Shape Memory Alloy (SMA) A Multi Purpose Smart Material

Parveen Kumar, Sindhu Kumar

***Abstract*— Shape memory alloys are mostly functional intermetallics which are now practically being used for making actuators, couplings, medical guide wires etc., and are also used for smart materials, which already exist. In this paper, various developments on shape memory alloys and martensitic transformations, on which shape memory effect and superelasticity are based, are reviewed. Along with this, we have also discussed the ductility and density of point defects in inter-metallics, as they are major problems in intermetallics in general. These materials have the tendency to regain their original shape after a deformation that seemed irreversible.**

***Index Terms*— Intermetallics, miscellaneous, Shape-memory e€ects; Shape-memory alloy applications**

I. INTRODUCTION

Shape Memory Alloys (SMA's) are novel materials which have the ability to return to a predetermined shape when heated. When an SMA is cold, or below its transformation temperature, it has a very low yield strength and can be deformed quite easily into any new shape--which it will retain. However, when the material is heated above its transformation temperature it undergoes a change in crystal structure which causes it to return to its original shape. If the SMA encounters any resistance during this transformation, it can generate extremely large forces. This phenomenon provides a unique mechanism for remote actuation.

A shape memory alloy (SMA, smart metal, memory metal, memory alloy, muscle wire, smart alloy) is an alloy that "remembers" its original, cold forged shape: returning the predeformed shape by heating. This material is a lightweight, solid state alternative to conventional actuators such as hydraulic, pneumatic, and motor based systems. Shape memory alloys have applications in industries including medical and aerospace.

Shape Memory materials have the ability to regain their permanent shape after a deformation that seemed irreversible. The shape recovery is triggered by an external stimulus which is mainly a temperature that passes a critical point. But it depends on the specific material which type of energy should be added to trigger the shape recovery. There are for example also materials that are triggered by radiation. The shape memory alloys (SMA) use a martensite austenite transformation to achieve the shape memory effect (SME) and the super elastic effect. Shape memory polymers (SMP) on the other hand have different types of mechanisms. The characteristics of the polymer chains or the characteristics of the different phases in the material are responsible for this effect. A SMA gets its permanent shape by heat treatment and the permanent shape of a SMP is in general obtained during fabrication.

This rare phenomenon offers a wide range of possible applications. Imagine for example a damaged car bumper that regains its original shape after a heat treatment. Shape memory materials can also be useful in aerospace applications. The unfolding of antennas or other equipment can be driven by the shape memory effect. The external stimulus can be an electric current that creates Joule-effects in the SMA. This manner of unfolding can result in a weight reduction of spacecrafts or satellites. Another application is a heat engine which uses the SME to convert thermal energy in mechanic energy.

II. HISTORY OF SMA

A Swedish physicist Arne Olander discovered "the Shape Memory Effect" (SME) in goldcadmium (AuCd) alloy in 1932. The alloy could be deformed when cool and then heated to return to original "remembered" shape. The metal alloys with SME are called "Shape Memory Alloys" (SMA). In 1958, SME was demonstrated at the Brussels World's Fair, where the SME was used to cyclically lift a load mass. Researchers of U.S. Naval Ordnance Laboratory found SME in nickel-titanium (NiTi) alloy in 1961 by accident, while studying the heat and corrosion resistance of NiTi. Today, the NiTi alloys are commonly referred to as "Nitinol", for NiTi Naval Ordnance Laboratory.

The benefits of NiTi alloys, such as lower costs, smaller dangers (from health standpoint) and easier manufacturing and machining methods refreshed the interest in SME and its applications. In 1970's, commercial products began to emerge. First devices were static, taking advantage of a single dimensional change, for example fasteners, couplings and electrical connectors. Then, SMA devices started to perform dynamic tasks as actuators. Ambient temperature-controlled valves and clutches were the first applications, later actuators with resistive heating and thus electrical control were proposed to be used in micro-robotics, for example. More sophisticated devices are studied continuously, for example [2, 3, 4].

