SHAPE MEMORY MATERIALS AND THEIR APPLICATIONS IN AIRCRAFT MORPHING: AN INTROSPECTIVE STUDY

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ABSTRACT

Smart materials are intelligent materials that are capable of responding to external stimulus, viz., heat, light, and chemical. Among the smart materials, there is a class of stimulus-responsive materials which are capable of recovering their original shape when subjected to even large loads and inelastic deformations. These materials are termed as shape memory materials. These materials are employed in a various disciplines due to their characteristic properties. In our study, we will enumerate the important class of shape memory materials i.e., shape memory alloys and shape memory polymers and their applications of shape memory materials in the field of aircraft morphing. A brief discussion of these materials will be provided along with the phenomenon of aircraft morphing. The study will contribute in providing an insight review of the shape memory materials being developed for aircraft morphing.

Keywords: shape memory materials, shape memory alloys, shape memory polymers, aircraft morphing, aerodynamic efficiency.

INTRODUCTION

Shape memory materials (SMMs) are those which can "retain or memorize" a plainly visible (lasting) shape, be controlled and ""settled or fixed"" to a brief and torpid shape under particular states of temperature and stress, and after that later unwind to the initial, stress free condition under thermal, electrical, or ecological command [1-5]. This recovery is related with elastic distortion saved before manipulation.

SMMs have stirred extraordinary consideration from researchers and scientists because of their ability to recollect two shapes at various conditions. This gives materials incredible potential for application in sensors, actuators, smart devices, and media recorders [6]. There are various kinds of advance and unconventional SMMs like the shape memory alloys (SMAs) and shape memory polymers (SMPs) as illustrated in Figure-1.

The functional mechanism of shape memory effect (SME) in SMAs is the reversible martensitic transformation system, while as dual segment or domain system mechanism endures the SME in SMPs. One of the newest types of SMM is shape memory hybrid (SMH), composed of at least two non-SME components and sharing the same mechanism as SMPs [1]. Likewise, the new shape memory ceramic (SMC) have the same mechanism as of the SMA which is reversible phase transformation.

SMPs can retain a lasting shape and customizable to one or numerous brief shapes [7]. They recoup their unique changeless shapes from brief disfigurements under outside stimuli, such as electrical, light, electromagnetic fields, and temperature variety has been the fundamental actuation jolt because of inbuilt thermal phase transition in polymers [7-10].
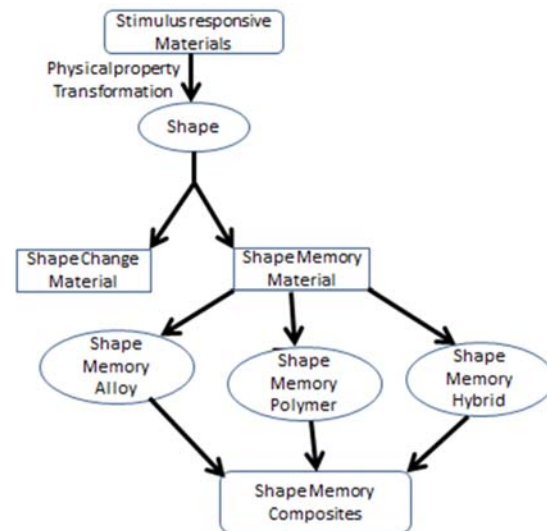

Figure-1. A schematic of tree of SMMs.

The SME, pseudo elasticity or large recoverable stroke (strain), high damping capacity and adaptive properties, induced by the reversible phase transitions in materials, are some of the significant properties of SMMs making them convictive for intelligent/smart composites [3, 5, 11, 12]. The effective quality of SMMs is to predict thermal, mechanical magnetic, even electric stimulus and display the actuation.

SMMs may sense thermal, mechanical, magnetic or electric stimulus and exhibit actuation or some pre-determined response, making it possible to tune some technical parameters such as shape, position, strain, stiffness, natural frequency, damping, friction and other static and dynamical characteristics of material systems in response to the environmental changes. There are some alloys, ceramics, polymers and gels that depicted SME characteristics [5].

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A significant breakthrough was achieved by Naval ordinance laboratories, USA in 1971 by observing that NiTi alloy showed significant recoverable strain, thereby attracting various engineering applications [13]. Currently, many of the new SMA system developed are available for the commercial market. A significant research in the field of thin film NiTi based SMA is on progress, and has great potential as an actuator in micro-electromechanical systems (MEMS) [14, 15].

Therefore, our study is aimed to review the SMMs related to the discipline of aircraft morphing. The main contribution of this study is to evaluate the applications of SMMsin aircraft morphing. Firstly, we provide a general description of aircraft morphing and then the study will be followed by the sections explaining the essentials of SMAsand SMPs respectively. Each of these sections will be accompanied by the applications of these materials in aircraft morphing. Finally, we will summarize the main conclusions of the study.

