Application of shape memory alloys in engineering – A review

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Abstract: Shape Memory Alloy is a smart alloy which retains their original shape under thermomechanical or magnetic variation. Shape Memory Alloy are widely used in different engineering field because of its superior properties and variety of application. Recent research of SMA has been applied in the field of Aerospace, Automotive, Biomedical, and Robotics. This memory effect is due to the presence of austenite and martensite crystalline structures. These alloys are bio-compatible, lightweight, and also possess a high force-to-weight ratio. Due to this SMA actuators are very much suitable for soft robotic applications. However, due to high cooling times during phase change, SMA has small bandwidth and low operating frequencies. This alloy can replace a sensor as it performs the same work done by sensors or transducer. An extensive review of history, material characterization, and opportunities of SMA in the engineering field.

Keywords: SMA; Biomedical; Phase change; Alloys

1. Introduction

This alloy is referred to as a smart alloy that can be deformed and returns to its pre-deformed shape when subjected to temperature change. In general, Shape memory alloys (SMAs) can memorize their earlier form when triggered by a certain stimulus like thermomechanical or magnetic variation. This alloy is also called to be memory alloy or smart alloy or muscle wire, Figure 1[1] Recent technology demands ‘smart’ systems with intelligent functions. To be specific, for the automotive industry: increased weight directly results in high fuel consumption resulting in high cost of the product. SMA offers multiple degree of magnitude when compared to traditional materials. Hence, the requirement in the field of engineering and applications has increased in consumer products and manufacturing applications. Even though other alloys, low in cost are available in the market, stability, practicability and thermo-mechanic performance are of concern. Nickel Titanium-based alloys are preferred more for various applications. Previous studies have showcased the application of this effect in micro-structural mechanisms and various other engineering fields [2]. In any application, SMA is subjected to cyclic continuous load to ensure mechanical properties like fatigue, stress-strain effect, and fracture. In this work, the shape memory materials properties and characterization are also being discussed and how it will be applied to the engineering field according to its properties.

2. Shape memory alloy

Shape Memory Alloy has unique characteristics such as memory effect, thermomechanical, and superelasticity. These alloys are good to memorize the process between two transformation phase that
is temperature or magnetic field dependent (SME) [3]. Thermomechanical is a property when the smart material is subjected to large plastic strain, it can recover its original position (shape or size) by applying heat. Super elasticity is a property that the material is capable to recover its original form from non-linear strain instantaneously upon stress removal or load removal [4].

2.1 History of SMA
Initially, in 1930 the shape memory effect was identified. A Swedish physicist by the name, Arne Olander, identified that gold-cadmium alloys were able to exhibit the effect. Otsuka and Wayman identified the pseudoelastic behavior of Au-Cd alloy. Similarly, the shape memory effect has observed in materials like Copper-Aluminium-Nickel alloy in the 1950s. W.Buehler and Wang explored this effect in a NiTi alloy, which is called as nitinol (Ni-Ti). This Nitinol alloy was first discovered by the United States Naval Ordinance Laboratory.

Since the 1980s, the utility of Ni-Ti alloy has been in many areas due to the lightweight and more compact nature. In the 1990s, this technology was introduced in the Shape memory material community [5].

2.2 Phase Transformation in shape memory alloy
Shape memory alloy exists with varied crystal structures in two different phases when it is subjected to some external factor. SMAs have a simple application of deforming by applying force and recovering to their original shape either heating to a particular temperature or applying a magnetic field. SMAs can have six-phase transformations (High phase temperature - austenite and Low phase temperature – Martensite). The transformation happens by shear lattice distortion. When the Shape Memory alloy is heated, its temperature gets increases and after a certain temperature limit, the martensite structure begins to transform into an austenite structure. Change of structure happens from austenite to martensite upon cooling without the application of an external factor. The phase change of martensite to austenite is said to be forward transformation. The austenite to martensite phase transformation is said to be “reverse transformation”. In practical, these alloys may be produced by electron beam, Vacuum and plasma melting but vacuum melting is considered to be the best. Transformation begins at \( A_s \) and ends at \( A_f \) is the temperature where the transformation is completed. Reversal to martensite happens during the cooling process at Ms and ends at Mf temperature [6].