Parveen Kumar, Mechanical Engg. Dept, Echelon Institute of Technology, Faridabad, Haryana
Sindhu Kumar, Mechanical Engg. Dept, Echelon Institute of Technology, Faridabad, Haryana

III. PRINCIPLE OF OPERATION

Shape Memory Alloys, for example Ag-Cd, Au-Cd, Cu-Al-Ni, Cu-Sn, Cu-Zn-(X), In-Ti, Ni-Al, Ni-Ti, Fe-Pt, Mn-Cu and Fe-Mn-Si alloys, are a group of metallic materials having ability to return to a previously defined shape when subjected to appropriate thermal procedure.
The SME occurs due to a temperature and stress dependent shift in the material's crystalline structure between two different phases, martensite (low temperature phase) and austenite (high temperature phase). The temperature, where the phase transformation occurs, is called the transformation temperature. Figure 1 is a simplified representation of material's crystalline arrangement during different phases.

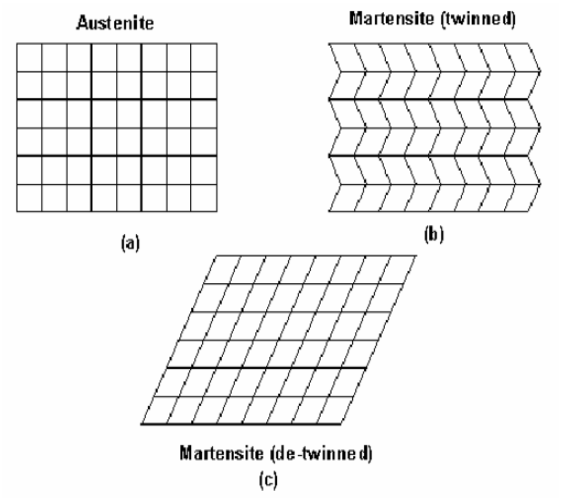

Figure 1: Crystalline arrangement of SMA in different phases.

In austenite phase, the structure of the material is symmetrical; each "grain" of material is a cube with right angles (a). When the alloy cools, it forms the martensite phase and collapses to a structure with different shape (b). If an external stress is applied, the alloy will yield and deform to an alternate state (c). Now, if the alloy is heated again above the transformation temperature, the austenite phase will be formed and the structure of the material returns to the original "cubic" form (a), generating force/stress.
An example of an SMA wire is represented in Figure 2. If the wire is below the transformation temperature (and therefore in the martensite form), it can be stretched with an external stress. Now, if the wire is heated to austenite phase, it will generate force/stress and recover the original, shorter, shape.
Also, hysteresis and non-linear behaviour are seen from Figure 2. The change in the SMA crystalline structure is not thermodynamically reversible process due to internal frictions and creation of structural defects. When heated, SMA follows the upper curve, As is the temperature, where austenite phase starts to form and in Af the material is 100 % austenite. When the alloy cools, it follows the lower curve: Ms is the temperature, where martensite starts to form and in Mf the alloy is 100 % martensite.

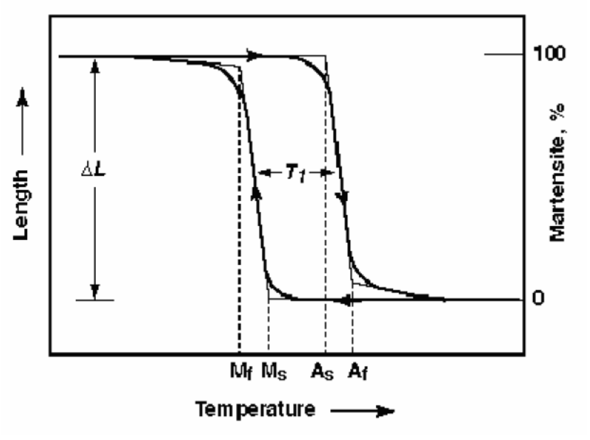

Figure 2: Contraction of an SMA wire as a function of temperature.

IV. TYPES OF SMA

1. One way memory effect

•When a shape memory alloy is in its cold state, the metal can be bent or stretched and will hold this shape until heated above the transition temperature.
•Upon heating, the shape changes to its original.
•When the metal cools again, it will remain in the hot shape until deformed again.
•In this case, cooling from high temperature does not cause macroscopic shape change.

