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Smart Robotic Morphing Wing for Active Aerodynamics using Shape Memory Alloy

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Abstract: ***This research paper focuses on Shape Memory Alloys (SMA), their unique properties, training, power requirements along with their present applications. It also discusses in detail a new potential application of SMAas asmart robotic morphing wingfor active aerodynamics in UAVs and racecars. The paper presents the methodology for design and the conceptual design for the robotic wing. The various UAVs and Drag Reduction systems used currently, their merits and demerits are discussed, and a comparison is made between the existing system and the proposed system. Further, the airfoil selection, SMA training method, and process flow are also discussed.***

Keywords: Shape Memory Alloy, smart robots, active aerodynamics, morphing wings, Drag Reduction System

1. Introduction

In recent times smart devices have proven to increase the performance and efficiency in performing a given task in every walk of life. Robotics finds its application from defense industry to consumer products. Smart materials which can be trained and change shape are an ideal fit for soft robotics or places where actuation mechanisms cannot be placed due to various constraints.

The shape memory alloys (SMA) are materials that can retain their shape and when deformed return to their original shape as a response to external stimulus. They have ability to recover a large elastic deformation under thermomechanical loading. They display two distinct phases - martensite (low temperature phase) and austenite (high temperature phase). The metal can be deformed at lower temperatures when a SMA is in martensite form easily. Martensite to austenite transformation takes place when the metal is heated. In the austenite phase, the alloy will remember the original shape before deformation. Although many different alloys demonstrate the shape memory effect, but only a few which can recover from a large amount of strain/strain and still come back to their original shape, or generate a very high restitution force are of any interest for commercial use.Many materials exhibit the shape memory effect (SME), such as Cu-Zn, Cu-Zn-Se, Fe-Mn-Se, Au-Cd, etc.SMA based on Nickle Titanium alloy are the shape memory alloys used regularly in commercial applications, as they demonstrate great mechanical properties with shape memory characteristics and have a longer life, andbetter response time as compared to the others.

Applications

Vibration dampers for rocket launching and in jet engines incorporate SMAs. Similarly, a variety of actuator applications in jet engines are using Shape Memory alloys, which helps to significantly reduce their weight and increase efficiency.Wing-morphing technologies are another application.Development of variable camber flap, airfoil and ailerons is in progress.

SMA has been widely used in robotics as micro and mini actuator alloy biomimetic robotic such as earthworm, tapeworm, lizard, crawler robot and even human hand has been modeled. NASA is even planning to reinvent wheel using shape memory alloy

2. Literature Review

2.1 Properties of SMA

Shape memory alloys (SMAs) can be obtained in austenite or martensite states.The phase transformation plays the most important role in the SMA’s properties. Austenite has a cubic crystalline structure and is the original high temperature state whereas martensite is the low temperature state that shows a softer tetragonal or monoclinic crystalline shape.If stresses exist, the transformation from austenite to martensite may lead to detwinned martensite. The transformation from austenite to twinned martensite leads to negligible macroscopic change. Under the application of sufficient thermal or mechanical stress, the reorientation of twinned martensite into detwinned martensite can take place. These crystallographic effects are observed in each individual grain in polycrystals, and the total macroscopic change of the material is based on the total change of all the grains. Due to variation in orientation and local stress concentrations, this micromechanical normalizing leads to a smoother material response, because different grains experience transformation at different points in the thermomechanical loading path. For the scope of this paper, polycrystalline SMA components will be assumed. The transformation from austenite to martensite begins, in the absence of stress, at a temperature known as the martensite start temperature (Ms). The transformation continues to evolve as the temperature is lowered until the martensite finish temperature (Mf) is reached. When in the absence of stress, the SMA is heated from the martensitic form, the reverse change begins, at the austenite start temperature (given by As), and on reaching the austenite finish temperature (Af), the material is purely austenite. There is a hysteresis between the two transformation zones. Austenite transformation will always complete at a higher temperature than martensite transformation (Af>Mf). The temperatures at which the martensitic transformation start, and finish vary with stress, this is an important aspect of SMA.