AIRCRAFT MORPHING

The past decade has seen tremendous growth in the application of smart materials technology to today's commercial and military aircraft [16]. One area that holds considerable promise for greatly improving aircraft performance is morphing structures [16]. The morphing wing has attracted many research attention and effort in the aircraft technology development because of its advantage in lift to drag ratio and flight performance.

Since from the wright brother concept, the morphing technology has adapted in large areas to increase the performance of the aircraft which work efficiently during each flight envelope. Over a hundred years later, unconventional aircraft adaptability, often called "aircraft morphing" has become a topic of considerable renewed interest. In past two decades this interest has been largely fueled by advancements in multifunctional or smart materials and structures.

Mission morphing requires large-scale shape change to adapt to different flight conditions. It involves making major external shape changes such as span, area and sweep to adapt to a changing mission during flight[17, 18]. Dramatic configuration changes such as200% change in aspect ratio, 50% change in wing area, change in wing twist, and change in wing sweep for multi-mission aircraft are paid much attention in recent researches [19].

The aim of such designs is to develop a fleet of a single type of morphing aircraft capable of fulfilling a variety of missions and functions under various flight conditions. For example, the aircraft should have high aspect ratio and low sweep angle for efficient low-speed flight, and low aspect ratio and high sweep angle wing for high speed flight. Table-1 enumerates the advantages of morphing wing aircraft over fixed-wing geometry.

Table-1. Advantages of morphing wing aircraft over fixed-wing geometry[20].

Morphing category	Morphing methods	Advantages
Large	Folding	Increase the critical Mach number Decrease parasitic drag
	Sweep	Increase the critical Mach number Decrease high-speed drag
	Span telescoping	Increase L/D, loiter time, cruise distance Decrease engine requirements
	Deployable	Increase L/D, loiter time, cruise distance Decrease engine requirements
Medium	Twist	Increase maneuverability Prevent tip stall
	Winglet bending	Increase L/D, maneuverability Decrease induced (tip vortex) drag
	Chord telescoping	Increase low-speed airfoil performance
	Variable camber	Increase airfoil efficiency Delay separation
Small	Variable airfoil	Increase high-speed airfoil performance
	Bulging	Increase wing efficiency Decrease compressibility (wave) drag

Morphing wing design can be achieved by the rotation of either the whole wing or some parts of the wing. It leads to variable dihedral wings or sweep [19, 21]. A telescopic wing is a device having one or more segments of progressively smaller cross-section. This kind of structure can change the span and wing area, which is equivalent to changing aerodynamic performance, by extending and contracting wings.

The morphing configuration belongs to the two-dimensional in-plane operation. It is important for unmanned aerial vehicles (UAVs) to be able to stow their wings and control surfaces into very small volumes to allow gun launch or packaging into aircraft mounted aerial drop assemblies and rapid deployment on the ground or in-flight [22]. Inflatable wings provide a solution with packed volume more than 10 times smaller than their deployed

one. The strength and stiffness of the inflatable wing is controlled by the internal pressure and the modulus of elasticity of the restraint material [22].

The need to investigate design of a skin material that combines the two inherently different mechanical properties: stiffness and compliance drew many new challenges [23]. The brilliant skin basically to transmit the streamlined burdens to the internal structures [24-26]. Consequently, the brilliant skin ought to be anisotropic with low in-plane stiffness and high out-of-plane stiffness. The smart skin is additionally required to have an adequate strain capacity, which implies when it is disfigured the material does not have plastic distortion [27, 28].

Composite folded structures are anisotropic with a moderately high stiffness parallel to the corrugation direction and generally with low stiffness towards perpendicular direction[27]. Thereby, flexible skins sound attractive, but designing a skin that can transfer aerodynamic loads to the under structure is a challenge. The more flexible the skin is the more attachment points are necessary to avoid pillowing effects.

Two of the more promising materials for skins are elastomers and composite skins manufactured with SMPs [29, 30]. Ideally, control of the glass transition temperature of the SMP, either thermally or optically, provides on demand control over the storage modulus. This utilizes the potential in a transforming trailing edge, firstly by corrugated laminates and afterward by corrugated sandwich structures to conquer its downside of the low out-of-plane stiffness[31]. The honeycomb structure is additionally anisotropic.

Lockheed Martin has proposed a z-shape morphing vehicle concept and verified its properties through ground and wind tunnel tests of UAV [32, 33]. Cornerstone Research Group (CRG) has improved the manufacture technique of SMPs for seamless skin: the wing skin can deform based on the packaging or deploying states of the hinge using SMPs at the conjunction parts [34].