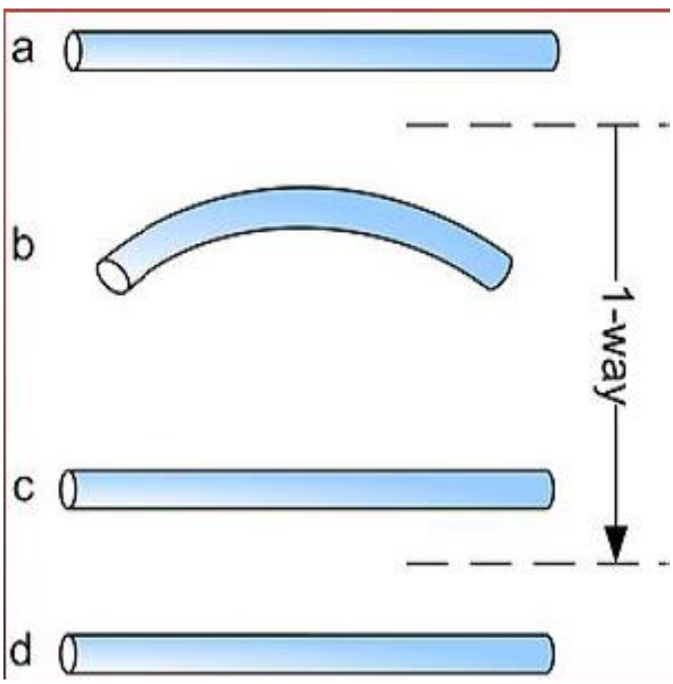

Figure 3: One Way SMA

2. Two way memory effect

•This is the effect that the material remembers two shapes: one at high temp and the other at low temperature.
•These metals show shape memory effect during both cooling and heating.

•The metal can be trained to leave some reminders of the deformed low temp condition in the high temp phases.
•Above a certain temp, the metal loses the 2 way memory effect. This is called "amnesia"

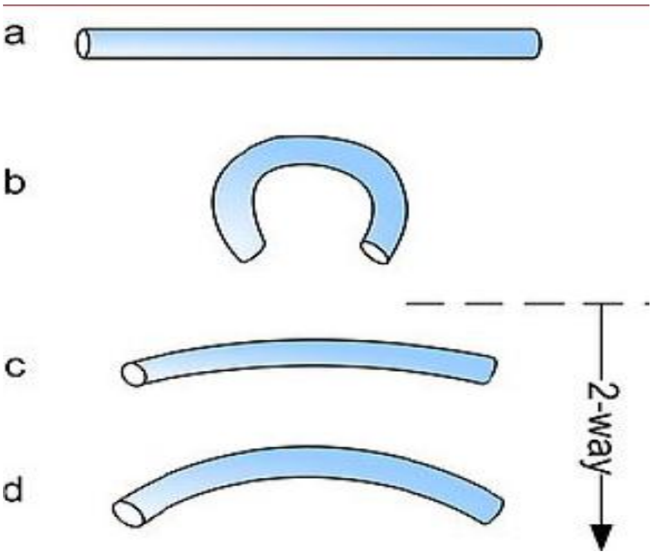

Figure 4: Two Way SMA

V. APPLICATIONS OF SMA

There are quite a few devices utilizing SMA commercially available. Some of these are described below. Raw material for SMA elements is available from several companies, as well as ready-touse (heat treated) SMA wires, expanding and contracting springs, and superelastic tubes.

- **Frangibolt non-explosive release mechanism for spacecrafts**

The Frangibolt release mechanism by TiNi Aerospace, Inc. is designed for spacecraft to provide safe and controllable deployment of spacecraft payloads. Utilizing an expanding SMA cylinder with integrated heater element, the device is able to break the bolt connecting the load to the spacecraft. The release is therefore possible without explosives.
Several different models for different bolts and payload weights (up to 5000 lbf/2300 kg) are manufactured. The device is re-usable after compression of the SMA element with external tool.

Figure 5: Frangibolt non-explosive release device.

- **Pinpuller non-explosive release mechanism for spacecrafts**

The pinpullers, also manufactured by TiNi Aerospace, Inc., are SMA wire actuated devices designed for securing and releasing of payloads in spacecrafts. As Frangibolt, the pinpullers offer small size, re-usability, reliability, safety and efficiency.