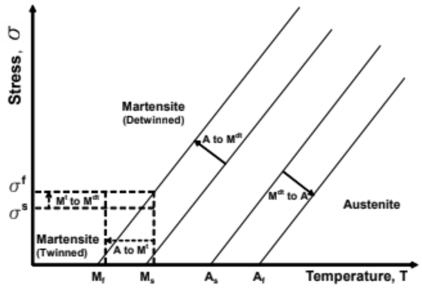

Figure 1: Stress dependence martensitic temperatures [1]

2.2 Shape memory Effect

The stress-free shape memory effect is the phenomenon which allows for recovery of the seemingly permanent deformation observed during detwinning. At the beginning of the loading (point A in Figures 2 and 3) the SMA is in its original austenitic phase. When the applied stress is low or zero or absent, the SMA transforms after dropping its temperature and cooling into martensite. In this cold martensite form it has the twinned or self-accommodated configuration which can be seen by B in Figures 2 and 3. As stress is applied, deformation takes place and large macroscopic strains are observed, causing the martensitic phase to be reoriented to fully detwinned state, (indicated by C in Figures 2 and 3). The elastic part of the total strain is recovered on unloading, while the inelastic part of the strain due to the detwinning process remains unchanged,because of the stability of de-twinned martensite. This point is shown by D. On reaching the temperature As, by heating the SMA at no stress, the opposite transformation to the original austenitic phase begins, whichstops at the austenite stop temperature Af. The inelastic strain due to reorientation is recovered, and thus the original shape (before deformation B–C) is regained.

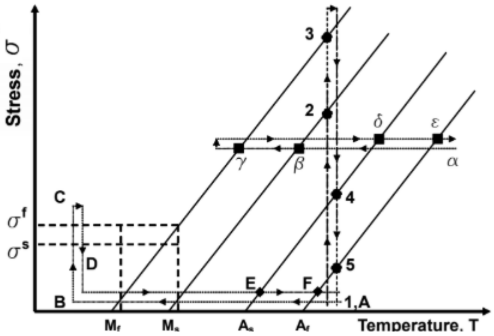

Figure 2: Phase Diagram stress-free SME [1]

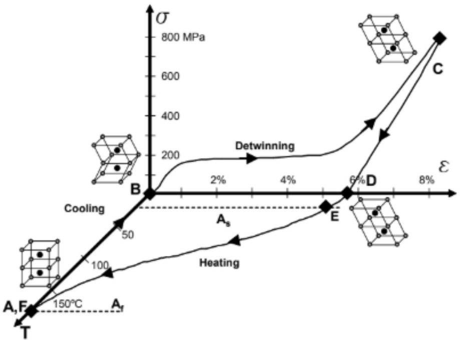

Figure 3: Stress-strain temperature cure for NiTi [2]

Large strains are associated with the phase transformation by the SMA. These stresses are developed by the combination ofboth the change of the crystal lattice structure from austenite to detwinned martensite, and the change in the elastic modulus during the change. However, this elastic contribution is minor.

2.2.1 One-way memory effect

The metal can be bent or stretched and will hold those shapes when it is in the cold or martensite state. Upon heating, the shape changes to its original. It will remain in the hot shape, until deformed when the metal cools again. Cooling from a high temperature, above Af does not cause a macroscopic shape to change in one way memory effect. Thus, we can conclude that a deformation is necessary to create the low-temperature shape.