![Figure 1. Crystal structures and Phases](image-url)
In the beginning, the austenite phase starts to deform and changes to twinned martensite. Application of the load to the materials in the twinned martensitic phase, enables to reverse and detwin the martensite which causes a change in shape and the deformed configuration under removal of the applied load (Figure 2). This phenomenon of heating of SMA above Af will result in reverse form phase change and shape recovery exists and again cooling back to a temperature below Mf will result again in twinned martensite. This Process of phase transformation from one phase to another is said to be the Shape Memory Effect, Figure (3-5) [7].

According to the effect, SMAs can be categorized into three characteristics. They are 1) Single-way shape memory effect 2) Double-way shape memory effect 3) Pseudo elasticity.
2.2.1 Single-way effect
The material subjected to deformation will retain its deformed shape under cold condition and gets back to original shape upon heating.

2.2.2 Double-way effect
Memorizing the form at the top and bottom temperatures are referred to as a double way effect. It provides partial recovery strain produced by one-way SMAs for the materials under consideration.

2.2.3 Pseudo elasticity
After the application of the mechanical type of loading, SMA gets back to the original shape at various temperatures of austenite and martensite in the absence of a thermal effect.

2.3 Engineering effect of SMA
The shape memory and pseudo effects are the important properties to be reviewed and understood nowadays [8]. Initially, the alloy is in its parent austenitic phase. Removal of stress will result in a martensitic phase upon cooling in the twinned form. At higher stress, the martensitic phase is transformed to a fully detwinned form, which can be observed as large macroscopic strains. Further heating at lower load, phase change to austenitic phase begins, reaches As, and ends at Af. Due to inelastic strain, the SMA regains the original form.

Figure 4. Experimental stress-strain temperature.[7]  
Figure 5. Pseudo-elastic loading paths.[7]
3. Applications of SMA
Research around the globe is attempted to improve the areas and attributes of SMAs, by improving identifying new compositions and temperature ranges. So, the intensive research work has to continue for improving fatigue life and stability of SMA. The most widely used SMA in engineering fields are 1) Aerospace application 2) Automotive application 3) Biomedical application.

3.1 Aerospace application
This industry is looking for improved materials and solutions for its applications. Wind morphing is a practical solution that can be met in different conditions [9]. Researchers have brought to light both the shape memory and pseudoelastic effects in solving industrial problems of aerospace. Implementation of this technology in fixed-wing aircraft, rotorcraft, and spacecraft has gained importance. It describes the aerospace application of alloys and the challenges faced by the designer of such a system [10].

SMA coupling of hydraulic lines has impressive application in fighter jets, people gathered their great interest in aerospace application. Some of the applications are sealers, actuators, vibration-dampers, etc, Figure (6-7).

![Figure 6. SMA airplane wing](image1)

![Figure 7. Boeing variable chevron](image2)

A program was used to develop and demonstrate the shape memory alloys to optimize the performance of lifting bodies. An SMA tube was used to initiate wing expansion by twisting. Though the alloy was able to deliver the required actuation the tube, in particular, was not able to deliver at full effort span wing. This work was performed by the Air Force Research Lab (AFRL). The Smart and Aircraft and Marine Propulsion System Demonstration (SAMPSON) program introduced the use of such materials in modifying the geometry of inlet conditions of different propulsion systems of aircraft. Validation was done on a full-scale F-15 inlet. First wind tunnels was developed at NASA in which one SMA is set in opposition to another [11].
This effect can be used to rotate the inlet cowl to change its cross-section of area. SMA bundles were loaded in two different directions, heating one bundle resulting in deformation which is used to recover its original form. After the bundle in heating condition was cooled, the earlier detwinned bundle was again heated, and actuation occurred in the opposite direction [12-13]. The Adaptive Nozzle made of SMA is a most developed product which is used to aid noise reduction in gas turbine engines. In aircraft, SMA thin plates are attached to Ti-6Al-4V alloy. At a high power setting, the hot SMA will actuate and employ the serration in the air flowing of engines. At low power settings, the engine allows Ti-component which is passive elastic is used to reset the serration of SMA to returned configuration [14].