SHAPE MEMORY ALLOYS (SMAs)

SMAs are typical temperature-sensitive metallic functional materials with super elasticity and shape recovery characteristics [35]. The conventional SME involves the formation and deformation of thermally induced martensite and its reverse transformation. The shape recovery process usually takes place over a temperature range, showing relatively low-temperature sensitivity. Figure-2 illustrates the phase transition and crystal domain arrangements that emerge with the SME.
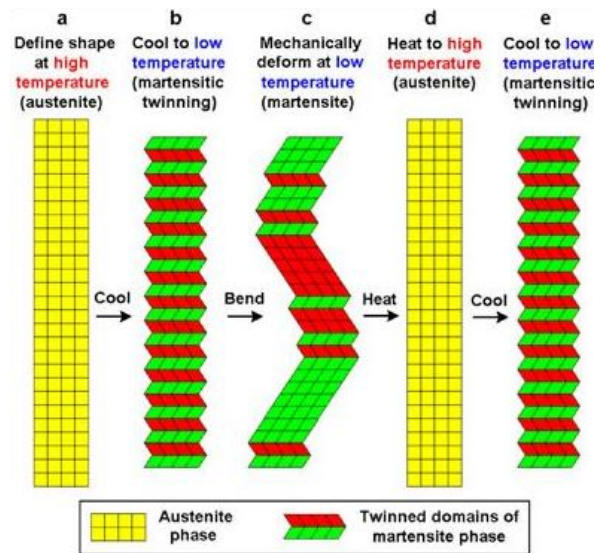

Figure-2. Phase transition and crystal domain arrangements along with SME [36].

The importance of SMAs had not been immediately recognized until 1962, when William Buehler and Frederick Wang revealed the SME in a NiTi alloy, which is also known as nitinol (derived from the material composition and place of discovery, i.e., a combination of NiTi and Naval Ordnance Laboratory) [13].

Since then, the demand for SMAs for engineering and technical applications has steadily increased in numerous commercial fields, such as in consumer products and industrial applications, structures and composites, automotive, aerospace, mini actuators and MEMS, robotics, biomedicine, and even fashion.

Although iron-based and copper-based SMAs, such as Fe–Mn–Si, Cu–Zn–Al, and Cu–Al–Ni, are low cost and commercially available, their instability, impracticability (e.g., brittleness), and poor thermo-mechanic performance make them unattractive. By contrast, Cu-based SMAs are commercially attractive because of their low cost and interesting properties when vibration isolation and suppression is required in engineering applications, including isolation platforms for sensitive experimentation and manufacturing and the stabilization of large space structures [37].

In Cu-based SMAs, the elastic strain energy stored during thermally-induced martensitic transformation depends on the sample size and external biasing stress. The origins of these dependencies are related to the variation in martensite variant structure with sample size and external stress.

NiTi-based SMAs are preferable for most applications [38]. As an example, the silicon wing with integrated NiTi strips is shown in Figure-3. However, each material offers a unique advantage for particular requirements or applications. In the 1990s, the term "shape memory technology" was introduced to the SMM community [39].
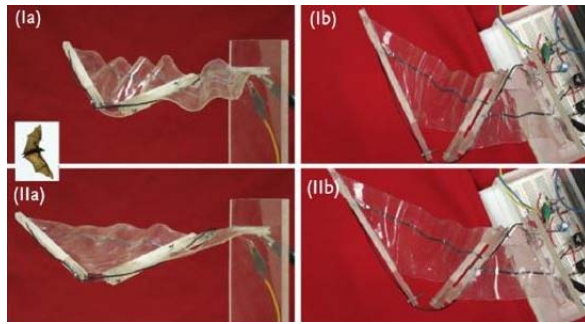
Figure-3. A bio-inspired silicon wing stimulated by joule heating with integrated NiTi SMA strip. Front (a) and top (b) views before (I) and after (II) heating [5].

SHAPE MEMORY POLYMERS (SMPs)

SMPs exhibit the SME, where an external stimulus (e.g., light, heat, electricity, magnetism, microwaves, moisture, or a change in pH) helps SMPs achieve significant macroscopic recovery. In this process, the material transitions between a glassy state (hard) with a high Young's modulus (greater than 3 GPa) and an elastic state (soft) with a low Young's modulus (1-10 MPa); hence, a distinguished change in stiffness occurs [8, 40].

SMPs are usually utilized as actuators in deployable space structures, that is, in a weightless environment. Their wide use is attributed to their low recovery forces [41]. However, SMPs show high potential for applications requiring a morphing skin because of their variable stiffness.

SMP morphing skins are capable of withstanding aerodynamic loads in the glassy state and tolerate large deformations (up to 100% strain) in the elastic state. Therefore, they can accommodate morphing structures [42]. Composites of SMPs have been fabricated by putting carbon fibers, glass fibers, or elastic fibers together with an SMP resin, which improves the mechanical performance of SMPs [40, 43, 44].

