
- Supramolecular Polymers.
- Encapsulation Self-healing Mechanisms.
- Responsive Smart Materials.
- Thermo-Responsive Materials.
- Electro-Responsive Materials.
- Magneto-Responsive Materials.
- Light-Responsive Materials.
- Chemo-Responsive Materials.
- Moisture-Responsive Materials.
- pH-Responsive Materials.

An overview of the above SMs is provided below.

Shape Memory Materials

The type of smart materials which possess the ability to return to their original contours are known as the shape memory materials. This mechanism can be triggered by the application of various techniques such as changing the temperature of the material. In a few cases, user can control the way they react by regulating their surroundings properties. Figure 1 exhibits the complex flower biomimicry achieved using shape memory polymer [3].

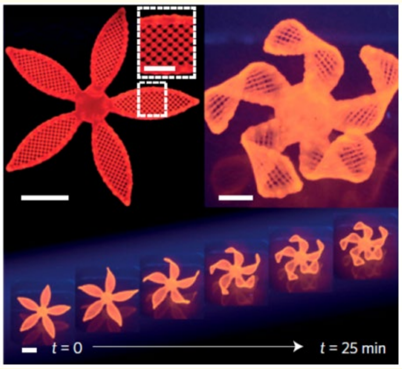

Figure 1: Complex Flower Biomimicry using Shape Memory Polymer.

Shape Memory Alloys

SMAs are metallic alloys that undergo solid-to-solid phase transformation. Phase transition from austenite to martensite that result in macro-scale effect due to changes in the crystallographic structure are the key transformation related to shape memory alloys. They have the tendency to react to chemicals from which they transform back to their original shapes. Figure displays the shape memory alloy model.

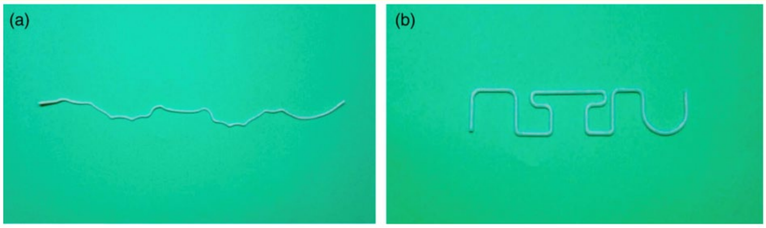

Figure 2: Shape Memory Alloy Model.

Shape Memory Polymers

SMPs are polymers which possess an elastic behavior which can be controlled in the presence of the various responsive techniques such as chemical imbalance in the surroundings of the material. This changes the shape of the body and can be controlled with the regulation of the Responsive Technique.

Shape Memory Ceramics

SMCs are very difficult to achieve as the generic properties of the ceramics is brittle and unable to undergo deformation, such properties make it very hard to deform without any catastrophic failure. However, very few of the scientists were able to discover a way to make them.

Metamaterials

Metamaterials are the type of smart materials which cannot be found in the natural modes. Manufacturing of such materials can be performed by various techniques like chemically. In general, these change the microstructure of the material which cannot be fabricated through machining [4].

Super Wood

The super wood is created from a natural wood, which undergoes a remarkable compression by the maximum removal of 'Lignin' (polymer) The natural wood is boiled in NaOH and Na_2SO_3 sequentially which changes the composition in the material. This can be a low-cost, high-performance, lightweight alternative to many other metals and materials currently being used. Figure 3 presents the densification and strength enhancement of super wood material.

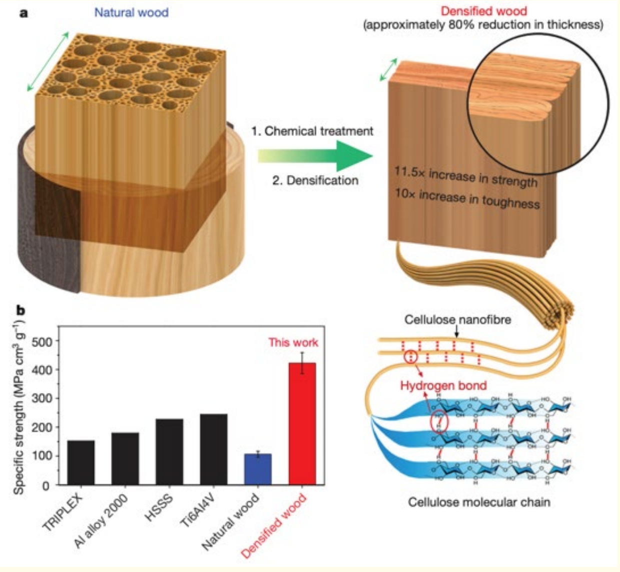

Figure 3: Super Wood.