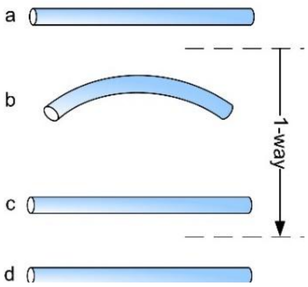

Figure 4: One way shape memory effect [8]

2.2.2 Two-way memory effect

The effect where the material remembers two different shapes is the two-way shape-memory effect. The two shapes are namely, one at low temperatures, and one at the high temperature. Materials having shape memory effect both during heating and cooling are said to possess two-way shape memory effect. Even without the application of any external force, the two way shape memory effect can be seen. This is possible because the SMA undergoes training with the two shapes. When the alloy learns to behave in a certain way, the alloy is said to be trained. Usually, the SMA remembers the cold temperature shape but forgets it as soon as it is heated. Having said thatwe can train the SMAtoremember its old shape by leaving some small crystallin reminders of the original low-temperature condition even during the hightemperature phases.

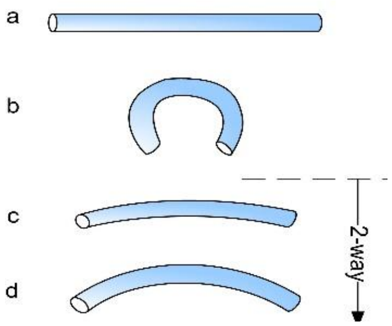

Figure 5: Two-way shape memory effect [8]

2.3 Pseudoelasticity

Whenever a shape memory alloy is at a temperature above AF, a property called pseudoelasticity can be observed. The macroscopic behavior of SMA is shown by the stress-strain curve (σ-ε) in the left figure below. This shows the pseudoelastic property of the SMA. Until the martensitic transformation, a mechanical loading causes an elastic change.

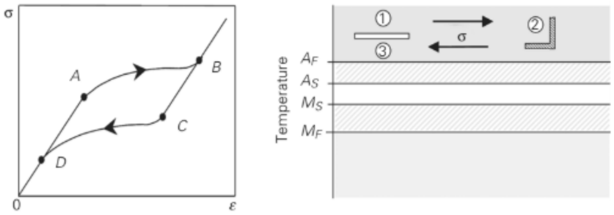

Figure 6: Pseudoelasticity [9]

A linear response is seemed for higher values of stress. Further, an elastic recovery of the shape memory alloy is seen during the unloading process. Reverse martensitic transformation can also be seen form points C to D. From point D onwards, the SMA exhibits an elastic discharge. However, there is a hysteresis loop associated with energy dissipation. This is because the path of the forward martensitic transformation and the reverse transformation path are not coincident.

3. Need for smart robotic morphing wing

3.1 Unmanned Aerial Vehicles

Traditionally UAVs have had fixed wings, and this limits the usage of the robot. The properties of the robot are thus defined by the wing design which in turn is dictated by the airfoil used. Hence a fixed wing UAV does not have the facility to change its characteristics mid-flight. Various control surfaces are thus required to steer the UAV or give it additional parameters for lift and drag, like the flaps, ailerons, gurneys etc. The SMA can be used to have a morphing wing which can be remotely actuated or can change its shapebased on the environmental factors. The smart wing can prove to be a huge help to change parameters of the UAV mid-flight.SMA in UAVs is used in the wing design, it helps the gliders have maneuverable properties and a maneuverable plane have gliding parameters. The wings are made of SMA wires or sheets and are internally actuated. The wires change the shape and gain the shape of the desired airfoil thus changing the properties of the UAV. It is also used in flapping wing UAV which closely resembles nature and takes the shape of a winged animal or insect. Here the SMA wires are used as primary actuation to help replicate the muscles and flap the wings.

3.2 Drag Reduction System

The drag reduction system (or DRS) is a driver-adjustable wing arrangementwhich can reduce aerodynamic drag to increase top speed. This in turn promotes overtaking. It consists of an adjustable rear and front wing of the car, which can move in response to driver commands or environmental conditions. The car's top speed is limited by the drag produced by the car itself. Various types of control can be used to actuate the wings such as driver controlled, driver initiated and active control. Several types of actuation methods may be used like pneumatic, electrical, electro-mechanical, or robotic wing.

