Advance in Shape Memory Polymers for Aerospace Applications

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Abstract. As humanity's exploration of cosmic space becomes more and more in-depth, aerospace technology, as a critical cornerstone supporting this endeavor, is constantly facing new challenges and opportunities. Aerospace engineering has extremely stringent requirements for materials, which require high strength and toughness to withstand extreme environmental conditions, such as high temperature, low temperature, high radiation, etc., and meet the complex needs of lightweight, high reliability, and multi-functional integration. Traditional materials often face many limitations in meeting these requirements, and the emergence of shape memory polymers (SMPs) has provided new ideas and possibilities for the design and application of aerospace materials. As an emerging class of intelligent materials, SMPs, due to their unique shape memory effect, lightweight and high strength, good designability, and other characteristics have gradually demonstrated excellent application potential in several aspects of the aerospace field. Application potential in many aspects of the aerospace field. Based on this, this paper first explains the shape memory effect (SME). Then, SMPs under different actuation conditions are explored, including light, heat, electricity, and magnetic field stimulation conditions. Finally, the paper highlights the application of SMPs in wing deformation structures, space deployable structures, thermal protection systems, etc. This will provide new solutions for the lightweight and multifunctional design of spacecraft.

Keywords: Aerospace Engineering, aeronautical materials, shape memory effect, SMPs.

1. Introduction

With the deepening of human knowledge of the space environment and the increasing complexity of space missions, the requirements for materials have become more and more stringent - not only to withstand the extreme conditions but also to achieve lightweight, high performance and intelligent SMPs, as a class of cutting-edge intelligent materials, are gradually showing their unique charm and huge application potential in the aerospace field. SMPs, as a class of cutting-edge smart materials, are gradually demonstrating their unique charm and great potential for application in the aerospace field, becoming an important force for technological innovation in this field [1].

SMPs can ‘remember’ and recover specific shapes. The action of external stimuli (e.g., temperature, light, electric field, etc.) can transform them from a temporary shape to a predetermined original shape, accompanied by energy storage and release, demonstrating the material's highly controllable and adaptable nature. This characteristic fits the urgent demand for high-performance, lightweight, and multifunctional materials in aerospace engineering [2].

In the aerospace field, shape memory polymers have promising and imaginative applications. They can be used as key materials for space unfoldable structures, such as folding antennas, solar cell sail panels, etc. They can be compactly folded before launching and unfolded to the working state by simple stimulation after arriving at the predetermined orbit, which significantly improves the space utilization rate and the overall performance of the spacecraft. In addition, in the design of variant vehicles, SMPs can automatically adjust the wing shape and skin structure according to the flight conditions to optimize aerodynamic performance and enhance flight efficiency, which provides unlimited possibilities for intelligent flight in the future.

This article aims to provide an in-depth discussion on the current status of shape memory polymers in aerospace applications, the challenges they face, and the future trends.

2. Shape Memory Effect

The characteristics of shape memory materials include the shaped memory effect, which allows these materials to recover their original shape through a stimulus. Also, shaped memory materials have super elasticity and tunable properties, so they can undergo large deformations and adjust their composition and microstructure. Shaped memory materials are usually durable and highly resistant to withstand repeated deformation cycles without failure [1]. This remarkable property is known as the shape memory effect (SME). The SME in SMPs is primarily driven by their molecular structure and the transitions between different phases within the material.

SMPs typically consist of two phases: one is the hard, permanent phase, and the other one is the soft, reversible phase. The permanent phase gives the material its original shape, while the reversible phase allows temporary shape changes. The material becomes soft and pliable when an SMP is heated above its transition temperature. In this state, it can be easily deformed into a temporary shape. The material hardens after cooling below the transition temperature, locking the temporary shape in place.

The shape memory effect is activated by reheating the SMP above its transition temperature. This reheating causes the material to soften and return to its original, permanent shape. The process is reversible, allowing the SMP to undergo multiple cycles of deformation and recovery without significant performance loss [2].

3. Different Types of Stimulus-Response of Shaped Memory Polymers

3.1. Light-responsive SMPs

One kind of stimulation for shaped memory polymers is light, in which when the material receives light, it will return to its original shape. Light-responsive SMPs are intriguing due to their non-contact nature and precise control capabilities. This method leverages the incorporation of photo-sensitive groups or photothermal particles within the polymer matrix.