Self-Healing Materials

The materials which possess the ability to heal any physical damages and/or defects on their original form. This ability of the material is called 'self-healing'.

Microvascular Self-Healing Material

This 'self-healing' process in the materials is contiguous to 'capillary action' in humans. These materials consist of small pockets called capsules. They consist of the healing material which fills the damaged area. These capsules are spread throughout the 3-D microvascular network just like the human vascular system. Figure 4 exhibits the principle involved and the schematic of microvascular self-healing materials [5].

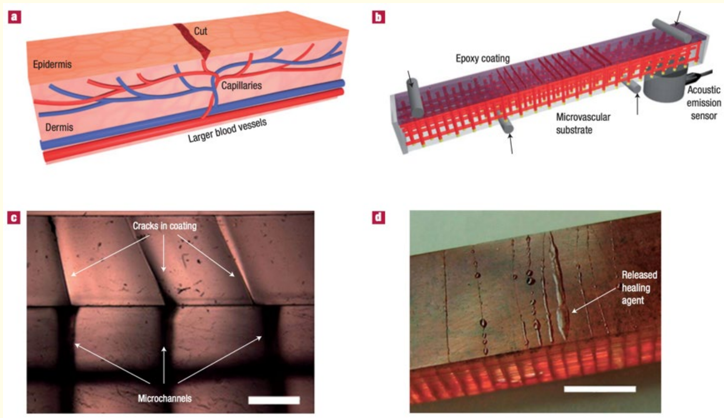

Figure 4: 3-Dimensional Microvascular Self-Healing Materials.

Supramolecular Polymers

These are the type of self-healing smart materials which are capable to bind themselves through the damaged part by forming the broken bonds of the polymers.

Encapsulation Self-healing Mechanisms

The smart materials which have cells (capsules) present in their bodies, which contain healing material that is activated when the body faces any kind of catastrophe. These are similar microvascular self-healing materials but the capsules are not placed throughout the body and it can be controlled with respect to the design.

Additive Manufacturing of Smart Materials

Smart Materials for Processing via Fused Layer Modeling

Fused Layer Modelling is an additive manufacturing process in which the layers are created by the filament material. The filament material is called ‘wood-filled filament’ which consists of lay wood. Complex structures were created using the active wood material and some other plastics. The observation(deformation) was made around the climatic surroundings. Figure 5 portrays the development of hybrid structure using wood filament and Acrylonitrile Butadiene Styrene (ABS) [6].

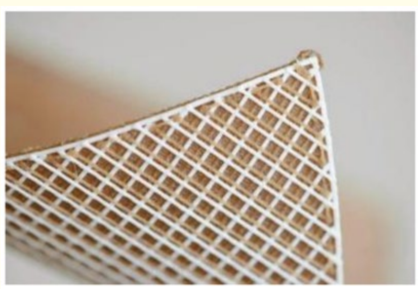

Figure 5: Hybrid Structure of Wood Filament and ABS.

Bio-inspired Heart Valve Prosthesis Made by Silicone Additive Manufacturing

A valve of the human heart has been printed using additive manufacturing of smart material which consists of silicone. These silicone gels are photo-cured which makes it smoother and have been analyzed with 3 different structures. These valves further need to be embedded with electro-responsive materials which can regulate the valve with the pumping action of the heart. Figure 6 exhibits bioinspired heart protheses made using AM [7].