Morphing skins based on SMP composites have been designed and tested in sweep wings, telescoping wings, variable camber wings, folding wings, and deployable wings [30, 41]. For example, an SMP composite was prepared with a combination of solution blending of various nano-composites [45]. A recovery rate of 95% within 45 seconds at 40 DC voltages was observed (Figure-4). Such SMP composite is preferable in various actuators, sensors, and deployable devices. The SMP composite skin changes its shape when heated while maintaining a smooth and seamless wing surface.
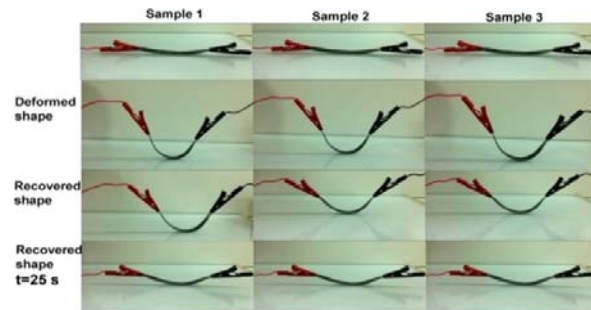

Figure-4. Shape recovery at DC voltage of 40 V [45].

SMPs are categorized according to functions (functionally graded, two-way, multi-shape, self-healing, and foams), and their development has been prompted by intensive research [46, 47]. Today, SMPs and shape memory polymer composites (SMPCs) are included in applications ranging from the outer space to submarines (including aerospace, biomedicine, automobiles, and textiles).

The main characteristics of SMPs and SMPCs are their variable material properties above and below the transition temperature (melting transition temperature or glass transition temperature (T_g) based on the nature of the polymer configuration) [48]. For example, when the temperature is higher than T_g, the polymer is in the rubber state and is considered a viscous material; however, the polymer is in the glass state and is considered an elastic material when the temperature is below T_g.

SMPs exhibit viscoelastic behavior when they are near the transition temperature, at which point the polymer properties change rapidly and the elasticity modulus decreases by approximately two orders of magnitude [7, 49, 50]. Figure-5 shows the typical thermo-mechanical cycles of SMPs or SMPCs in the process of shape memory and recovery [8].

The process of shape recovery comprises the following steps: (1) original step, which involves fabricating the original shape of the SMP; (2) heating step to above T_g, which involves deforming the SMP to a pre-deformed shape; (3) cooling step, which involves reducing the temperature to below T_g and removing the constraint; (4) reheating step, which involves increasing to a high temperature state and recovering the original shape.
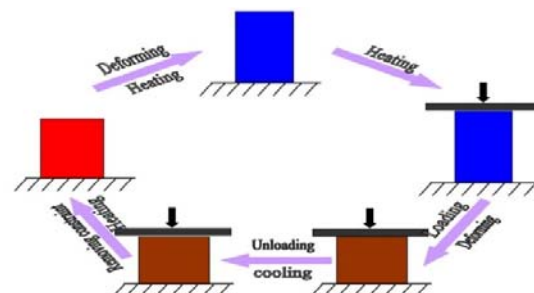

Figure-5. Typical thermo-mechanical cycle processing of a SMP/SMPC under compression testing [8].

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The application of SMPs is also hindered by the fact that these materials are macromolecular smart materials that are able to respond to an external stimulus by changing their macroscopic properties (such as shape and color) and then recover its original shape from its temporary shape [8, 9, 51]. SMPs also have the unique advantages of being inexpensive and lightweight and show other remarkable features, such as low density, high shape deformability, good manufacturability, bio-degradability, and an easily tailorableTg compared with SMAs [8]. A comparative analysis of the properties of SMPs and SMPCs is presented in Table-2.

Table-2. Comparative properties of SMPs and SMPCs [52].

Mediocre Values	SMP	SMPC
Cost	20 €/kg	500 €/kg
Density	0.9–1.25 (g/cm^3)	6–8 (g/cm^3)
Shape recoverability processing	Up to 500%, Easy (<200 °C, low pressure)	Up to 8%, Hard (>1,000 °C, high pressure)
Tailoring of transition temperature, stiffness, biodegradability, and functional grading	Easy	Hard
Response time	Measured in seconds	Measured in milliseconds
Number of cycles	Very low	High
Recovery stress	4–10 MPa	200–400 MPa
Strength	5–100 MPa	700–2,000 MPa

However, SMPs suffer from a number of drawbacks, such as low recovery stress and low deformation stiffness [53]. As a solution, SMPCs have been developed for practical applications. The results of the studies on SMPCs show that SMPCs achieve higher strength and higher stiffness than SMPs and that SMPCs possess certain special characteristics depending on the added fillers, thus proving to be advantageous relative to SMPs [54, 55].

