Review Article

BIOMEDICAL
Journal of Scientific & Technical Research

ISSN: 2574 -1241

DOI: 10.26717/BJSTR.2025.63.009948

Advances in Shape Memory Alloy Applications for High-Performance Aerospace and Defence Systems

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ARTICLE INFO

Received: October 23, 2025

Published: November 07, 2025

Citation: Vedant Utikar. Advances in Shape Memory Alloy Applications for High- Performance Aerospace and Defence Systems. Biomed J Sci & Tech Res 63(5)-2025. BJSTR. MS.ID.009948.

ABSTRACT

Abbreviations: SMAs: Shape Memory Alloys; SME: Shape Memory Effect; SE: Super Elasticity; NiTi: Nickel–Titanium; HTSMAs: High-Temperature SMAs; UAVs: Unmanned Aerial Vehicles; FRPs: Fiber-Reinforced Polymers;

Introduction

Shape Memory Alloys (SMAs) are a class of advanced functional materials capable of recovering their original shape upon heating or mechanical unloading after deformation. This unique shape memory effect (SME) and super elasticity (SE) arise from reversible solid-state phase transformations between the martensitic and austenitic phases [1,2]. Among various smart materials, SMAs are particularly attractive to the aerospace and defence industries, where demands for lightweight, adaptive, and multifunctional components are increasing. The aerospace sector seeks materials that can reduce system complexity while enhancing performance and reliability in harsh environments [3]. Similarly, the defence industry values materials that enable adaptive structures, self-healing capabilities, and high resilience under extreme conditions [4]. This review summarizes SMA fundamentals, key material systems, and their aerospace and defence applications, emphasizing technological challenges and research trends.

Fundamentals of Shape Memory Alloys

Composition and Types

The most widely used SMAs are Nickel–Titanium (NiTi) alloys, or Nitinol, known for their exceptional mechanical strength and repeatable transformation behavior [5]. Other systems include Cu-based (Cu–Zn–Al, Cu–Al–Ni) and Fe-based SMAs, which are less costly but have limited cyclic stability [6] (Figure 1). More recently, high-temperature SMAs (HTSMAs) such as NiTiHf, NiTiPt, and TiPd have been developed for aerospace environments exceeding 200°C [7].

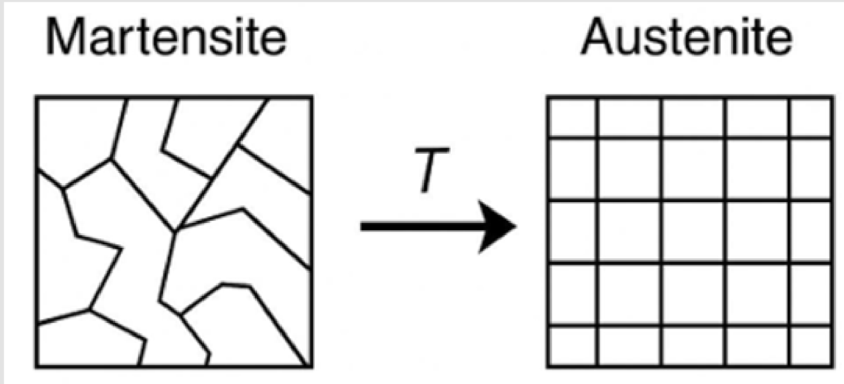

Figure 1: Schematic representation of phase transformation between martensite and austenite in NiTi alloy.

Mechanisms of Action

SMAs exhibit a martensitic phase transformation, a diffusion less rearrangement of atoms that changes crystal structure without altering chemical composition [1]. Heating or cooling triggers transformation between the high-symmetry austenite and low-symmetry martensite phases. This transformation underlies the shape memory effect, while stress-induced transformations yield super elasticity [8].

Thermomechanical Properties

Key parameters include transformation temperatures (Ms, Mf, As, Af), hysteresis width, and cyclic stability. NiTi SMAs show strain recovery up to 8% and excellent damping capacity [9]. Compared with traditional aerospace materials (e.g., Ti–6Al–4V), SMAs offer active adaptability in addition to mechanical strength.