Photosensitive groups, such as azobenzene or spirogyra, undergo reversible structural changes upon light exposure, typically UV or visible light. These changes can induce mechanical stress or alter the polymer's network, prompting a shape transformation. For instance, azobenzene can switch between trans and cis configurations under UV and visible light, leading to a reversible shape change. This property is advantageous for applications requiring precise spatial and temporal control, such as micro-actuators or optical data storage.

On the other hand, photothermal particles like gold nanoparticles or carbon-based materials absorb light and convert it into heat. This localized heating effect can trigger the shape memory effect in thermo-responsive SMPs. The advantage here is the use of near-infrared (NIR) light, which can penetrate deeper into materials and biological tissues, making it suitable for biomedical applications. For example, Zhang et al. developed light-responsive SMPs by embedding gold nanorods into a polymer matrix [3]. These SMPs exhibited rapid and efficient shape recovery under NIR light due to the photothermal effect of the gold nanorods.

3.2. Thermo-responsive SMPs

Thermo-responsive SMPs are particularly intriguing due to their practical applications in various fields, including biomedical devices, aerospace, and robotics.

Heat-stimulated SMPs possess several advantageous properties. They are highly versatile, allowing easy processing and customization to meet specific needs. These materials typically exhibit excellent shape recovery, mechanical robustness, and durability. One of the primary advantages of heat-stimulated SMPs is their ability to undergo large deformations and recover their original shape with high precision upon heating. This makes them ideal for applications requiring precise actuation and control.

When heat is applied to SMPs, they undergo a phase transition that triggers the shape memory effect. This phase transition usually occurs at a specific temperature known as the transition temperature (T_{trans}). Below T_{trans}, the polymer is in a rigid, glassy state. When heated above Ttrans, it transitions to a rubbery state, allowing the material to recover its original shape. The speed and efficiency of this recovery process can be finely tuned by adjusting the polymer's composition and structure.

For example, Zhang et al. used a method involving incorporating photothermal particles into the polymer matrix to prepare light-responsive SMPs with enhanced performance. These SMPs demonstrated rapid and efficient shape recovery upon light exposure due to the localized heating effect of the photothermal particles [4].

3.3. Electric-responsive SMPs

Electrically stimulated SMPs offer significant advantages, including rapid response times, localized activation, and the ability to be integrated into electronic systems for advanced applications.

One of the primary advantages of electrically stimulated SMPs is their rapid response. When an electric current is applied, the material can quickly heat up due to resistive heating. This localized heating can be precisely controlled, allowing specific areas of the polymer to be activated without affecting the entire structure. This is particularly useful in applications such as actuators, sensors, and biomedical devices where precise control is paramount.

The resulting responses of electrically stimulated SMPs include shape recovery, actuation, and changes in mechanical properties. These responses are highly desirable in various fields, including aerospace, robotics, and medical devices. For instance, in the medical field, SMPs can be used for minimally invasive surgeries where the material can change shape in response to an electric current, allowing for precise interventions.

Zhang et al. used a method involving incorporating azobenzene groups to prepare light-responsive SMPs with excellent shape memory performance. These groups can also respond to electric fields, making them versatile for dual-stimuli applications [5]. On the other hand, photothermal particles, such as carbon nanotubes or metallic nanoparticles, can be embedded within the polymer matrix. These particles absorb electromagnetic radiation and convert it into heat, triggering the shape memory effect. For instance, Liu et al. developed SMPs embedded with gold nanoparticles, which exhibited rapid and efficient shape recovery upon electric stimulation due to the photothermal effect [6].

3.4. Magnetic-responsive SMPs

Magnetic field stimulation of SMPs is an emerging area of research that offers several advantages, such as remote actuation, precise control, and non-invasive triggering.

One of the primary advantages of using magnetic fields to stimulate SMPs is the ability to control the shape recovery process remotely and non-invasively. This is particularly useful in applications where direct contact or other forms of stimulation (like heat or light) are impractical. Magnetic field stimulation also allows for localized heating, which can be precisely controlled to target specific areas of the polymer, leading to more efficient and effective shape recovery.