3.2 Automotive application

The application of SMA in the automotive actuator is classified as follows. 1) Low power for comfort 2) high power vehicle control 3) high-frequency control. However, the first category is generally most suitable than the other two categories. Earlier literature has shown wear resistance and bio-compatible nature of the alloys are best compared to conventional materials [1].

In recent times, manufacturers are eagerly presenting and implementing SMAs in their vehicles. The pressure control valve which works under thermal expansion is embedded in Mercedez-Benz automatic transmissions. Manufacturers like Daimler, Mercedes, and Benz produced pneumatic valves with SMA for their car seats. The SMAs also referred as smart composites and it is being utilized in doing multifunctional operations.

![Image](image1)

**Figure 8.** Emerging General motors SMA [15].

![Image](image2)

**Figure 9.** Automotive application [1].
The application of the concept in automotive batteries is going to be of great challenge. The majority of applications are easily achievable with NiTi SMA. The SMA actuators have been looked at as a substitute to electromagnetic actuators in the field of automotive replacing many electronic components. Due to its capacity to adapt to change, it finds application also in the area of aerodynamics, Figure (8-9) [15]. Recently, Chevrolet was the first vehicle fitted with an actuator made of SMA to close the trunk lid. The versatility of SMA actuator also useful in designing the Pantograph and Eagle mirror, Figure 10. The enormous potential of SMAs has been further developed in recent advanced technology by the designers in design making [1].

![Figure 10. Eagle Mirror Prototype.](image)

### 3.3 Bio-Medical Application

The application of SMA in the bio-medical field can be categorized into three. 1) Orthodontic field 2) Orthopedic field 3) Vascular field 4) Neurosurgical field. It was introduced in the biomedical field in 1975, by Dr. Andreasen of Lowa University. The Usage of Ni-Ti Wires in the buccal cavity at the austenitic phase has been employed for recent years in dental diagnosis with multi-brackets. These NiTi wires generate an all-round force for the brackets for good dental movement. SMAs wire also found application in Palatal arches. Table 1 illustrates the historical developments of alloys in the bio-medical field, Figure 11.

![Figure 11. SMA orthodontic wires and distractors.](image)
Pseudo elastic behavior of SMA in Orthodontic field, for orthodontic distractors [17]. The Pseudo elastic effect of the Ni-Ti alloy is also used as a nail in fractured elongated bones. In both Orthodontic and Orthopaedic treatments, physiotherapy of partially atrophied muscles is exploited through the properties of SMA materials [18].

Figure 12. SMA plate for mandible fracture.[16]  Figure 13. Spinal vertebrae spacer.[16]

Simpon filter was the first ever used vascular instrument in SMA application. NiTi alloys are also used as a neurosurgical stents. Stents are nets made up of metallic which opens a stenotic vessel that enables the flow of blood to peripheral tissues. Recently stenotic and cardiac valves were made of this alloy. Coils, stents, and micro guidewires are also the other applications of this alloy, Figure (12-14) [18]. The stents treatments aim to recover the flow of blood flow through the narrowed lumen. Because of the rigidity of SMA coils and stents, they are preferred over the conventional or classical type one. Micro guide waves are used for positioning the stent [16].

| Year | Device                                      |
|------|--------------------------------------------|
| 1963 | Discovery of nitinol                       |
| 1971 | Orthodontic braces                         |
| 1983 | Nitinol stent                              |
| 1977 | Simon Vena cava filter                     |
| 1995 | Laparoscopic retractor                     |
| 2000 | Abdominal wall lift                        |
| 2007 | Endoscopic bleeding control device         |
| 2008 | Thin film microtube and stent              |
4. Conclusions

Although, there are more than 10000 patents have been published, only three important fields of various applications are discussed in this paper. After the first successful commercially After 1969, the demands for SMAs alloy have been drastically increasing day by day. Particularly in the bio-medical application, there has been a lot of inventions is being introduced to society. Apart from manufacturing applications like aerospace and automotive; biomedical fields are also introducing new SMA alloys.

Design of SMA for future application is being considered among communities. The new developments in the area of fabrication and treatment of SMAs are to be more robust while designing any applications. Introducing the new design approaches and novel applications are also developed in future trends and finally, the computational models of SMA behavior are studied for further advancements.

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