APPLICATIONS IN AIRCRAFT MORPHING

Shape memory alloys (SMAs)

SMA application design has changed in many ways to be commercially applicable to a broad range of industries, including automotive, aerospace, robotics, and biomedicine [56]. Currently, SMA actuators have been successfully applied in low-frequency vibration and actuation applications [57]. Extensive systematic and intensive research is conducted to enhance the performance of SMAs, with a focus on increasing their bandwidth, fatigue life, and stability.

The laser shock indentation of martensitic NiTi is an effective means of producing two-way shape memory that can be harnessed to achieve robust surface form memory [57]. Compared with quasi-static indentation using spherical indenters, laser shock indentation produces surface form memory amplitudes that are about five times greater. As a result, SMA elements are attractive for the development of aerodynamic applications given that this actuation solution prevents the introduction of flow-disturbing control elements [58].

The thermal and mechanical properties of SMAs allow new design solutions for actuators, structural connectors, vibration dampers, sealers, release or deployment mechanisms, inflatable structures, and manipulators [13]. In modern vehicles, the number of sensors and actuators are increasing tremendously because of the demand for safe and comfortable vehicles with excellent performance [59].

The emerging drive by wire technology offers a wide range of opportunities for SMA actuators to serve as an alternative to electromagnetic actuators in automotive applications [59]. In these devices, SMAs in the form of wires or strips are usually embedded in thermoplastic and thermosetting polymer matrices to function as active elements [58]. SMA-based actuators provide a high force-to-weight ratio, long fatigue life, and high corrosion resistance [60]; hence, these materials have been used in many applications, such as active helicopter rotor blades, adaptive airfoils, and the deployment of control surfaces and flaps [61].

Several studies deal with the use of SMAs as linear actuators to realize reconfigurable airfoils that enable an increase in the efficiency of the wing in flight at several different flow regimes. Sofla *et al*. [21] recently proposed a design for a shape morphing wing for small aircraft that takes advantage of an antagonistic SMA-actuated flexural structural form that enables the changing of the wing profile by bending and twisting, thus improving the aerodynamic performance [62].

More recently, the Boeing Company developed an active aerodynamic device known as variable geometry chevron, which can reduce noise during takeoff and increase cruise efficiency [63]. The SMA morphing

capability, in conjunction with the simplicity and compactness of active deformable structures, provides substantial performance benefits.

Compared with other types of standard actuation, an SMA control system allows the design of devices with lesser complexity, higher overall reliability, easier serviceability, cheaper implementation, and more compact arrangement in conjunction with improved lightness. A smart, soft composite comprising SMA wires and glass fibers within a soft polymeric matrix was used to fabricate morphing winglets [64], as shown in Figure-6.
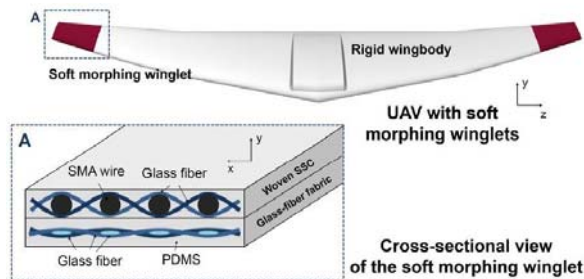

Figure-6. Schematic diagram of morphing winglet employing SMA wires [64].

Morphing winglets were implemented at the wing tips of a WASP 4/7-scale UAV, and the aerodynamic characteristics were investigated using wind tunnel testing with various attack angles. That investigation showed that when the morphing winglet was actuated, the lift-to-drag ratio increased by 5.8% relative to the flat wing geometry for an attack angle greater than 5°.

An active structure of a morphing wing commonly designed for subsonic cruise flight conditions is composed of three principal subsystems; (1) flexible extrados, (2) rigid intrados, and (3) an actuator located inside wing box [65]. The four-ply laminated composite flexible extrados are powered by individually controlled SMA actuators.

One such adaptive structure wing was developed using an antagonistically positioned SMA material, which flexes the wing, as shown in Figure-7. This methodology uses the results of the constrained recovery testing of a selected SMA. This prototype with morphing laminar wing powered by SMA actuators [21].