Pneumatic Actuation
Pneumatic are simple and reliable. They are powered by a high-pressure tank regulated by the required force needed. The disadvantage of this method is that in case of multi-element wing, multiple linkage need to be used which results in a heavier system.

Direct Electronic Actuation
Electronic system consists of using servos directly mounted on each element, thus the number of servos required will be equal to the number of wing elements to actuate. However, the major problem is the packaging of the motors inside the wing itself. The weight of the two motors itself, used will be concern too.

Electro – Mechanical Actuation
Electro-mechanical actuation is similar to direct electronic actuation. It also uses servo motors to actuate the wings however, the wings are actuated through a link connected to the wings rather than direct mounting of the motor to the wings.

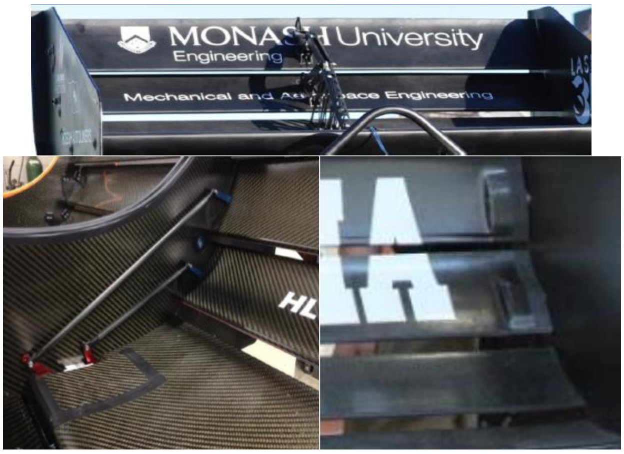

Figure 6: Types of DRS in FSAE [6]

The above actuation systems are generally heavy and bulky. They change the total angle of attack of the element, thus reducing the downforcetoo.Shape memory alloys can be used for morphing of wings and active aerodynamics for the reduction of drag in a racecar. The elements shape can be changed instead of altering the angle of attack. Thus, the requirement for an external power source and bulky mechanism is eliminated. The shape memory alloy wires would also reduce the weight of the element, it also gives more control to the driver and much more specific and precise control on the downforce and drag of the racecar. It can also autonomously be actuated by sensors on the wings. Thus, forming a smart robotic wing

