AEROSPACE APPLICATIONS OF SHAPE MEMORY ALLOYS

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Keywords: *space materials science, shape memory alloys, aerospace applications, smart materials in aerospace, perspective materials, metal alloys*

Abstract: *Shape Memory Alloys (SMAs) are advanced materials with unique properties, such as the shape memory effect and superelasticity, making them highly valuable for aerospace applications. This paper reviews their use in actuators, morphing structures, vibration control, thermal management, and damage detection systems. SMAs improve fuel efficiency, adaptability, and performance in applications like morphing wings and reconfigurable spacecraft. Despite challenges like fatigue and cost, recent advancements are overcoming these limitations. This review highlights SMAs' current roles and future potential in next-generation aerospace systems.*

АЕРОКОСМИЧЕСКИ ПРИЛОЖЕНИЯ НА СПЛАВИ С ПАМЕТ НА ФОРМАТА

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Ключови думи: *космическо материалознание, сплави с памет на формата, аерокосмически приложения, интелигентни материали в аерокосмическото пространство, перспективни материали, метални сплави*

Резюме: *Сплавите с памет на формата (SMAs) са усъвършенствани материали с уникални свойства, като ефект на памет на формата и свръхеластичност, което ги прави много ценни за космически приложения. Тази статия разглежда тяхното използване в задвижващи механизми, преобразуващи структури, контрол на вибрациите, управление на топлината и системи за откриване на повреди. SMA подобряват горивната ефективност, адаптивността и производителността в приложения като трансформиращи се крила и преконфигурируеми космически кораби. Въпреки предизвикателства като умора и разходи, последните постижения преодоляват тези ограничения. Този преглед подчертава настоящите роли и бъдещия потенциал на SMA в аерокосмическите системи от следващо поколение.*

Introduction

Shape Memory Alloys (SMAs) [1] are a class of smart materials that have the unique ability to recover their original shape after being deformed when exposed to specific stimuli, such as temperature changes. These alloys exhibit two remarkable properties: the shape memory effect (SME) and superelasticity, which have made them increasingly attractive in various high-tech industries [2–6]. Among these, the aerospace sector stands out as one of the most promising fields for the application of SMAs due to its stringent demands for lightweight, adaptive, and high-performance materials.

In aerospace engineering, materials are required to withstand extreme conditions, including large temperature variations, high mechanical loads, and long-term fatigue. Traditionally, materials used in aircraft and spacecraft have been optimized for strength, durability, and weight, but the introduction of smart materials like SMAs has opened new possibilities for reconfigurable structures, adaptive systems, and enhanced durability. SMAs provide unique advantages, such as the ability to replace heavier, complex mechanical systems with lightweight, self-actuating components. These capabilities align perfectly with the ongoing push for more fuel-efficient, reliable, and adaptable aerospace technologies.

The purpose of this paper is to explore the diverse applications of SMAs in the aerospace industry [2–4]. By integrating SMAs into aircraft and spacecraft systems, engineers can develop morphing wings, SMA-based actuators, vibration control mechanisms, and thermal management systems that significantly improve the performance, safety, and efficiency of modern aerospace vehicles. While SMAs hold great potential, they also present certain challenges, such as fatigue resistance, temperature sensitivity, and high production costs, which must be addressed for widespread adoption.

This article will first review the fundamental properties and behavior of SMAs, followed by an examination of the specific aerospace applications where these materials have already been implemented or have strong potential for future use. Additionally, the limitations and ongoing advancements in SMA technology will be discussed, along with future research directions to further enhance their integration into aerospace systems. Through this review, we aim to provide a comprehensive understanding of the current and future role of SMAs in aerospace engineering.

The main properties of the shape memory alloys

A Shape Memory Alloy (SMA) is a type of metal alloy that can return to a pre-defined shape after being deformed when exposed to a specific stimulus, usually heat. The main properties of such alloys include:

1. Shape Memory Effect (SME): When the alloy is deformed at a lower temperature, it can "remember" its original shape and revert to that shape when heated above a critical temperature.

2. Superelasticity (or Pseudoelasticity): At certain temperatures, the alloy can undergo large deformations (up to 8-10%) and recover its original shape without the need for heating, due to stress-induced phase transformations (martensitic transformation).

3. Transformation Temperature: Each alloy has a specific temperature at which the transition between the austenitic and martensitic phases occurs. This temperature can be changed by alloying or heat treatment.

4. Corrosion Resistance: Many shape memory alloys, especially nickel-titanium (nitinol), have good anti-corrosion properties, making them suitable for use in aggressive environments.

5. High Strength and Toughness: SMAs have high strength and toughness, allowing them to withstand significant loads.

6. Good Biocompatibility: Some alloys, such as nickel-titanium, have excellent biocompatibility, making them ideal for medical applications such as dentistry and orthopedics.