In the 1990s, aerospace researchers focused on the morphing capability and system-level optimization under various flight conditions of active and adaptive structures; examples include the DARPA program for aircraft "smart wings," the Smart Aircraft and Marine Propulsion System Demonstration program for jet engines, and a number of other programs [41, 66-70]. In addition, Boeing also developed an active serrated aerodynamic device with SMA actuators, known as a variable geometry chevron, and installed it on a GE90-115B jet engine (for the Boeing 777-300 ER commercial aircraft) [71].
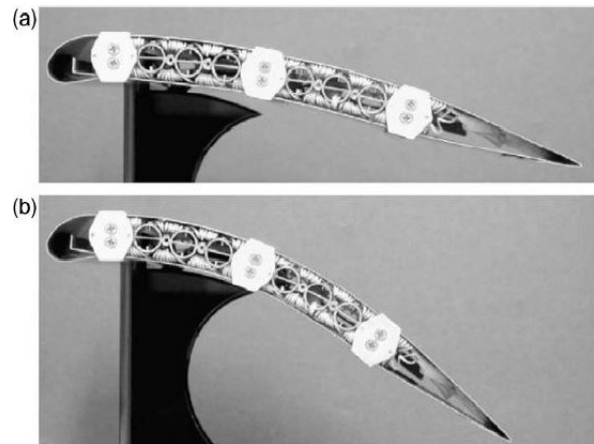

Figure-7. Bending achieved in a prototype aircraft wing by heating of SMA strips. (a) Unmorphed and (b) morphed [21].

This device has been proven effective in reducing noise during takeoff by maximizing the chevron deflection and increasing the cruise efficiency by minimizing the chevron deflection during the remainder of the flight.

A preliminary design study with finite element simulations presented by Icardi and Ferrero verified that an adaptive wing for a small UAV, which is driven completely by SMA devices, could bear the aerodynamic pressure under any flight conditions without any weight increase or stiffness loss compared with other conventional actuators [72].

A significant amount of research has also explored rotor technology (rotorcraft) with SMAs, including rotor blade twisting, rotor blade tracking tab, rotor control, and rotor blade tip morphing [73]. The lifting surfaces of current aircraft are designed as a "compromise" geometry that allows aircraft to fly in a range of flight conditions, although the performance in each condition is likely to be sub-optimal [74]. This outcome is attributed to the need for the structure to be rigid enough to support high cruise speeds and payloads and be optimized for a single condition (cruise for airplanes and hover for helicopters).

The idea behind morphing is to overcome some of the limitations of current technology by adapting the geometry of lifting surfaces to pilot input and different flight conditions characterizing a typical mission profile. This approach, however, gives rise to an interesting paradox. The same structure must endure external aerodynamic loads without suffering appreciable deformations and, when needed, dramatically change its shape to fit the current flight condition [73].

Nevertheless, SMAs can present some limitations, such as the long-term performance and reliability of SMA actuators, particularly when overheated and overstressed over long periods, which may result in a considerable reduction of fatigue life. Similarly, SMAs have generally been considered to suffer from a slow response because of heating and cooling restrictions [75].

In terms of morphing aircraft, SMAs are used for twist and camber morphing and control authority [76, 77]. Therefore, various measures must be considered to improve actuator design and thereby achieve the desired response. In addition, the need to reduce the overall power consumption is essential to maintain the system-level benefits of any morphing technology.

Different strategies must be envisioned to optimize the performance or power reduction of such technologies according to specific morphing applications. This goal represents the main contribution of the present work. The properties of SMAs are given in Table-3.

Table-3. Important properties of SMAs with their outcomes [78].

SMA Traits	Consequences
SME	Material can be used as an actuator, providing force during shape recovery.
Pseudo elasticity	Material can be stressed to provide large, recoverable deformations at relatively constant stress levels.
Hysteresis	Allows for dissipation of energy during pseudo-elastic response.
High Act. Stress (400-700 MPa)	Small component cross-sections can provide substantial forces.
High Act. Strain (8%)	Small component lengths can provide large displacements.
High Energy Density (~ 1,200 J/kg)	Small amount of material required to provide substantial actuation work.
Three-Dimensional Actuation	Polycrystalline SMA components fabricated in a variety of shapes, providing a variety of useful geometric configurations.
Actuation Frequency	Difficulty in quickly cooling components limits use in high-frequency applications.
Energy Efficiency (10%-15%)	Amount of thermal energy required for actuation is much larger than mechanical work output.
Transformation-Induced Plasticity	Plastic accumulation during cyclic response eventually degrades material and leads to failure.

Shape memory polymer (SMPs)

Compared with other traditional materials, SMPs offer many advantages, such as high strain recovery, low cost, low density, easy shaping procedure, and easy control of recovery temperature [79, 80]. SMPs can be fixed into a temporary shape and then reverted to its original shape by using an external motivator. Given the deformation process of designed morphing structures, using smart materials is reasonable because they could resolve the inconveniences caused by complex and heavy mechanical linkages.