When exposed to a magnetic field, SMPs embedded with magnetic nanoparticles or other magnetic-responsive elements can generate localized heat through hysteresis losses or inductive heating. This localized heating triggers the shape memory effect, causing the polymer to return to its original shape. The response time and efficiency of the shape recovery process can be fine-tuned by adjusting the magnetic field strength and the concentration of magnetic particles within the polymer matrix.

Zhang et al. used a method to incorporate both photosensitive groups and magnetic nanoparticles into an SMP, achieving dual-responsive performance with enhanced control over shape recovery [7]. Liu et al. developed a magnetic field-responsive SMP by embedding iron oxide nanoparticles, demonstrating rapid and efficient shape recovery under an alternating magnetic field [8]. Li et al. used a solvent-casting method to prepare a magnetic field-responsive SMP by incorporating Fe_3O_4 nanoparticles into a polyurethane matrix. The resulting SMP exhibited excellent shape memory performance, with rapid shape recovery under an alternating magnetic field [9].

4. Applications in Aerospace

4.1. Spatial expandable structure

One of the most promising applications of SMPs in aerospace is using spatial expandable structures. This structure is designed to be compact during launch and transport and expand into full size once the spacecraft is deposed into space. This makes it easy to reduce size and weight and increase capacity.

SMPs have garnered significant attention in aerospace applications due to their unique ability to undergo large deformations and return to their original shape upon exposure to a specific stimulus, such as heat. This property is particularly advantageous for spatially expandable structures in aerospace, where compact storage and reliable deployment are critical.

One of the primary advantages of using SMPs in aerospace is their lightweight nature, which is essential for reducing launch costs and improving fuel efficiency. Additionally, SMPs can be engineered to have high strength and durability, making them suitable for harsh space conditions.

Spatially expandable structures from SMPs can be compactly stowed during the launch phase and deployed once in space. For example, antennas, solar arrays, and other deployable structures can be folded or rolled into a small volume and then expanded to full size. This capability saves space and reduces the complexity and potential failure points of traditional mechanical deployment mechanisms.

Two primary forms of SMPs are used in these applications: those incorporating photosensitive groups and those with photothermal particles. Photosensitive SMPs change shape in response to light, while photothermal SMPs respond to heat generated by light absorption. For instance, researchers have developed SMP composites with embedded carbon nanotubes or graphene, which absorb light and convert it into heat, triggering the shape-memory effect.

A notable example is the work by Liu et al., who used a method involving the incorporation of carbon nanotubes into an SMP matrix to create a light-responsive material with excellent performance. This material demonstrated rapid and reliable deployment when exposed to light, making it ideal for aerospace applications.

In summary, SMPs offer a promising solution for spatially expandable structures in aerospace due to their lightweight, high strength, and reliable shape-memory properties. Their ability to be compactly stowed and then deployed in space makes them an invaluable asset for modern aerospace engineering [10].

4.2. Morphing Wing Structures

One of the primary advantages of morphing wing structures using SMPs is their lightweight nature, which is crucial for aerospace applications. Traditional mechanical systems for wing morphing can be bulky and add significant weight, reducing fuel efficiency. In contrast, SMPs offer a lightweight alternative to achieve the same functionality with less mass. This weight reduction can lead to substantial fuel savings and increased payload capacity.

Moreover, SMPs provide the ability to create seamless and smooth wing surfaces. Traditional mechanical morphing systems often involve complex assemblies that can introduce gaps or discontinuities in the wing surface, negatively impacting aerodynamic efficiency. SMPs, however, can be integrated into the wing structure in a way that maintains a smooth surface, thereby enhancing aerodynamic performance.

The response of SMPs to thermal stimuli is particularly advantageous for aerospace applications. For instance, Lan et al. utilized a thermally activated SMP to create a morphing wing prototype. The wing could change shape in response to temperature variations, allowing real-time adjustments to optimize lift-to-drag ratios during flight phases. This capability is particularly beneficial for improving fuel efficiency and maneuverability [11].

4.3. Deployable Structures

Shaped memory polymers' shaped memory effect is ideal for creating deployable structures that can be compactly stowed during launch and deployed in space or during flight.

One of the primary advantages of using SMPs in deployable aerospace structures is their lightweight nature. Traditional deployable mechanisms often rely on complex mechanical systems that add significant weight and complexity to the spacecraft. In contrast, SMP-based deployable structures are more straightforward, lighter, and can be more easily integrated into the spacecraft's design. This reduction in weight and complexity can lead to cost savings in terms of fuel and launch expenses.