7. Artisanal processing and forming: Shape memory alloys can be easily processed and formed into various products, which opens up wide possibilities for their application in various industries.

8. Energy Efficiency: In some applications, such as drive mechanisms, SMAs can achieve high efficiency by using thermal energy for activation.

9. Relatively low density: This property makes them attractive for use in the aerospace industry where structural mass is important.

Common SMAs include Nitinol (Nickel-Titanium alloy) and copper-based alloys, and they are used in a variety of applications, such as medical devices (e.g., stents), robotics, consumer products, and aerospace components.

Types of shape memory alloys depending on the composition

Shape Memory Alloys (SMAs) can be classified based on their composition, which defines their properties, phase transformation temperatures, and performance. Here are the main types of SMAs based on their composition:

1. Nickel-Titanium Alloys (Nitinol)

• Composition: Approximately 50% Nickel (Ni) and 50% Titanium (Ti).

• Properties:

- Excellent shape memory effect and superelasticity.
- High fatigue resistance and corrosion resistance.
- Biocompatible, making it ideal for medical applications.

• Applications: Stents, medical implants, orthodontic wires, actuators, and aerospace components.

2. Copper-Based Alloys

• Copper-Aluminum-Nickel (Cu-Al-Ni)

- Composition: Primarily copper, with aluminum (around 11-14%) and nickel (around 3-5%).

- Properties: Moderate shape memory effect, lower cost than Nitinol, but more brittle and less durable.

- Applications: Industrial actuators, couplings, and aerospace components.

• Copper-Zinc-Aluminum (Cu-Zn-Al)

- Composition: Copper and zinc (with aluminum as a stabilizing element).

- Properties: Similar to Cu-Al-Ni but generally more affordable. However, less stable over repeated cycles and more susceptible to fatigue.

- Applications: Thermomechanical devices, actuators, and less critical structural components.

• Copper-Zinc (Cu-Zn)

- Composition: Primarily copper and zinc.

- Properties: Cheaper, with reasonable shape memory properties but inferior fatigue resistance.

- Applications: Often used in research, simple switches, and actuators.

3. Iron-Based Alloys

• Iron-Manganese-Silicon (Fe-Mn-Si)

- Composition: Iron (Fe), with manganese (Mn) and silicon (Si) as key alloying elements.

- Properties: Lower cost, lower shape memory effect, and generally used for applications that require larger, slower changes in shape.

- Applications: Damping systems, pipe couplings, and less demanding structural components.

• Iron-Nickel-Cobalt-Titanium (Fe-Ni-Co-Ti)

- Composition: Iron alloyed with nickel, cobalt, and titanium.

- Properties: Higher strength, moderate shape memory effect, and better temperature performance compared to Fe-Mn-Si.

- Applications: Used where cost efficiency is important, such as in industrial applications and coupling devices.

4. Gold-Cadmium (Au-Cd)

• Composition: Gold (Au) and cadmium (Cd).

• Properties: Exhibits shape memory properties but is not commonly used due to the high cost of gold and toxicity concerns related to cadmium.

• Applications: Limited to research and experimental purposes.

5. Silver-Cadmium (Ag-Cd)

• Composition: Silver (Ag) and cadmium (Cd).

• Properties: Similar to gold-cadmium alloys but more cost-effective. Cadmium toxicity limits widespread application.

• Applications: Primarily used in experimental research.

6. Other Experimental or Specialty Alloys

• Nickel-Iron-Gallium (Ni-Fe-Ga): Research-oriented alloys showing promising magnetic shape memory properties, which are still under development for specific applications like sensors and actuators.

• Titanium-Niobium (Ti-Nb): Investigated for medical applications due to its biocompatibility and lower elastic modulus compared to Nitinol.

Key Differences Based on Composition:

• Nickel-Titanium (Nitinol): Offers the best overall performance in terms of shape memory, superelasticity, and fatigue resistance.

• Copper-Based Alloys: More cost-effective but less durable, with a higher risk of brittleness and lower fatigue resistance.

• Iron-Based Alloys: Lower performance compared to Nitinol but useful for industrial applications where cost and high-temperature performance are priorities.

• Gold/Silver-Cadmium: Mainly for experimental purposes, with limited practical use due to cost and toxicity concerns.

Each composition offers a unique balance of properties suited for different applications, ranging from medical devices to industrial actuators and aerospace components.

Types of SMAs depending on the crystal structure

Shape memory alloys (SMAs) can be classified by their crystal structure type. The main types include:

1. Austenitic alloys:

- These alloys have a face-centered cubic (FCC) or body-centered cubic (BCC) crystal structure at high temperatures (austenite). Upon cooling, they transform into a martensitic phase, which has lower symmetry (usually trigonal or orthogonal).