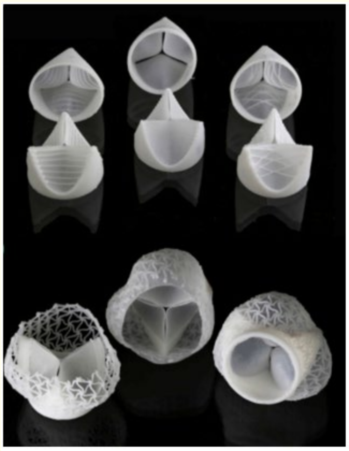

Figure 6: Fabricated Valve Section and Complete Valve of Human Heart Using AM.

Multi-material 3D Printed Soft Actuators Powered by Shape Memory Alloy Wires

Soft Actuators were made using Shape memory alloys as shown in the figure below. These are a combination of soft materials and rigid structure which is wrapped around the SMA wire. These actuators tend to bend through the soft materials and the rigid bodies give it the direction where it should be bending. Figure 7 showcases schematic of an actuator that is based soft multimaterial SMA [8].

Figure 7: Additively Manufactured Soft Multimaterial SMA Based Actuator.

Additive Manufacturing of Ni-Ti Shape Memory Alloys using Pre-mixed Powders

The additive manufacturing was performed on Ni-Ti filament material through investigation on different methods for determining the optimum manufacturing process. Directed energy deposition (DED), selective laser sintering (SLS) and selective electron beam melting (SEBM) were considered and the ratio of Ni-Ti was taken as 1:1 in the form of pre-mixed powder. The optimum printability has been obtained by the DED method. Figure 8 illustrates the various AM processes [9].

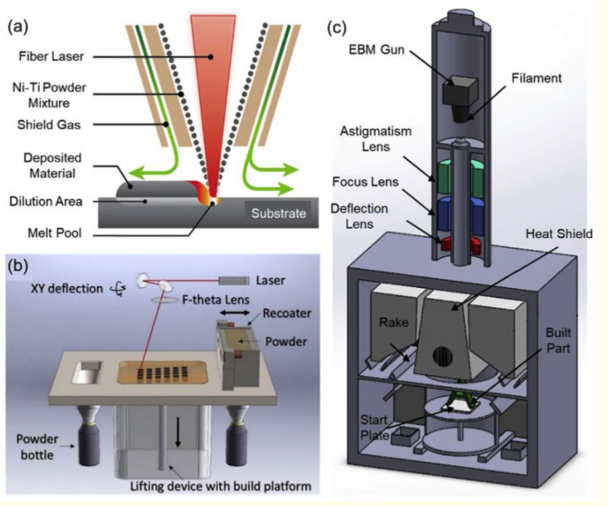

Figure 8: Illustration of AM Processes; (a) DED, (b) SLM & (c) SEBM.

Additively-Manufactured Lightweight Metamaterials for Energy Absorption

Manufacturing of metamaterials has been performed by stereolithography. A complex lattice has been designed to complete the structure by uniformly distributing them. Polymers with this structure tend to be light in weight with a significant amount of strength before a complete catastrophe. Figure 9 showcases the schematic of an AM octet-truss [10].

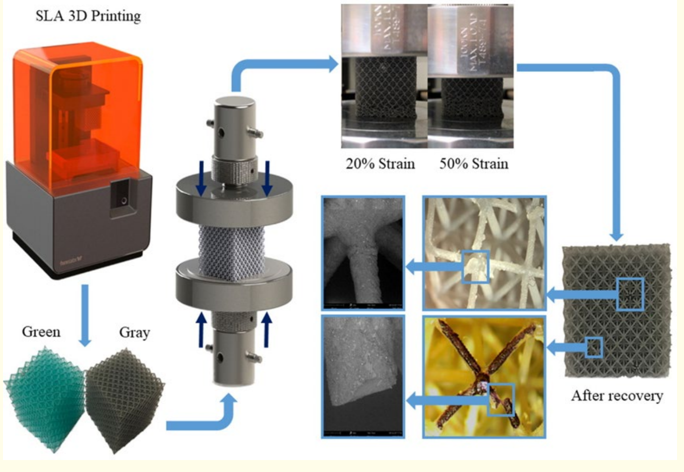

Figure 9: Schematic of AM Process of an Octet-Truss Metamaterial.

Additive Manufacturing of Self-healing Elastomers

Stereolithography process is employed in the manufacturing of self-healing elastomers. These materials tend to react over a temperature of 60°C and form the bond broken between them. Figure 10 displays the application and evaluation of a self-healing elastomer for a shoe sole application [11].