Aerospace Applications

Actuation Systems

SMAs act as compact actuators replacing bulky hydraulic systems. Their silent operation, high power density, and simplicity make them ideal for morphing wings, variable geometry inlets, and adaptive control surfaces [10,11]. NASA's "SMA-based morphing aircraft" project demonstrated NiTi actuators for aerodynamic control [12].

Vibration Damping and Noise Reduction

SMA's damping capability allows suppression of structural vibrations in aircraft fuselages and engine mounts [13]. Embedding SMA wires within composites enhances fatigue resistance and vibration control, improving comfort and extending service life [14].

Coupling, Sealing, and Fastening Devices

SMA couplers are used for self-locking joints and fuel-line connectors, maintaining tight seals despite temperature fluctuations [15]. They enable remote, maintenance-free operation in spacecraft and satellites.

Space Applications

In space systems, SMAs are deployed in antenna mechanisms, solar arrays, and deployable booms due to their reliability and lubrication-free actuation [16,17]. They are also used in thermal control systems for adaptive temperature regulation.

Defence Applications

Smart Structures and Armor Systems

SMAs contribute to self-healing armor and impact-absorbing composites. Integrating SMA wires into protective structures enhances energy dissipation and post-impact recovery [18].

Adaptive Munitions and Guidance Systems

SMA actuators are integrated into missile guidance fins, adaptive triggers, and precision-guided weapons due to their high actuation force and small form factor [19,20].

UAVs and Stealth Technology

In unmanned aerial vehicles (UAVs), SMAs enable morphing surfaces that optimize aerodynamic efficiency and radar signature [21]. Adaptive skins with embedded SMA wires maintain surface smoothness and reduce radar reflectivity [22].

Reliability in Harsh Environments

Military and aerospace systems require high reliability under extreme vibration and temperature. SMAs maintain mechanical performance under these conditions, though cyclic fatigue remains a limitation [23].

Challenges and Limitations

Despite their advantages, SMAs face key barriers:

- **Fatigue and Cyclic Degradation:** Microstructural fatigue limits long-term reliability [24].

DOI: 10.26717/BJSTR.2025.63.009948

- **Slow thermal Response:** Thermal actuation can be slower than electromagnetic systems [25].
- **Manufacturing Precision:** Alloy composition and processing control are critical for consistent transformation behavior [26].
- **Control Complexity:** SMA actuation is nonlinear and temperature-dependent [27].
- **Cost and Scalability:** NiTi remains costly for large aerospace applications [28].

Emerging Trends and Future Prospects

High-Temperature SMAs

New NiTiHf, NiTiPt, and TiPd-based alloys exhibit stable transformations up to 400°C, making them suitable for jet engines and hypersonic vehicles [7,29].

Hybrid and Composite Systems

Integration of SMAs with fiber-reinforced polymers (FRPs) creates adaptive materials combining strength, damping, and actuation [30].

Integration with Smart Control Systems

Combining SMAs with sensors, microcontrollers, and AI-based feedback systems enables intelligent morphing and self-correcting structures [31].

Sustainability and Lifecycle Considerations

Efforts toward recyclable SMA alloys and eco-efficient manufacturing are ongoing to reduce the environmental footprint of aerospace and defence systems [32].

Conclusion

Shape Memory Alloys represent a transformative material platform for aerospace and defence innovation. Their combination of lightweight actuation, adaptability, and multifunctionality enables new design paradigms for morphing structures, vibration control, and adaptive mechanisms. However, progress is needed in fatigue life, response speed, and cost reduction to achieve full-scale deployment. Continued advancements in high-temperature alloys, hybrid composites, and intelligent control integration will position SMAs as key enablers of next-generation adaptive aerospace and defence technologies.

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ISSN: 2574-1241

DOI: 10.26717/BJSTR.2025.63.009948

Vedant Utikar. Biomed J Sci & Tech Res