Static deformation analysis of wings under aerodynamic loads has also been conducted to verify the strength and stiffness of SMP materials [81, 82]. One study investigated the application of SMPs in designing a deployable morphing structure [27]. During deformation, the proposed SMP filler was used to realize accurate shape recovery. After the recovery of the original shape of the

SMP filler, a standard airfoil was formed simultaneously, as shown in Figure-8. The designed deployable morphing structure was deployed within 98 seconds after being heated with 80 W resistance heating film. The deformation process was steady and accurate, and the drawbacks of traditional deployable technology were overcome.
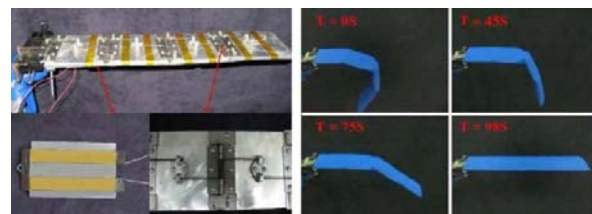

Figure-8. Shape recovery of SMP filler in adaptive structure [81].

Today, researchers are greatly attracted to the design of new types of morphing wing skin [23, 83]. One type involves SMPs and SMPCs that are able to change their shape according to an external stimulus and maintain normal efficiency. A z-shape morphing vehicle concept and a verification of its flight properties through ground and wind tunnel tests on UAVs was proposed by Lockheed Martin [84].

Yu *et al.* proposed the concept of a morphing wing with SMPs and SMPCs. They compared the deployment process of carbon fiber-reinforced SMPs with SMA wire-reinforced SMPC and elastic steel slice-reinforced SMPC [85]. Results showed that the elastic steel slice-reinforced SMPC and SMA-wire-SMPs show a faster recovery speed than carbon fiber-reinforced SMPs. Furthermore, Yin *et al.* developed the concept of a variable camber wing, as shown in Figure-9. They performed a related experiment to measure the deformation mechanism [86].
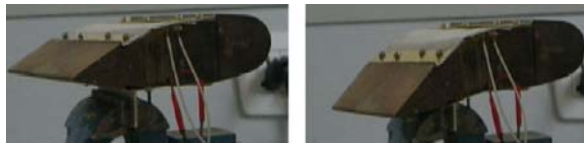

Figure-9. Deformation of a variable camber wing: (a) original configuration and (b) morphing configuration [86].

Bearing in mind that SMPCs exhibit variable mechanical properties under low/high temperatures, the authors fabricated a variable stiffness styrene-based SMPC tube reinforced with carbon fiber and embedded it into a flexible silicon rubber skin. Their experimental results indicated that the variable stiffness SMPC tube significantly affected the deformation of the morphing skin and deflection gradually increased with time [87].

The Cornerstone Research Group Inc. (CRG) presented results of an ongoing research and development of adaptive wing structures employing SMPs [88-90]. Their objective is to develop and demonstrate viable composite materials and process technology to support multiple structural morphing applications.

The CRG enhanced the manufacturing technique for SMPs to achieve seamless skin; the improved wing skin can be deformed on the basis of the packaging or deploying states of hinges that use SMPs at joined parts [84]. An SMP-based wing skin with an embedded elastic electrode to enable skin elongation along the chord length was developed by the CRG, as shown in Figure-10.

Other prototypes that are still under development, includes chord morphing wings, seamless span morphing wings, and folding wings. The advanced technologies applied include CRG's SMP Veriflex™, dynamic modulus composites Veritex™, and dynamic modulus foams Verilyte™ [70].

Figure-10. SMP wing skin developed by CRG [91].

Besides, inflatable skins and elastomer skins feature large strain capability for morphing but low stiffness for resisting aerodynamic loads [30]. Corrugated structures and segmented structures are transformable and stiff, but they lack a smooth surface [43]. Novel variable stiffness materials are urgently needed to solve this problem. Similar to plastic, SMPs are stiff in their glassy state [43], and they become soft and rubbery with a large strain capability.

Nevertheless, SMPC morphing skins were applied using a variable camber wing structure [43, 92]. The variable camber wing with SMPC skin was found to be applicable to aircraft takeoff and landing. When heated above Tg, SMPC skins gradually become glassy as the temperature cools down. Resultantly, SMPC skins can withstand aerodynamic loads under a glassy state with a high modulus and alter their shape under a rubbery state with a low modulus.

SMP skins have already been investigated as folding wing, chord morphing wing, variable camber wing, deployable wing, and shear morphing wing [29, 84-86, 93]. In one application, elastic fiber-enhanced SMPCs were used in a variable morphing wing structure as adaptive skins (Figure-11). The structure comprised a fixed leading edge, a trailing edge, a metal sheet, a pneumatic artificial muscle (PAM) actuator, and SMPC skins.
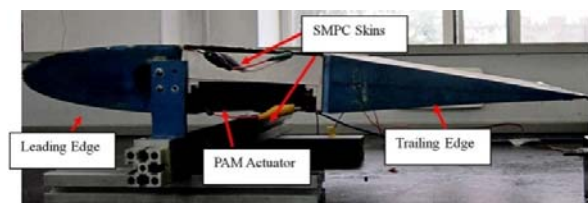

Figure-11. Camber morphing wing with SMPC skin [43].