4. Methodology

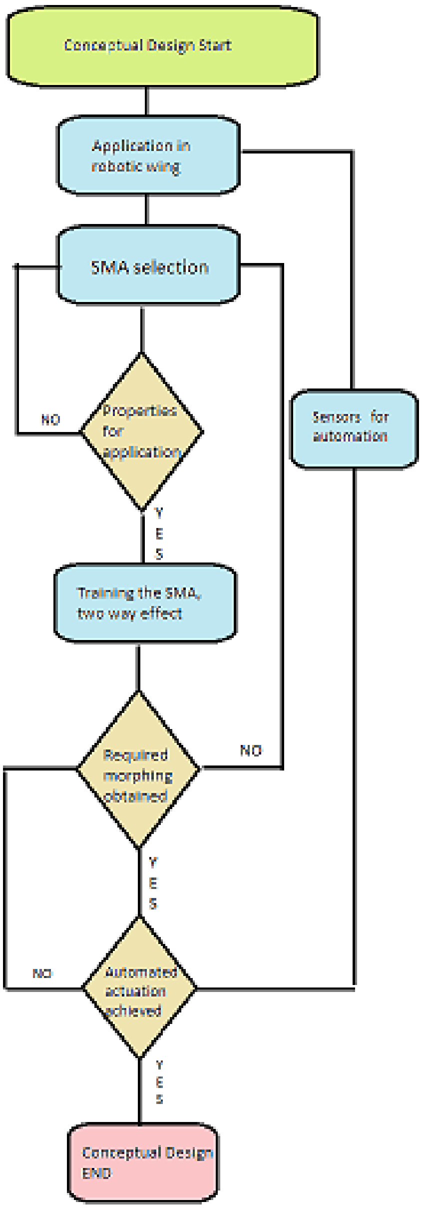

Figure 7: Methodology

5. Conceptual design

5.1 Robotic wing SMA selection

A variety of alloys exhibit the shape-memory effect. To control the transformation temperatures of the SMA alloying constituents can be adjusted. Among various material available we chose NiTi alloy because of its superior mechanical properties.Some common systems include the following:

Ag-Cd 44/49 at.% Cd
Au-Cd 46.5/50 at.% Cd
Cu-Al-Ni 14/14.5wt% Al 3/4.5wt%
Cu-Al-Ni-Hf
Cu-Sn approx. 15 at% Sn
Cu-Zn 38.5/41.5 wt.% Zn
Cu-Zn-X (X = Si, Al, Sn)
Fe-Pt approx. 25 at.% Pt

Fe-Mn-Si
Co-Ni-Al
Ni-Fe-Ga
Ni-Ti approx. 55–60 wt% Ni
Ni-Ti-Hf
Ni-Ti-Pd
Ni-Mn-Ga
Mn-Cu 5/35 at% Cu

Table 1: Properties of NiTi [1]

Properties	*Austenite*	*Martensite*
Density	6.45 g/cm^3	
Electrical Resistivity	$82*10^{-6}$Ω.cm	$76*10^{-6}$Ω.cm
Thermal conductivity	0.18 W/cm. K	0.086 W/cm. K
Thermal expansion coeff	$11*10^{-6}/^{o}C$	$6.6*10^{-6}/^{o}C$
Magnetic permeability	< 1.002	
Magnetic susceptibility	$3.7*10^{-6}$emu/g	$2.4*10^{-6}$ emu/g
Elastic modulus	75-83 GPa	28-40 GPa
Yield strength	195-650 MPa	70-140 MPa
Poisons ratio	0.33	

5.2 Training method of SMA

Two-way training was carried out on two pieces of wire to teach it to take shape even when cooled. Various Two-way training methods through which wire can be trained are as follows:

- One-time Martensite deformation.
- Thermomechanical cycling.
- Constrained cycling of deformed martensite.
- Pseudoelastic cycling.
- Reheating treatment.

From above mentioned techniques, thermomechanical cycling provided best 2-way effect in wire. Problem with One way martensite deformation method was that loading it beyond its recovery limit seriously deteriorates its hot shape. Reheating is comparatively new method and not much data is available regarding it. Hence, we decide to go with thermomechanical cycling in which best results were obtained from shape memory alloys and combined shape memory and pseudoplastic cycling.Figure below clearly shows maximum recoverable shape

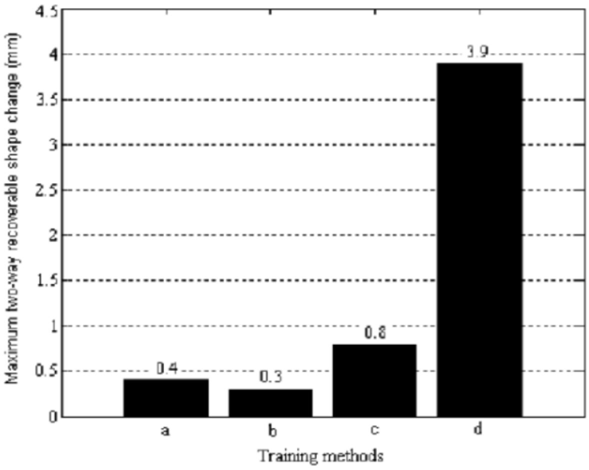

Figure 8: recovery by different methods [10]

Hence, in order to determine the strain that can be recovered we decided to perform a small training experiment as follow:

Specimen was cooled below Mfi.e at room temperature.