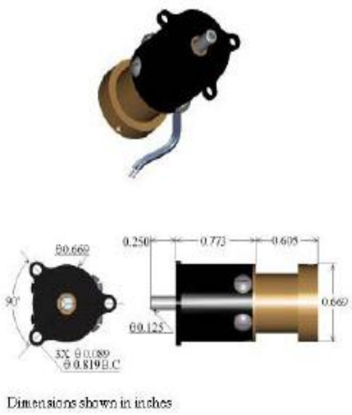

Figure 6: Pinpuller release mechanism.

- **Proportional pneumatic microvalve**

TiNi Alloy Company manufactures a pneumatic microvalve using TiNi thin film. The valve is able to control the airflow proportionally, replacing a conventional solenoid valve. Although in a prototype phase, the commercial distribution of the device should start soon.

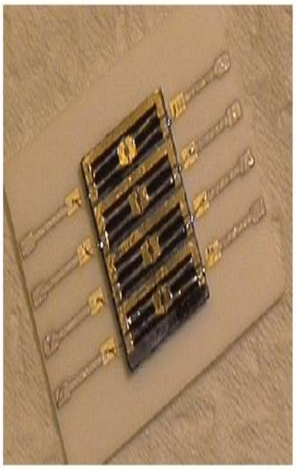

Figure 7: An array of four microvalves, the size of the array is 12.5 mm x 15 mm.

- **SMA actuated microrobots**

Japanese Toki Corporation has designed several microrobots utilizing SMA wires. IR controlled 8-legged microrobot, IR controlled microsubmarine, Micro Arm Robot and others have been constructed, but not sold commercially. Toki has developed an own SMA material called "BioMetal".

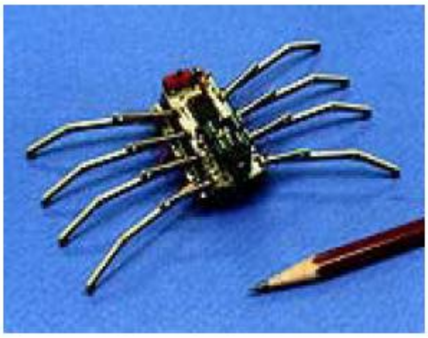

Figure 8: 8-legged microrobot with BioMetal wires.

• Linear SMA actuator

Advanced Materials and Technologies Corporation has several actuators driven by SMA elements, including an actuator generating linear movement and a maximum of 30 N force with a NiTi spring. More devices can be found from their web site.

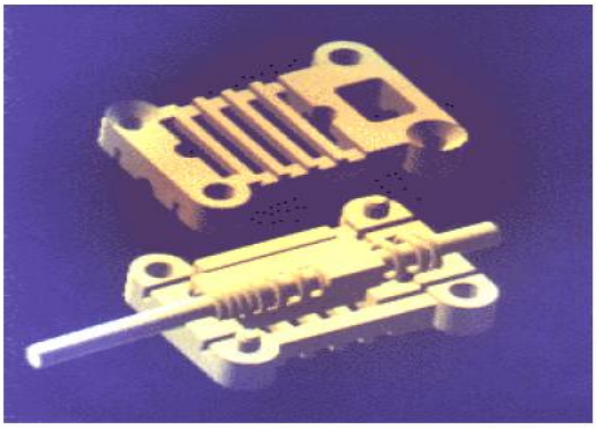

Figure 9: A linear NiTi actuator by AMT.

• Medical devices

There are many applications in medical field. For instance: dental archwires, microsurgical tools, micrograppers, stents, catheters, guiding wires for catheters, implants.

Figure 10: Surgical tools, microgripper and stents.

VI. CONCLUSION

SMA materials offer interesting possibilities for actuator applications. The benefits such as, a large force with small dimensions and weight, a large deformation and relatively simple heating and cooling arrangements give opportunities to design micro-scale devices. On the other hand, the disadvantages such as, the requirement for a bias mechanism, large heating currents, long cooling times, cycling effects and non-linear due to the deformation hysteresis and drift reduce the overall competitiveness of SMA actuators.

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