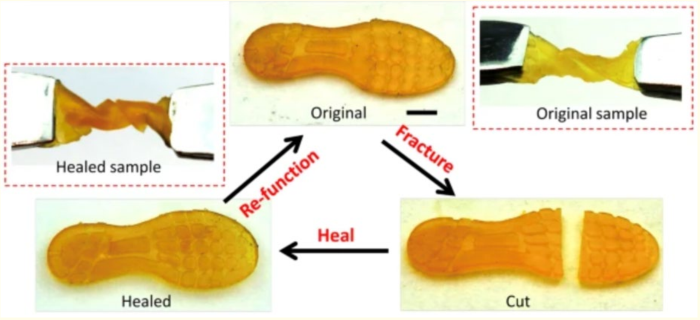

Figure 10: Self-Healing Elastomers.

Research Trends

Nabila Shehata et al. [1] presented an overview of the smart materials, their classification and mechanisms. Smart materials are revolutionizing the current and the future research of the material sciences hence are called as the materials of the next generation.

Julien Gardan et al. [2] classified different types of smart materials with various examples, which have been fabricated with the help of additive manufacturing techniques.

K.R. Ryan et al. [12] has given a comprehensive classification of the smart materials which have been used in additive manufacturing.

Jianwei Song et al. [4] invented super wood, which has been synthesized by making the common wood interact with some chemicals, thereby changing its microstructure and improving the properties significantly.

Kathleen S. Toohey et al. [5] carried out research on 3-D microvascular self-healing materials. Research involved fabrication and testing of these materials for assessing the self-healing properties.

Erfan Rezvani Ghomi et al. [13] presented an overview on the application of additive manufacturing processes in the biomedical industries. The advances have been expressed with help of different examples and how these have affected with respect to the time.

S Kliem et al. [6] designed a complex structure that has been formed using additive manufacturing of wood with different compositions. These smart materials tend to react when exposed to the water and by returning to their original form upon drying of water. This trend difference among the different materials have been observed.

Fergal B. Coulter et al. [7] designed and fabricated a human heart valve. Manufacturing of the valve was performed in an unorthodox manner where additive manufacturing was used to create the whole complex structure with silicone.

Akbari S et al. [8] designed shape memory alloys which were used to create a soft actuator for the robotics application. The developed alloy has an ability to react in a different contour than compared to the conventional actuators which move in a linear or circular direction.

C. Wang et al. [9] performed investigation to understand the printability of different additive manufacturing processes. The Ni-Ti alloy acts as a smart material i.e., shape memory alloy. However, to manufacture it with the help of additive manufacturing has certain drawbacks and concludes with the optimum printability process.

Mehrdad Mohsenizadeh et al. [10] designed a complex lattice metamaterial using additive manufacturing. The metamaterial has significant strength and toughness with relatively less weight as compared with the common materials like steel or aluminum.

Kunhao Yu et al. [11] designed and fabricated self-healing elastomers. These materials regain the bond at the fracture when in contact and the temperature is over 60°C.

Smart materials are being explored further for their applications in various field. Some of the current trends that are noted through literature are given below:

Mechanical Engineering Applications [12]

- Aerospace Components
- Electronic Devices
- Soft Robotics

Biomedical Engineering applications [5].

- Tissue engineering/regenerative medicine.
- Pharmaceutics/drug delivery.
- Artificial organs.

Other Applications [12].

- Smart Clothing.
- Textile.
- Culinary.

Conclusion

The advancement in the material sciences has resulted in the development of Smart Materials. The smart materials open up a huge spectrum of combination of material properties which cannot be obtained by the metrological properties. Hence, the introduction of smart materials to the additive manufacturing processes gives it a major advantage over its drawbacks such as limited time constraints and large-scale production, and also a proclivity can be observed in the bio-medical and industrial applications. The combination of different types smart materials can further optimize the utilization of the product, as the combination of self-healing, shape memory, responsiveness to different sensations can be used to replicate an organ. Hence revolutionizing the organ transplantation in the medical industries.

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Conflict of interest

Authors declare that there are no conflicts of interest.

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