- Example: nickel-titanium alloys (nitinol), which are composed of nickel and titanium in varying ratios.

2. Martensitic alloys:

- These alloys have a martensitic phase that forms when the austenitic phase is rapidly cooled. Martensite can have different crystal structures, depending on the composition of the alloy. The main types of martensite include trigonal, orthogonal, and monoclinic structures.

- For example, in nickel-titanium alloys, martensite can be trigonal and orthogonal.

3. Iron-based alloys:

- Some iron-containing alloys also exhibit shape memory. In such alloys, martensitic transformation can occur depending on the alloying (e.g., carbon, manganese, or nickel) and the processing conditions.

- Example: iron-nickel alloys.

4. Copper-based alloys:

- Copper can also be used in shape memory alloys. These alloys can exhibit lower transformation temperatures than nickel-titaniums.

- Example: copper-aluminum and copper-zinc.

5. Aluminum-based alloys:

- Some aluminum alloys also have shape memory, although they are less common

Historical development of SMAs

The development of SMAs has a rich history with key milestones:

Early Discoveries (1930s - 1950s) - 1932: The "shape memory" concept emerged when some alloys returned to a set shape upon heating; 1950s: The term "shape memory" became linked to specific alloys like nickel and titanium.

Key Innovations (1960s - 1980s) - 1962: Discovery of nickel-titanium alloy (Nitinol) showing the shape memory effect; 1960s: Research explored various SMA compositions.

Commercialization (1980s - 1990s) - 1980s: SMAs were first used in medical devices; 1990s: Improved processing and expanded applications.

Advancements (2000s - Present) - 2000s: Research enhanced SMA properties; 2010s: Increased use in smart materials, additive manufacturing boosting possibilities.

SMAs' ability to "remember" shapes continues to drive innovations with promising future applications.

Common Shape Memory Alloys Used in Aerospace [2–4]

Nickel-Titanium (Nitinol):

• Primary Material: Nitinol, an alloy of nickel and titanium, is the most widely used shape memory alloy in aerospace applications due to its superior properties. It exhibits both shape memory effect and superelasticity, making it ideal for components requiring flexibility, precision, and durability. Its high fatigue resistance allows it to withstand repeated cycling without significant loss in performance, and its biocompatibility makes it suitable for use in medical applications, although its primary value in aerospace lies in its mechanical properties.

• Key Applications: Nitinol is commonly used in actuators, where the shape memory effect is harnessed to create motion when the material is heated. Actuators based on Nitinol are used for deploying spacecraft components like antennas and solar panels. Nitinol is also employed in fasteners that self-tighten when heated, ensuring secure connections in critical aerospace systems. Another innovative application of Nitinol is in morphing structures, such as adaptive wing surfaces or control surfaces that change shape in flight to optimize aerodynamics.

Copper-Based Alloys:

• Cu-Al-Ni and Cu-Zn-Al Alloys: Copper-based shape memory alloys, such as Cu-Al-Ni and Cu-Zn-Al, offer a more cost-effective alternative to Nitinol. These alloys are capable of exhibiting the shape memory effect but generally have lower fatigue resistance and are less durable compared to Nitinol. However, their affordability makes them suitable for specific applications where high fatigue life is not critical.

• Aerospace Applications: While copper-based SMAs are not as widely used in aerospace as Nitinol, they are applied in areas where cost efficiency is a priority. These alloys have been considered for use in non-critical components, such as brackets, damping devices, and temperature-triggered mechanisms, where the shape memory effect can be exploited without the need for the superior fatigue properties of Nitinol.

Other Experimental SMAs:

• Iron-Based SMAs: Fe-based SMAs are gaining interest due to their low cost and potential to withstand higher temperatures compared to nickel-titanium alloys. Although they have lower recoverable strain and exhibit reduced shape memory properties, they could be suitable for applications where cost and temperature resistance are more important than elasticity. Research is ongoing to enhance their performance and durability in aerospace contexts.

• Magnetic Shape Memory Alloys (MSMAs): Novel magnetic SMAs, such as Ni-Mn-Ga, are being explored for their ability to change shape in response to a magnetic field rather than heat. These materials are still in the experimental phase but could offer new possibilities for aerospace applications, especially in sensor and actuator systems where rapid, controlled shape change is needed without thermal activation. MSMAs show promise in reducing the reliance on complex mechanical systems by offering precise, responsive motion control through magnetic actuation.

Aerospace Applications of Shape Memory Alloys

1. Actuators (see Fig. 1)

• Role of SMAs in Actuation: Shape Memory Alloys (SMAs) play a crucial role in actuation systems for deploying and controlling various aerospace components. When subjected to a temperature change, SMAs contract or expand, enabling precise mechanical movement. These materials are used in landing gear systems, wing flaps, and morphing wings, where they help enhance flight performance and operational efficiency. For example, in morphing wings, SMAs adjust the wing shape during flight to improve aerodynamics and fuel efficiency.