However, some issues still exist in the repeated usage of pure thermoset SMPs. First, after a thermal–mechanical cycle, a slight out-of-plane deformation occurs in pure SMP samples [29]. This issue can be settled through an applied predefined strain. Second, for bearing the bending loads, SMPs are too brittle in the glassy state. Third, stress concentrations occur near the joints, which rips easily at high temperatures [94]. Thus, reinforcement materials such as glass fibers or carbon fibers have to be

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mixed into pure SMPs to improve their mechanical properties [95].

SMPCs exhibit high modulus and strength but their elongation strain is low. Glass fiber-enhanced SMPCs may fracture under a large extension strain because fibers can only withstand small extension strain. Elastic materials were mixed into pure SMPs to improve toughness by up to 200%. As a result, a large strain was achieved [96]. Such efforts could improve the reliability of SMPs. In the study, elastic fiber-enforced SMPCs were first fabricated. Then, the mechanical recovery and thermal properties of SMPCs were investigated. Finally, morphing skins based on SMPCs were installed on a variable camber wing structure to demonstrate their possible and appropriate applications.

Another study mixed elastic fibers into pure SMPs to improve the mechanical properties [43]. The 20% volume fiber-enforced SMPC skins were used in a variable camber morphing wing structure. The SMPCs clearly enhanced the toughness of the SMPs at room temperature with an acceptable reduction in Young's modulus, which made the materials tenacious in their glassy state. The SMPCs enhanced the strength and Young's modulus of the SMPs at high temperatures, thus indicating that elastic fibers can improve the safety of using SMPCs above Tg. The elastic fibers significantly enhanced the tear strength especially at high temperatures.

In terms of their application, SMPC structures are easy and safe to install. In a practical morphing aircraft, the application of such materials requires testing under flight conditions, including low-temperature conditions and the presence of dust, sand, rain, and hail. An investigation was conducted to addresses the basic characterization of SMPs as suitable structural materials for morphing aircraft applications [29].

Tests were carried out for monotonic loading in high shear at a constant temperature and at temperatures well below or just above Tg [29]. The SMP properties were dependent on temperature and time. The return of the SMPs to their original shapes needed to be unfettered. The testing results indicated that SMPs could be an attractive and promising component of skin materials for morphing aircraft. Their multiple state abilities allow them to easily change their shape. Once cooled, they are able to resist large loads.

However, the applications of SMPCs in aerospace are restricted by factors such as the limited types of high-temperature SMPCs suitable for the harsh space environment. Given their light weight, high strength–weight ratio, low density, low cost, low part count, simple design, good manufacturability, high shape deformability, and easily tailorable glass transition temperature, SMPs and SMPCs are expected to gain increasing potential in the development of multiple dimensions and in possible applications in aerospace.

CONCLUSIONS

SMMs offer numerous possibilities for the development of components and devices that are light, strong, stiff, and resistant to extreme environments in aerospace applications. The nano-layered and nano-composite coatings developed in recent years can sense corrosion and mechanical damage to aircraft skins, assess chemical and physical damage, promote adhesion and fatigue resistance, and offer self-cleaning possibilities.

Therefore, the development of SMMs as intelligent materials in the past few decades has paved a way to accomplish such properties. SMMs have stirred extraordinary consideration from researchers and scientists because of their ability to recollect two shapes at various conditions. This gives materials incredible potential for application in sensors, actuators, smart devices, and so on. The applications of SMAs and SMPs as smart actuators, sensors and smart skin for aircraft wing have proved beneficial for the industry. Wing structural morphing is a one of such dominant research topics in subsonic aerodynamic applications compared with other methods for enhancing aerodynamic proficiency. Research on airfoil morphing (which includes span, sweep, camber, and thickness distribution changes) has advanced with the use of various smart material technologies.

Also, the categorization of morphing based on the method of actuation causes a relatively distinct division of aircraft size, i.e., 1) conventional actuators are used in all aircraft sizes (except nano- UAVs), and 2) smart actuators are used in rotorcraft blades, and UAVs. Conventional actuators represent a vastly common actuation method in airfoil morphing, but they are being rapidly replaced by SMMs.

Furthermore, the optimization techniques utilized by many researchers have resulted in noteworthy developments, including novel smart actuators. However, significant technological challenges need to be addressed to make morphing airplanes a reality. Nonetheless, wing morphing has shown great promise and may eventually allow planes to be designed for all operating maneuvers with full efficiency.

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