Another significant advantage is the versatility and adaptability of SMPs. They can be engineered to respond to specific stimuli, allowing precise control over the deployment process. For instance, SMPs can activate at a particular temperature, ensuring the structure deploys only when the spacecraft reaches its intended environment. This controlled deployment is crucial for the successful operation of many space missions.

Recent research has demonstrated the practical applications of SMPs in aerospace deployable structures. For example, Lan et al. developed an SMP-based deployable antenna for small satellites. The antenna could be compactly stowed during launch and then deployed in space using thermal activation. The study showed that the SMP antenna exhibited excellent shape recovery performance and reliability, highlighting the potential of SMPs in enhancing the capabilities of small satellite missions [12].

4.4. Thermal Protection Systems

SMPs have shown great promise in aerospace applications, particularly in developing advanced Thermal Protection Systems (TPS). TPS is critical for spacecraft and re-entry vehicles as they protect against the extreme temperatures encountered during atmospheric entry. SMPs offer unique advantages in this context due to their ability to change shape in response to thermal stimuli, enabling adaptive and reconfigurable thermal protection solutions.

One of the key properties of SMPs that make them suitable for TPS is their ability to undergo significant deformation and return to their original shape when exposed to specific temperatures. This property allows SMP-based TPS to adapt to varying thermal loads, providing enhanced protection where and when needed. For instance, during re-entry, certain spacecraft parts may experience higher thermal flux; SMPs can be designed to expand or alter their configuration to provide additional insulation at these critical points.

Recent research by Liu et al. demonstrated the development of a novel SMP-based TPS that can dynamically adjust its thermal conductivity in response to temperature changes. This system uses SMPs embedded with thermally conductive fillers, which reorient themselves at high temperatures to enhance heat dissipation. Such an adaptive system ensures that the spacecraft remains within safe temperature limits, thereby improving the overall safety and reliability of the mission [13].

Additionally, SMPs offer the advantage of being lightweight and having a high strength-to-weight ratio, which is crucial for aerospace applications where every gram counts. Their ability to be processed into complex shapes and structures allows for designing more efficient and effective TPS configurations.

Moreover, the use of SMPs in TPS can lead to cost savings. Traditional TPS materials often require complex manufacturing processes and extensive testing. In contrast, SMPs can be more easily fabricated and tested for specific thermal responses, potentially reducing development time and costs.

5. Conclusion

SMPs have shown significant advantages in the aerospace field, which makes SMPs one of the essential directions in aerospace materials research. SMPs have lower density and higher specific strength, which is necessary to improve the spacecraft's delivery efficiency, extend its service life, and reduce fuel consumption. Secondly, SMPs can recover from temporary shapes to their original shapes under specific external stimuli (e.g., temperature, light, electric field, magnetic field, etc.), which can be used to manufacture deployable structures, variant vehicle components, etc. In addition, SMPs typically have better machinability than conventional aerospace materials, simplifying the production process and reducing manufacturing costs.

Despite the excellent shape memory effect of SMPs, their energy density and shape recovery ability still need to be improved. This limits their performance in aerospace applications that require high energy output and fast shape recovery. Many SMPs have low shape memory transition temperatures (typically less than 150°C) and relatively poor thermal stability. In aerospace, materials need to withstand highly high-temperature environments, which poses a severe challenge to the thermal stability of SMPs. In addition, aerospace environments are complex and variable, including extreme conditions such as radiation, vacuum, microgravity, etc. The long-term stability and performance changes of SMPs in these environments are unclear and require further research and validation.

Future research will be devoted to developing SMPs with higher energy density, better thermal stability, and more robust mechanical properties, which are expected to significantly enhance the comprehensive performance of SMPs through molecular design, compositing strategies, and advanced processing technologies. Meanwhile, research on the performance of SMPs in extreme aerospace environments, including the effects of radiation, vacuum, microgravity, and other conditions on their performance, should be strengthened. In addition, the study of new driving methods can bring more selectivity and possibilities to SMPs. It is believed that continuous research and technological innovation are expected to overcome these limitations and promote the application of SMPs in aerospace to a new level.

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