It was then loaded in this state to give desired cold shape.

Unload it completely.

Then, heat it above Af temperature.

Repeat above steps 50 no. of time.

In this case, comparatively significant change was observed and approximately change in angle was 30 degrees but it’s hot shape memory was lost. Hence, it was again trained on a fixture and the iterations were increased to 200.

5.3 Airfoil selection

Table 2: Airfoil selection

Parameters	*CH10*	*E423*	*s1223*
CL0	1.22	1.13	1.2
CLmax	2.03	2.04	2.201
CDmin	0.009	0.011	0.02
CD0	0.011	0.012	0.02
CL/CDmax	134	127	68.2
CL/CD0	109	93	62.7
Stall Nature	Sudden	Gradual	Sudden

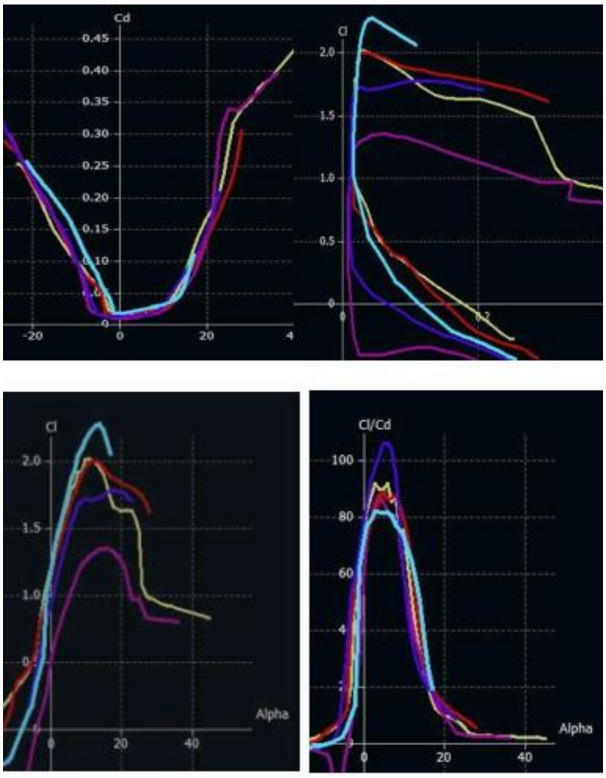

Figure 9: Airfoil Selection parameters

6. Conclusion

This paper thus presents the brief introduction on Shape memory alloys, its effects like shape memory effect namelyone- and two-way shape memory effect, and pseudoelasticity. A potential SMA application area in robotic morphing wing has been discussed.This smart wing can be used for active aerodynamics where the performance of a glider or the wings of a racecar can be altered based on the real-time environmental conditions and track requirements respectively. This robotic wing can be used in UAVs to change lift characteristics and in racecars to reduce the drag of the vehicle. The application in UAVs can help in converting a maneuverable plane into a glider and vice-versa.The DRS of a race car plays a major role in cars aerodynamics and control which can be altered using morphing wings. The possible use of the above can also be found in turbine blades. Alloy chosen for the concept is NITINOL due to its superior characteristics like higher strength, better response time, low current requirement, and longer life. Various airfoilswere analyzed and among theseS1223 and E423 were selected for further analysis. Thus, the application of SMA for active aerodynamics in a smart robotic morphing wing is discussed and its use in UAVs and DRS has been talked about. The material selection, airfoil selection and the design flow are detailed above.

7. Future Scope

Detailed design of the robotic wing and CFD simulations of the FSAE car to verify the drag reduction results is the logical next step. Further, a prototype of the SMA wing should be made to test the concepts proposed in this paper. The morphing temperature of the SMA can be practically ascertained through lab experiments and the alloy should be trained to obtain the best results between two airfoils. Moreover, the SMA can be tested with various sensors and battery outputs for the best possible combination.

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