• Case Studies: One notable application of SMA-based actuators is in satellites, where they are used for deploying antennas and solar panels. SMA actuators, due to their lightweight and reliable performance, are essential for space applications. Another example is their use in military aircraft, where SMAs help adjust control surfaces in real time.

Fig. 1. Illustration of a SMA actuator used in aerospace applications.
The image highlights its internal structure and components in a futuristic aerospace setting (made by AI)

2. Fasteners and Couplings

• Self-Tightening Fasteners: SMAs are used in aerospace as self-tightening fasteners that can adapt to temperature changes. Upon heating, SMA fasteners tighten, ensuring secure connections, which is especially useful in high-vibration environments like aircraft engines or wings. These fasteners not only improve reliability but also simplify assembly and disassembly, reducing the need for manual intervention during maintenance.

• Vibration Reduction: SMA couplings can reduce vibration in critical components, contributing to the overall stability of the aircraft structure. These couplings adjust to dynamic loads, helping to extend the lifespan of parts and minimizing wear and tear.

3. Vibration Damping and Noise Reduction

• Vibration Damping: SMAs are effective in damping vibrations and reducing noise in aerospace systems, which is crucial for maintaining the stability and durability of aircraft structures. SMAs work by absorbing and dissipating mechanical energy through the phase transformation between martensite and austenite.

• Examples: In landing gear systems, SMAs reduce vibrations during takeoff and landing, enhancing comfort and structural integrity. Similarly, in engine components, SMA-based damping systems help minimize harmful vibrations caused by high-speed rotating machinery, improving operational performance and extending the life of the components.

4. Morphing Aircraft Structures

• Adaptive or Morphing Wings: One of the most exciting applications of SMAs in aerospace is in morphing aircraft structures, where SMAs are used to change the shape of wings or control surfaces during flight. These adaptive systems help optimize aerodynamic performance, allowing aircraft to adjust to different flight conditions (e.g., cruise, takeoff, landing) without relying on complex mechanical actuators.

• Future Prospects: The potential of SMAs in fully adaptive aerospace designs is vast. Future aircraft may feature entirely morphing structures that can change shape on demand, improving fuel efficiency, speed, and maneuverability. SMAs offer a lightweight, energy-efficient solution to achieving such adaptability.

5. Spacecraft and Satellite Applications

• Deployment of Components: In space systems, SMAs are critical for deploying antennas, solar arrays, and heat shields. Their ability to generate motion through simple thermal activation makes them ideal for applications where reducing weight and complexity is a priority. Since space systems often require minimal manual intervention, SMAs are perfect for autonomous deployment mechanisms.

• Minimizing Weight and Complexity: By replacing traditional motors and actuators with SMA-based systems, space missions benefit from reduced weight and improved reliability. This not only minimizes launch costs but also simplifies the design and operation of space vehicles. SMAs also contribute to the structural integrity of heat shields and other essential components, ensuring protection during re-entry or other critical phases of spaceflight.

SMAs offer innovative solutions across a wide range of aerospace applications, improving efficiency, performance, and reducing system complexity. Their unique properties make them indispensable for future developments in adaptive and smart aerospace technologies.

While SMAs offer remarkable benefits for aerospace applications, they face challenges related to cost, long-term durability, temperature sensitivity, and manufacturing difficulties. Addressing these limitations is essential for expanding the role of SMAs in future aerospace innovations.

Future trends in SMAs for aerospace include the development of advanced materials with superior performance, the integration of SMAs into smart systems, the use of 3D printing for customized components, and the potential creation of fully adaptive aircraft. These innovations hold the promise of transforming aerospace designs, making them more efficient, responsive, and adaptive to changing conditions.

Conclusions

Shape Memory Alloys (SMAs) are valuable in aerospace due to their ability to change shape with temperature variations. They are utilized in actuators, fasteners, vibration damping systems, morphing structures, and spacecraft mechanisms, providing advantages like reduced system complexity and improved reliability. However, challenges such as high costs, temperature sensitivity, and long-term durability need to be addressed for broader adoption.

The role of SMAs in aerospace is expected to grow as advancements in materials and manufacturing improve performance and affordability. New alloys with better fatigue resistance and temperature stability will address current limitations, while integrating SMAs into smart systems will enable adaptive aircraft designs. Additive manufacturing allows for the customization of SMA components, enhancing their utility in aerospace sectors.

Ongoing research focuses on improving material properties such as fatigue strength and temperature control, as well as innovative integration methods for complex aerospace systems. Key focus is on optimizing performance in extreme conditions, as well as exploring fully adaptive aircraft and spacecraft equipped with SMA technology. Further investment will enable the transformative potential of SMA to be exploited in aerospace engineering.

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