Nitinol a Shape Memory Alloy - A Review

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Abstract— Shape memory alloys (SMAs) belong to a class of shape memory materials (SMMs), which have the ability to 'memorise' or retain their previous form when subjected to certain stimulus such as thermo mechanical or magnetic variations. SMAs have drawn significant attention and interest in recent years in a broad range of commercial applications, due to their unique and superior properties. One such of those unique materials called Nitinol has been explained. Researchers have been carried out to evaluate the mechanical behaviour of Ni-Ti alloys, including their tensile, torsion and fatigue properties. The present work presents the phase transformations, elastic behaviour, properties and methods of manufacturing and training of Ni-Ti alloy of both Superelastic as well as thermally activated wires.

Key words: Phase Transformation, Nitinol, Ni-Ti, Superelastic, Thermally Activated

I. Introduction

The technology push, towards 'smart' systems with adaptive and/or intelligent functions and features, necessitates the increased use of sensors, actuators and micro-controllers; there by resulting in an undesirable increase in weight and volume of the associated machine components. The development of high 'functional density' and 'smart' applications must overcome technical and commercial restrictions, such as available space, operating environment, response time and allowable cost. