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Advancements and Future Directions of Shape Memory Alloys in Aerospace Applications-A Comprehensive Review

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Abstract: This paper focuses on applications of shape memory alloys (SMAs) to deal with complex engineering problems. They come under the category of shape memory materials (SMMs). They can regain their original shape by heating above a specific critical temperature (shape memory effect), and they depict complete recovery of plastic strain induced by removing the applied stress under isothermal conditions (Superelasticity). This article presents a review of SMAs applications in the aerospace field highlighting wing morphing, variable geometry chevrons, smart wheels, rock splitters for space missions, variable area nozzles, and vortex generators. In the beginning, a general overview of SMAs is provided which includes the history of SMA development, general characteristics, and fabrication of SMAs. Subsequently, the design aspects of SMAs are discussed, along with the examination of diverse types of SMMs such as SMAs, SMPs, HTSMAs, and thin film SMAs. The deduced findings depict the significance of SMAs as smart materials. The transformation temperature for Shape memory alloys like NiTi goes up to about 100 °C and actuation stresses well beyond 200 MPa, thus rendering them suitable for aerospace components. Lightweight SMA-based actuation systems can even reduce the cost by 2-3%. The challenges related to the high weight associated with wing morphing technology can also be addressed. This review synthesizes data from some 150 papers and attempts to map emerging trends, along with the existing research gaps, which might provide a direction for future SMA applications in aerospace systems. Through further rigorous research, these SMAs have the potential to address the challenges posed by complex engineering scenarios.

Keywords: Nitinol; Shape memory alloys; Smart materials; variable geometry chevrons; wing morphing

1. Introduction

Shape memory alloys (SMAs) are subcategory of shape memory materials (SMMs) that are classified as smart materials [1-4]. They were discovered by Arne Olander, a Swedish metallurgist at a meeting of the Swedish Metallurgical Society on 27 May 1932 [2),5-,8)]. He observed the rubber-like behavior of gold-cadmium alloy [5),8)]. They can regain their original shape while heating up to a critical temperature or any external stimulus even under changing load conditions (SME) and they depict complete recovery of plastic strain induced by removing the applied stress under isothermal conditions (Super elasticity) [1),9),10)]. SMAs exist in two distinct phases namely, Austenite and Martensite. These phases consist of three different crystal structures-twinned Martensite, deformed Martensite, and Austenite as illustrated in [2),7),11),12)]. Perhaps the discovery of SMA was in 1932 they were not very popular until the discovery of equiatomic NiTi alloy [2),10)]. They gained popularity due to their exceptional properties like biocompatibility, corrosion resistance, high specific actuation stress, high electrical resistivity, and many more [13)].

The aerospace industry is actively pursuing the development of new SMA technologies as well as the assimilation of SMAs into existing systems. The initial application of SMAs dates back to 1970 when they were utilized as hydraulic tubing couplings for the F-14 fighter jet. The attention on SMAs is increasing because of their

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ability to perform multiple functions by a single component [14]. The effective use of SMAs in the aviation sector can significantly improve aerodynamic performance and contribute to cost savings. Key features of SMAs are resolving constant issues in the aviation industry in terms of vibration suppressing, noise reduction, morphing wing structures, and thermal actuation without having to utilize complicated hydraulic systems. They serve to provide optimum aerodynamic characteristics and reduction in mechanical intricacy, which ultimately leads to greater fuel efficiency. Now days aerospace systems, a huge range of advanced materials are employed, having to comply with performance, thermal, or weight constraints. These ranges from PCMs for thermal control, super alloys against high temperature resistance, composites for light weight structures, and smart materials for adaptive functions. SMAs are among these possess unique thermo-mechanical properties rendering their use possible for multifunctional aerospace parts.

This work is organized in the following way: the introductory section provides a general introduction to the topic. Section 2 provides a general description of SMA and their governing effects, history of development, characteristics, and various methods of fabrication. A review of the design feasibility of SMAs is presented in section 3. In section 4, the various types of SMMs available are reviewed; giving special attention to high temperature shape memory alloys (HTSMAs). Several applications of SMA in the aerospace industry are reviewed in section 5, which includes wing morphing, variable geometry chevrons, vortex generators, variable area nozzle, rock splitter, and tires for extra-terrestrial missions and on UAVs. Section 6 describes the opportunities and future trends in SMAs along with the challenges associated with them. A summary of the main conclusions is in section 7. Section 8 contains the recommendations of the authors. Finally, section 9 contains the conclusions.

1.1. Motivation and Contribution behind the study

The motivation behind the study was the emerging importance of materials in the aviation industry as they contribute to the structural integrity, weight optimization, and overall efficiency of aircraft. They can become a significant part of achieving the aim of sustainable aviation by reducing fuel consumption. Thus, authors found that this agenda can be addressed by using SMAs. They have the potential to eliminate the usage of bulky and complex hydraulic mechanisms with a single SMA component, functioning as a machine. This innovation not only lowers the overall aircraft weight but also supports fuel efficiency, aligning with the broader goals of sustainable aviation practices.

This paper contributes to the existing body of knowledge on SMAs by synthesizing current research and providing a comprehensive overview of the field. Authors have systematically analyzed recent developments and emerging trends in SMA research, offering a critical evaluation of the literature. The article begins with a concise exploration of SMAs, delving into their fundamental characteristics. Subsequently, it underlines the application of SMAs within the aviation sector, specifically addressing their role in wing morphing, variable geometry chevrons, smart wheels, rock splitters designed for space missions, and vortex generators. This comprehensive article showcases the pivotal role of SMAs in shaping the trajectory of the aviation industry.

1.2. Methodology

This was undertaken to agree on a systematic and holistic literature review approach. Peer-reviewed articles, conference papers, technical reports, and patents associated with shape memory alloys (SMAs) were retrieved from major databases, including ScienceDirect, Scopus, Web of Science, IEEE Xplore, and Google Scholar.

Keywords such as "shape memory alloys," "smart materials," "aerospace applications," "NiTi," "morphing structures," and "SMA actuators" were used to search literature. Filters were implemented to give preference to recent developments between 2010 and 2024 while not neglecting some of the pivotal studies.

More than 150 primary sources have been reviewed. Publications that discuss SMA properties, design approaches, fabrication methods, and applications in aerospace systems were considered. Studies with experimental data are more acceptable, so an example would consist of case studies, such as those of NASA and Boeing projects, and technological innovations. This approach tries to meet the literature criteria and ensure that both old and new research related to aerospace-relevant SMA development is included.

2. Overview of Shape Memory Alloys

The historical development of SMAs is explained in this section along with their fundamental functional properties: pseudoelasticity and the shape memory effect. Key material characteristics and common manufacturing techniques associated with SMAs also are discussed.

2.1. History of SMA development

During the discovery of SMAs Olander observed the rubber-like behavior of gold-cadmium alloy [5),8]. After that SME was observed in copper-tin (Cu-Sn) and copper-zinc (Cu-Zn) alloy systems. The breakthrough in SMAs came with the identification of nickel and titanium alloys by William Buehler and Frederick Wang in the 1960s at the U.S. Naval Ordnance Laboratory, popularly recognized as Nitinol [5-7),15-17]. They contain nearly equal percentages of

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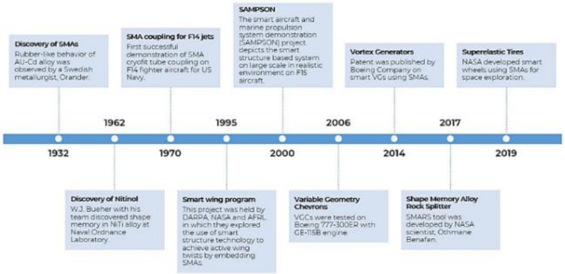

Fig. 1: Milestones of SMAs and their application in the aerospace industry

nickel and titanium [16] They are much more popular as compared to other SMAs because they possess excellent mechanical properties [18],[19],[20], corrosion resistant and biocompatible [18],[20-25] which makes them ideal for many applications such as stents, guide wires, antennae for mobile phones and aerospace applications which includes variable geometry chevrons, wing morphing, and many more [9],[10],[12]. On the first commercial application of SMA in 1970, they were used as hydraulic tubing coupling for F-14 fighter jets [16],[26],[27]. Several projects are being conducted by different organizations namely NASA (National Aeronautics and Space Administration), DARPA (Defense Advanced Research Projects Agency), and Boeing [2],[10],[12],[28]. Smart Wing Program and Smart and Aircraft and Marine Propulsion System Demonstration (SAMPSON) are well-known projects recognized by DARPA [10],[27],[29]. NASA and Boeing have issued several patents about the utilization of SMAs which include variable geometry chevrons, deployable vortex generators, shape memory alloy rock splitters (SMARS), and Superelastic tires [30],[31],[32]. Figure 1 depicts an overview of landmark events on the axis of time, related to SMA implementation in aerospace sciences.

2.2. Shape memory effect and pseudoelasticity

SMAs exist in two distinct phases namely, Austenite and Martensite. These phases incorporate three different crystal structures-twinned Martensite, Detwinned Martensite, and Austenite as illustrated in Figure 2 [12]. The martensite crystalline structure is stable at low temperature, and the austenite crystalline structure is stable at higher temperatures [2].

When a SMA is subjected to heat, it starts to transform from martensite to austenite phase. The temperature at which transformation starts is called as austenite-start-temperature (A_s) and the temperature where transformation finishes is known as austenite-finish-temperature (A_f). Beyond the A_s temperature, the SMA begins to contract and reverts into its original form. During the cooling procedure, the austenite converts into martensite phase at martensite-start-temperature (M_s) and concludes upon reaching

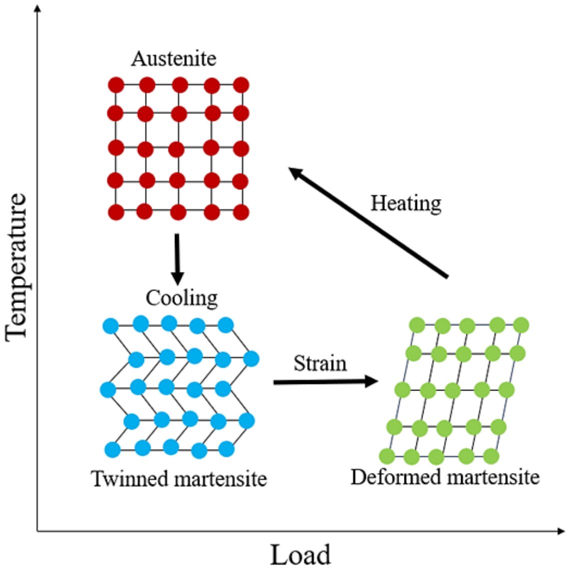

Fig. 2: Phase transformation in SMAs

martensite-finish-temperature (M_f). Upon inducing stress beyond a certain limit in martensite phase, the component will be permanently deformed similar to any usual metallic material.

Shape memory effect (SME) and pseudoelasticity occur due to these solid-to-solid phase transformation [21],[28],[33-36]. The phenomenon of complete restoration of plastic mechanical strain by unloading, heating, or cooling is known as the shape memory effect as illustrated in Figure 3 [12],[28],[37]. There are two types of SME: One-Way Shape Memory Effect (OWSME) and Two-Way Shape Memory Effect (TWSME) [34],[36],[37],[38]. OWSME is when a sample that has transformed to martensite during cooling, without deformation, is subjected to deformation in the martensitic phase. Subsequently, it is reheated into the austenitic phase, leading to a reversion to its initial shape and orientation [3],[6],[17],[38]. TWSME occurs without any need for external stress. The sample undergoes forward and reverse transformations upon heating and cooling cycles [17],[36],[38].

Superelasticity (SE) or pseudoelasticity is the complete recovery of plastic strain induced due to phase transformation by simply removing the applied stress under isothermal conditions as depicted in Figure 3 [21],[39],[40]. SMAs show a huge superelasticity of approximately 8% [20],[40],[41].

Both SME and pseudoelasticity processes present a special characteristic plateau phase in their stress–strain curve. In pseudoelasticity, the plateau is associated with the stress-induced martensitic transformation and arises from the nearly constant stress experienced by the specimen while recovering large strains. Both the shape and width of the plateau vary mainly with the alloying composition and the temperature of operation.

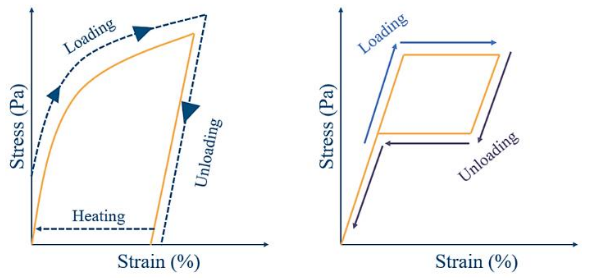

Fig. 3: SMA stress–strain behavior (i) The shape memory effect (ii) The pseudoelastic effect

2.3. Properties of SMA

SMA are divided into various categories such as iron-based SMAs which are used for pipe joints and fishplates for crane rails, copper-based (Cu-Sn, Cu-Al, Cu-Zn) SMAs possess higher actuation temperatures, thus they are used in automotive, robotics, and industrial applications and NiTi based SMAs 7),36). According to experimental results, CuAlMn SMA is suitable for cryogenic actuation and Super elastic applications 42). Similarly, the selection of the appropriate type of SMA can be based on the specific application requirements.

SMAs can also be used by embedding composites to provide post-impact resistance 41). Other properties of SMAs include wear resistance, damping properties, and many more, all compiled in Table 1.

Table 1: Compilation of properties of SMA as discussed by various researchers worldwide

Reference	Properties	Major Observations
1),10), 38), 43)	Weight reduction	The application of SMA components eliminates the need for the requirement of bulky hydraulic or electromechanical systems which help in weight reduction.
35),37),38),43),44),45),46)	Damping properties	SMAs can be used as acoustic liners to dampen engine noise, can be used as fuel line clamps to reduce fatigue damage, and in flutter control of fan blades. They can also be used as vibrational damping systems for UAVs.
20- 24),38)	Corrosion Resistant	This nature of SMA finds extensive use in the biomedical field, where it is employed in various applications such as guide wires and stents. The subcategory known as HTSMAs exhibits an elevated level of corrosion resistance, enabling their functionality in high-temperature and high-pressure conditions.
22),25),34),39),47)	Shape memory effect	SME is the ability of a material to “remember” its original position under the application of certain stimuli and this property is utilized for manufacturing actuators, wing morphing technology, and many more.
29),34),35),47)	Superelasticity	Superelasticity finds applications where increased elasticity under load conditions is necessary.
18),19),23)	Wear-resistant	Wear-resistant properties of SMAs are due to Superelastic behavior, shape memory effect, energy absorption property, low transformation stress, and higher recoverable strain.
6),10),17),48)	High power-to-weight ratio	With the integration of SMAs into actuators and structures, compact design configurations with improved reliability can be achieved.
1),10),11),49)	Fatigue	The phenomenon of functional fatigue is observed in cycling applications.
37),39),41),50),51)	Hysteresis	The hysteresis loop emerges through cyclical transformations of the martensitic state at varying temperatures.
18),21),23),25)	Biocompatible	NiTi alloy exhibits exceptional biocompatibility, making it suitable for numerous biomedical applications, including cardiovascular stents orthopedic implants, and surgical tools and instruments.

[25]	Resistant to oxidation	NiTi alloy possesses high oxidation resistance.
[48]	Silent operation	This property is used in making SMA-based actuators.
[48]	Flexibility in design integration	SMA-based actuators offer a wide range of design possibilities.
[12,18,21]	Energy dissipation	SMAs exhibit a high capacity for energy dissipation. However, the gradual microstructure changes caused by fatigue lead to a deterioration of this property.
[16]	Non-toxic	NiTi-based SMAs are non-toxic.
[10]	Reduced power consumption	Applications of SMA on various components lead to a reduction in power consumption.

2.4. Manufacturing of SMA

The chemical composition while making SMA is of utmost importance. Deviation from the required level of composition results in the deterioration of the properties of the alloy [52]. Another important consideration is in the temperature range of martensitic transformations temperature [26]. Active titanium and sensitive mechanical properties of shape memory materials make production difficult [53]. Despite using the latest fabrication methods, ensuring microstructure homogeneity, and preventing secondary phase transformation is still a significant challenge. This limitation can be overcome by using in-situ heat treatment methods [53]. Heat treatment processes like annealing are essential to reach microstructure homogeneity which affects physical and chemical properties [54]. Even the slightest change in the machining time can significantly alter the final part [55]. Electric discharge machining, electrochemical machining, and laser manufacturing are generally used for the machining of SMAs [3,7].

2.4.1. Additive manufacturing

Additive manufacturing (AM), which is popularly known as 3D printing is widely used in the production of SMAs [25,56]. It consists of various fabrication technologies, categorized by parameters such as allowable build volume, type of energy source, etc. [25]. It provides design flexibility, less wastage of raw materials, and is environmentally friendly as no harmful gases are released and parts produced are near net shape which means little to no machining is required [26]. Laser-engineered net shaping (LENS) technique can also be used to manufacture nitinol. The mixture of nickel and titanium powders is supplied through nozzles to laser focus [26]. The final products depict improved properties over classical nitinol [26]. The selective laser melting (SLM) method uses a high-powered laser beam to melt and fuse various metallic powders [57]. The final product formed is porous [7]. It is observed that SLM-produced nitinol possesses a broad temperature range for phase transformation and oxide formation can also be avoided [7].

2.4.2. Powder Metallurgy

Powder metallurgy is used to reduce the issues associated with casting, such as segregation or extensive grain growth. This method provides better control over chemical composition [58]. It avoids the need for thermos-mechanical treatment [59] However, this method often leads to chemical segregation, contamination, unsatisfactory functional properties, and porosity [53].

2.4.3. Spark plasma sintering

It comes under powder processing methods under metallurgy [60] used to produce lightweight porous SMAs with low density, clear SME, and adequate mechanical properties [61]. The method involves, mixing metallic powders to form the required stoichiometry composition by direct mixing or mechanical alloying. Heat is supplied to sinter the compacted powder at a temperature below the alloy melting point, ensuring metallurgical bonding between the powder particles [60].

2.4.4. Sputter Deposition

It is a widely used physical vapor deposition used to deposit thin films on substrates [62,63]. Direct current sputter deposition is mostly used for creating thin films of nitinol. This method allows the production of thin films with transformation temperature from 173K to 373K [64]. Nitinol-based micro-electro-mechanical systems are produced by this method [9]. The schematic of sputter deposition is shown in Figure 4.

3. Designing with SMAs

Since the discovery of SMAs, extensive research has been conducted, leading to the creation of some prototypes. However, only a handful of these prototypes have transitioned into real-world applications. Therefore, further rigorous research is imperative to realize sustainable aviation through the utilization of SMAs. The parameters that are considered while designing any SMA component are the operating temperature range, transformation temperature, microstructure, thermal conductivity, chemical conductivity, force required, required speed, and stroke required [2].

3.1. SMA design advantages

Integration of SMA components offers huge benefits.

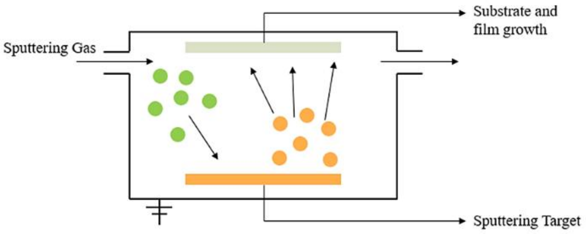

Fig. 4: Schematic of sputter deposition

These are jotted below:

- Designing with SMAs paves the way for simplified designs.
- Reduction in usage of material.
- Less manufacturing complexity.
- Sufficient actuation stress [1),21)]
- Due to their ability to actuate in a three-dimensional manner, SMAs can be employed in situations requiring deformations such as extension, bending, twisting, or a combination thereof [2),29)]

It can reduce the weight of the aircraft by replacing the bulky mechanisms and thus reducing the fuel consumption which further reduces the CO_2 and NOx emissions [66)]

3.2. SMA design challenges

Challenges in designing SMAs include the complexity of heat transfer into and out of SMA components. This complexity arises from characteristics such as high density, conductivity, and heat capacity, leading to a restricted response frequency in the system [29)]. Fatigue is a major concern in the aerospace industry. Experimental results on nitinol wire show that these components can be used for approximately 10,000 cycles and after that, they undergo a 2% transformation strain [29)].

In the first place, SMA design is a very sophisticated task and often requires computational modeling, for example, FEA, to simulate thermal and mechanical behavior under aerospace loading conditions. The technique allows for the foreseeable, preliminary evaluation of transformation behavior, stress distribution, and fatigue life before actual testing is carried out. Additionally, material selection in relation to transformation temperatures, actuation frequency, and environmental resistivity assumes prime importance in the successful integration of SMAs into flight components.

3.3. Examples in aerospace industry

The aerospace domain has good examples in the applications of SMA technology as demonstrated in realized projects. The very well-known instance is that of variable geometry chevrons employing SMA by NASA for jet engine noise reduction. The chevrons change shape passively with the temperature of the exhaust and hence need no complex actuation systems. Another example is morphing wingtip geometry for aerodynamic fine-tuning during flight with NiTi actuators of Airbus. These case examples affirm the realization of SMA integration into mechanical design and insert a more practical context to the considerations discussed.

4. Types of shape memory materials

Various SMAs are tailored for specific applications, with compositions and properties chosen based on the intended use. This diversity allows SMAs to cater to a broad range of industries and technological needs.

4.1. High-Temperature Shape Memory Alloys

SMAs that operate at temperatures above 100°C are categorized as high-temperature shape memory alloys (HTSMAs) [11),65)]. Examples of HTSMA include NiTi with additions of elements like Au, Hf, Pd, Pt, and Zr. The manufacturing of such SMA is a major challenge for aerospace industry [54)]. Training methods for HTSMAs are isothermal, isobaric, and cyclic methods [66)]. They can serve as damping materials for parts in turbo machinery [43)]. They can work in harsh corrosive environments [38)] Other properties of HTSMAs are mentioned in Table 2. Currently, the issue with HTSMAs is the degradation of functional properties [67)], precipitation formation, dislocation recovery, and vacancy diffusion [68)].

Table 2: Compilation of properties of HTSMA

Ref.	Properties	Major Observations
38)	Acceptable recoverable strain	HTSMAs exhibit acceptable recoverable transformation strain levels.
38)	Long term stability	This property is beneficial to handle the challenges associated with an elevated operating temperature.
69)	Thermal cycling stabilization	No significant degradation in the transformation temperature was observed within the acceptable range of thermal cycles.
38)	Poor workability	It poses a challenge in expanding the applications of HTSMAs, attributed to the ordered intermetallic structure prevalent in many HTSMA systems.
38)	Resistance to plastic deformation	It occurs during phase transformation, leading to a decline in the reversibility behavior of alloys.

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38)	Creep resistance	It is one of the challenges faced at elevated temperatures.
38)	Environmental Resistance	Ni-Al-based HTSMA exhibits adequate environmental resistance up to at least 1000°C.
70)	Low thermal hysteresis	Low thermal hysteresis (< 30 °C) was observed during thermal cycling at compressive stresses of 1700 MPa.

4.2. Magnetic Shape Memory Alloys

Magnetic shape memory alloys (MSMA) or Ferromagnetic shape memory alloys were developed in 1996 16),71). They possess higher operating frequency that is up to 1 kHz of frequency 4),11). They provide large strains 11). They can be operated only in low-temperature conditions 2) Examples of MSMA include NiMnGa, FePd, NiMnAl, FePt, and CoNiGa 7). The major limitations associated with the MSMAs are hysteresis, relatively low dynamics, and the need to use springs to return the transducer to its original position 51).

4.3. Thin Film Shape Memory Materials

Thin film shape memory materials can be applied directly onto micromachined substrates, or they can be utilized in their original form as micro actuators 11). They are produced by sputter deposition and are mainly Nti-based 9). Additions of oxides, nitrides, and ferroelectric layers with these films result in surface modification and vibration damping 72).

4.4. Shape Memory Polymers

Shape memory polymers (SMPs) depict better properties as compared to SMA as organized in Table 3 and they are relatively cheap 11). However, due to less actuation force of SMPs, SMAs are favored for most of the applications. In contrast to SMA, SMPs normally soften in the presence of the right stimulus 9). The reinforcement of microfibers into SMPs enables their utilization in self-deployable devices for spacecraft and devices for controlling vibrations 73).

Table 3: Comparison of properties of SMA and SMP

Ref.	SMA	SMP	Major Observations
11)	Relatively costly	Relatively cheap	SMPs are at least 10% cheaper than SMAs.
11)	Higher actuation force	Less actuation force	SMAs are preferred over SMPs for applications where higher actuation forces are necessary.
11),74),75)	Faster response	Passive response	Various types of SMAs and SMPs exhibit distinct response times, with SMAs generally demonstrating faster response times. For example, a certain type of SMA has a response time of range 0-6 seconds while that of SMP is 24 seconds.
9),20),73),76)	Less recoverable strain	Higher recoverable strain	SMPs can recover strain up to 400%.
9)	Presence of TWSME	Absence of TWSME.	SMPs cannot repeatedly shift between two shapes as they soften in the presence of a right stimulus.
9)	Difficult to fabricate.	Easier to fabricate.	Fabrication of high-quality porous SMA is difficult to fabricate but SMPs can be produced by many conventional polymer foaming processes.
73),77)	Relatively heavier	Lightweight	SMAs are heavier as compared to SMPs because metals possess higher densities as opposed to polymers.
9),78)	Difficult to tailor	Easily tailored	It is easy to customize the properties of SMPs as compared to SMAs.
9),79)	Suitable for cyclic actuation.	Not suitable for cyclic actuation.	SMAs are suitable for cyclic actuation while SMPs are not because of the tendency of SMPs to soften in the presence of a right stimulus.

5. Research applications in the Aerospace Industry

In the aerospace industry, the effective use of SMA is advantageous as explained in the following sections because of its inherent power-to-weight ratio 10). Figure 1 depicts an overview of milestone events on the axis of time, related to SMA implementation in aerospace sciences.

5.1. SMA for morphing aero structures

Morphing aerostructures represent a highly promising domain with significant potential for enhancing aircraft performance 80). Morphing refers to the continuous alteration of the shape of components depending upon the conditions 81).

5.1.1. Wing morphing

The spotlight on wing morphing has intensified with the advancement of smart materials. Morphing wings with a flexible leading edge are much easier to manufacture compared to traditional high-lifting devices such as slats and slots and they are much more trustworthy 82). It also provides a better lift/drag ratio 1) Traditionally, wing morphing relies on bulky hydraulic systems with complex mechanisms which was a major limitation earlier, but the advent of SMA enables the creation of lightweight wings, resembling origami folds 36),37),83),84). Folding wings on subsonic aircraft offer enhanced controllability and additional aerodynamic advantages 83). It also results in increased speed, reduced power consumption, roll control, and camber change.

5.1.1.1. SMA actuation of twist and rigid-body rotation

The smart Wing program was an initiative by DARPA, AFRL, NASA, and Northrop Grumman to incorporate SMA for wing morphing of unmanned combat air vehicles (UCAV). This investigation utilized SMA torque tubes for wing twists and flexible leading and trailing edges. The use of SMAs leads to the rigid body rotation of wings 49). SMAs were utilized for the variable stiffness spar (VSS) concept 49). The VSS mechanism comprises a segmented spar with articulated joints at the connections to wing ribs and an electrical actuator capable of rotating the spar by 90° 85).In this approach, certain conventional wing spars are replaced with the adaptive structures VSS, to regulate stiffness based on Mach number and altitude 86). A wing model based on the F-16 showcased that the SMA spar can enhance aeroelastic forces, leading to a substantial improvement in roll performance when compared to the conventional VSS concept. Moreover, placing the SMA spar near the trailing edge enhances the roll rate compared to the traditional VSS concept, achieving a 61% improvement. 85)

5.1.1.2. Shape memory alloy and similar actuation for camber

The SMA actuator mechanism is employed to dynamically alter the camber of an airfoil in a remotely piloted helicopter. SMA wires were embedded to bend the trailing edge of the rotor blade, facilitating the morphing of the airfoil's camber 49). Application of SMA for variable shape wings was investigated for an extremely light aircraft with and wingspan of less than a meter. The aerodynamic efficiency and flight control were much better compared to conventional actuators because of the high strength and low weight of SMAs 87). SMAs were also utilized to modify the airfoil shape, enhancing the Lift-to-Drag (L/D) ratio throughout the flight of an unmanned aerial vehicle (UAV). Optimal L/D was achieved by adjusting camber location and magnitude, favouring cruise efficiency with acceptable SMA response times for multiple flight conditions 88).

5.1.1.3. SMA actuation bandwidth

Thermal inertia limits the speed of SMA actuation. To achieve rapid cyclic actuation, efficient methods for both heating and cooling the alloy are essential. Traditional approaches involve resistive Joule heating and natural convection for heating and cooling, respectively. Increased electric current for resistive Joule heating can reduce activation times but requires more power. Cooling, typically slower than heating, requires specific attention for overall cyclic response improvement. Alternatives include utilizing engine-bleed hot air, which is cumbersome, or employing forced air for cooling in airborne applications. Some applications may leverage onboard hot/cold fluids for thermal exchange 49).

5.1.1.4. Reduction of power consumption with SMAs

Integration of SMA actuators reduces the power consumption 10). The composite structure of GFRP and SMA are combined to make an adaptive structure of cylindrical shape integrated with an electrical circuit. This process does not require a continuous supply of energy to sustain the desired shape 89).

5.1.2. Variable Geometry Chevrons (VGC)

The noise generated by aircraft during take-off and landing has very harmful effects on residents near the airport and these noises can result in sleep disorders, risk of cardiovascular diseases, and mental health problems 90),91). Turbofan engines force air out of their bypass chambers and turbines at speeds that are much higher than the speed of ambient air, the air interacts with the free-stream air, causing mixing. This mixing causes uncontrolled vortices, which in turn generates excessive noise. The chevrons aim to control the vortices that are shed from the engine nozzle by creating smaller vortices at each tooth of Chevron to allow the hot fast air being expelled from the engine to mix with ambient air more gently and Boeing 787 is one of the aircraft that is relying on chevrons for noise reductions [92),93),94)]. However, they also result in thrust loss and drag [10),93)]. To address this issue the VGC was developed which allows us to morph the chevron, optimizing it for noise reduction during takeoff and landing and adopting a configuration during cruise that minimizes the noise without compromising engine performance. They were successfully flight-tested on a Boeing 777-300ER with GE-115B engines and then NASA addressed the same chevron problem with a different design [29),93),95)]. The SMAs act as bending actuators and they are based on the principle of changing flow temperatures with altitude [29),95)]. The SMAs are embedded in such a way that at low altitudes and low speeds, the engine temperature is high due to which the chevrons automatically wrap into the jet exhaust flow to reduce the noise and at higher altitudes and high speed the temperature of the engine is low, thus the chevrons relax and straighten. [29),96),97)].

5.1.3. Variable area fan nozzle (VAN)

Controlling fan nozzle exit areas enables high-bypass-ratio turbofan engines, noise reduction, and improves fuel consumption [98),99)]. Experiments performed at Pratt and Whitney turbofan engines indicate the performance gains for these designs could reach up to 9% in thrust-specific fuel consumption (TSFC) compared to existing fixed-geometry engines [98)]. However, this concept tends to rely on heavy and complex integrations. With the advancement of SMA technology, such kind of issues can be addressed. A bundled cable actuator made of SMA can be used to move an array of flaps around the fan nozzle. The light weight of SMA-based actuation leads to cost savings of 2-3% and range enhancements of 5-6% compared to a fixed-geometry nozzle-geared turbofan [98)]. This experiment was performed at a NASA research centre and aimed to demonstrate the capability of the concept to achieve up to 20% variation in nozzle area under full-scale aerodynamic loads [97),100)].

5.2. Space Applications

SMAs find diverse applications in space exploration. SMA actuators contribute to precise movements in space mechanisms. Additionally, SMAs are used in thermal management systems, ensuring efficient heat dissipation. The potential use of SMAs in space applications can save costs while providing additional aerodynamic benefits.

5.2.1. Rock Splitter

To unveil the truths of the universe it is necessary to collect the sample for further investigation. However conventional methods for collecting the specimen involve explosives, drills, and hydraulics which are responsible for transportation and operational problems and can cause damage to the samples [101)]. To address this problem NASA's Glenn Research manufactured a tool that splits the rock and collects the sample without damaging the environment. This device is known as a Shape Memory Alloy Rock Splitter which is made from nickel-titanium-hafnium (Ni-Ti-Hf) [66)]. This composition can be used for a wide range of temperatures such as for high, ambient, or sub-zero transformation temperatures as per the requirements which is possible with different heat treatments [79)]. A borehole is made on the desired part of the rock in which a pre-compressed SMA is placed. Alternating current (AC) or Direct current (DC) is used to attain critical transformation temperature. Expansion of SMA can deploy stress of 1500 MPa which results in splitting. HTSMAs are used for this application as illustrated in Figure 5 [66),101)].a

Fig. 5: Use of SMA to split the rock [102)]

5.2.2. Smart wheels for extra-terrestrial roving missions

Exploring Mars is crucial for scientific discovery, human exploration, the planet's evolution, and many more. However, the design and material of the wheels of rovers have been major concerns recently. The rubber pneumatic tires cannot be used on Mars as rubber becomes brittle at -150°C temperature and tires can explode [103)]. Moreover, the distribution of rocks and other obstacles is dense on the Martian surface. The "Spirit" Mars rover submerged into soft sand and the "Curiosity" Mars rover landed at a Gaelic crater where the surface was harder than expected [104),105)]. Studies have shown that flexible tires instead of rigid ones help lower ground pressure and increase durability with better traction [103)]. To address these problems, NASA in collaboration with the US tire industry developed a non-pneumatic tire that is built by using a metal mesh made up of SMA as depicted in Figure 6. They can work in rocky terrain and even in the cold temperatures of Mars. They can undergo up to 10% recoverable strain [106)]. These intelligent wheels extend beyond applications in space exploration; they can also be utilized for various purposes, such as serving as landing gear for aircraft, wheels for off-road vehicles, and more. They also simplify wheel design since the use of SMAs eliminates the need for an inner frame, thereby reducing weight. [31)].By changing the designs of SMA geometry, a diverse range of tire sizes and stiffness levels can be achieved [40)]. This facilitates a four-tire rover design configuration instead of six tires as SMA

Fig. 6: SMA rover tire for Martian landscape [108)]

tires are much more efficient and it further helps in weight reduction [107),108)].

5.3. Vortex Generators

They are fixed devices present to maintain the airflow at low and delay stalls by creating a vortex that energizes the boundary layer close to the wing. Their height is between 10%-50% of the boundary-layer thickness [109)]. They control flow separation which results in energy saving [109)]. VGs are essential for take-off and landing; however, they typically contribute significantly to drag during other phases of flight. By using SMAs, VGs can be selectively deployed, thereby enhancing the overall flight performance. They are adjusted exactly according to environmental temperatures. SMA wires can be used to actuate wing surface VGs [29)]. Trials are being carried out on Boeing's eco Demonstrator 777 [110)].The collaborative endeavors of NASA and Boeing led to the development of deployable vortex generators (VGs) crafted from SMAs. They move when they sense the change in the environment as illustrated in Figure 7.

5.4. SMA for UAVs

The utilization of UAVs is rapidly increasing for a variety of real-life applications such as 3D mapping, military operations, disaster relief, and exploration of hazardous remote areas [112)]. They also offer cost-effective platforms for conducting experiments on navigation systems [113]. To mitigate vibrations in UAVs, an anti-vibration damping system made up of SMAs is installed to absorb structural oscillations [46)]. SMA-based actuation systems can be used in flight flap control of UAV systems with the required performance parameters [113)]. Utilization of SMA for morphing winglets of UAVs can increase the aerodynamic performance. A combination of SMA wire and glass fiber within a soft polymeric matrix is used for fabrication. Utilization of SMA-based actuators reduces stress concentrations and thus enables the single component to perform multiple functions [14)].

6. Future direction of SMA applications

SMMs are an emerging topic in the research field due to their unique shape memory behavior and superelasticity. Successful applications are limited to eyeglass frames, mobile phone antenna, pneumatic valves, and autofocus (AF) modules for smartphones [2)]. Rigorous research is carried out to utilize SMMs to their full potential.

Fig. 7: Vortex generator made up of SMA by NASA [111)]

6.1. Future trends in SMAs

The future of SMAs can be anticipated in three different levels: (1) Integration of SMA with other materials to get desired properties, by creating hybrids and composites, (2) Improving existing SMAs or developing new ones, and (3) Exploring new markets for them [2)]. The global market for SMAs is estimated to reach 45.8 billion dollars by the end of 2033 [114)]. The Carbon fiber reinforced polymer (CFRP) composites with embedded SMA wire have been utilized as a structural health monitoring (SHM) system and also provide ice protection capability [2)].For the utilization of SMAs in humanoid robots, bundled SMA actuators can be used which will improve the load carrying capabilities without much increase in cycle time [115),116)]. In addition to SMAs, exploration of other SMMs is crucial, allowing for effective combinations tailored to specific applications. More research on the structural behavior of SMAs should be investigated to utilize them to their full potential. Effective designs should be made by incorporating SMAs into a variety of different fields.

6.2. Challenges in SMAs applications

Besides many advantages that let SMAs enjoy a much under-rated reputation, a few constraints still need to be addressed. First of all, functional fatigue caused by cyclic loading leads to slow degradation of performance, mainly concerning aerospace applications. Hysteresis of the phase transformation also means a loss of energy and less precision in control. Cooling time between actuation cycles also limits the operation frequency of SMA actuators. Although strategies have been devised to reduce those drawbacks-involving redesign of alloys and design changes- these issues have prevented large-scale commercial adoption on their own. Hence, it is important to acknowledge the limitations associated with SMAs.

- Strain recoverability and fatigue resulting from repeated cycles is another issue related to SMAs. This can be addressed by developing technology that could detect slip propensity [1),28),39)], further research is needed for a complete understanding of the phenomenon.
- The longer retraction time even during the experimental stage is one of the major problems

with SMAs [10),115)]. The heating time can be shortened by elevating the by elevating the magnitude of the stimuli. Cooling time refers to the period required for the SMA wire to release its heat to the surroundings. This cooling duration relies on temperature, thermal conductivity coefficient and diameter of the SMA wire [115),117)]. By improving the design, by using coolants and by applying large stimuli the mentioned issues can be addressed [2),115)].

- The solid phase transformation between martensite and austenite takes place over different temperature ranges. Since these transformation ranges do not overlap, results in transformation temperature hysteresis. This phenomenon occurs due to irreversible phase transformation which results in difficulty in controlling SMA components [115),118)].
- Additionally, higher cost and complexity in manufacturing compared to conventional materials limit their use.

However, with the advancement of science and technology, these limitations will be surpassed, paving the way for the widespread adoption of SMAs.

7. Summary of proposed work

This review explores the aerospace applications of SMAs, renowned for their shape memory effect, superelasticity, and damping properties. Researchers globally have harnessed these characteristics for sustainable aviation, replacing hydraulic actuators with lightweight SMAs, and reducing aircraft weight and fuel costs. SMAs contribute to sustainable aviation by offering the possibility to substitute cumbersome hydraulic actuators with more straightforward and lightweight SMA actuators. This design simplification leads to a reduction in weight, subsequently lowering fuel costs. They help address one of the limitations faced in the development of wing morphing technology, which is an intricate design. Chevrons were developed to reduce noise pollution, but they adversely affect during the cruise, thus variable geometry chevrons were developed by using SMAs. Regulating the exit area of the fan nozzle enhances high-bypass-ratio turbofan engines, diminishes noise levels, and optimizes fuel efficiency which is achieved by using actuators made up of SMA. Experimental results show an increase in performance characteristics. Sending a mere 1kg of weight into space incurs costs amounting to thousands of dollars. The machinery employed for sample collection during space missions, such as hydraulics and drills, contributes to this weight. Thus, NASA has developed a tool named, shape memory alloy rock splitter which uses HTSMAs. Recent attention has focused on the performance of rover wheels. In response, NASA has come up with wheels constructed from SMAs to improve rover performance. These wheels possess the capability to adjust to the diverse terrain and temperature conditions on Mars. Vortex generators are static devices that help in maintaining the boundary layer flow during take-off and landing, yet they reduce efficiency during cruise by generating vortices. The SMAs allow for the creation of deployable vortex generators, thereby improving flight performance. The benefits of integrating SMAs into UAVs help to mitigate structural vibrations, flap control for various flight conditions, and morphing of winglets to increase aerodynamic performance.

8. Recommendations

There is an urgent need to develop the latest manufacturing techniques such as additive manufacturing and 3D printing to produce state-of-the-art SMA properties with minimal defects. Incorporating SMA with other smart materials, like piezoelectric materials can create a multifunctional system. Integration of SMAs in soft robotics will enhance flexibility and adaptability. The potential of SMAs can be explored for the development of deployable structures in space applications. Besides SMAs, it is essential to explore various SMMs, enabling the effective combination of these materials for specific applications. Continuous evolution of SMA technology is required to utilize them to their full potential.

9. Conclusion

The conclusion drawn is that SMA is a futuristic material that is still in the experimental stage, but it has wide applications in the modern world, from being used as a guide wire in biomedical applications to being used on Mars. Despite many research papers and patents on them the implementations are quite a few. One of the reasons is the intricate nature of their behaviour. SMAs offer unique properties like the shape memory effect; their optimization for specific uses requires ongoing refinement. The incorporation of SMAs with other SMMs has the potential to unlock new opportunities.

SMAs have been used in a wide variety of applications in different fields. In this review, the focus lies on applications in the aviation industry, representing the present article's main contribution. The overall view of SMA in aerospace includes wing morphing, vortex generators, variable geometry chevrons, variable area nozzles, and wheels for extraterrestrial missions, indicating the multifaceted nature of SMA in the aerospace field. The results have shown that fuel consumption reductions, savings in structural weight, and enhancements in aerodynamic performance are all important.

There are some research gaps remaining, even after the potentially promising prototype studies. The major areas of concern in these gaps include the limited fatigue life of SMAs under cyclic aerospace loading, slow actuation speeds due to thermal inertia, and difficulties in accurately modeling phase transformations. Other considerations to name might include the presence of testing standards and fabrication routes that are highly standardized and can be satisfactorily up scaled for faithful integration in a flight system. Following this trend, the existing gaps come to be the changes that must be made for SMAs to be accepted as reliable components in the mainstream aerospace engineering industry, rather than being treated purely as materials for the laboratory.

In future developments, more research could be undertaken to find alternative fabrication processes, improve adjustability of their properties, and promote cost-effectiveness. In any case, once these impediments are removed, they shall find commercial applicability in a wide array of domains that also generate huge cost savings.

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Nomenclature

AM	Additive manufacturing
DARPA	Defense Advanced Research Projects Agency
GFRP	Glass fibre reinforced polymer
HTSMA	High temperature shape memory alloys
LENS	Laser Engineered Net Shaping
MMMT	Multi-memory material technology
MSMA	Magnetic shape memory alloys
NASA	National Aeronautics and Space Administration
OWSME	One-way shape memory alloys
SAMPSON	Smart Wing Program and Smart and Aircraft and Marine Propulsion System Demonstration
SCSMA	Single crystal shape memory alloy
SE	Super elasticity
SLM	Selective laser melting
SMA	Shape memory alloy
SMAHC	Shape Memory Alloy Hybrid Composite
SMARS	Shape memory alloy rock splitter
SME	Shape memory effect
SMH	Shape memory hybrid
SMM	Shape memory materials
SMP	Shape Memory Polymer
SMPC	Shape Memory Polymer Composites
TSFC	Thrust specific fuel consumption
TWSME	Two-way shape memory alloys
UAV	Unmanned aerial vehicle
UCAV	Unmanned Combat Air Vehicle
VAN	Variable Area Nozzle
VG	Vortex Generators
VGC	Variable Geometry Chevron
VSS	Variable stiffness spar

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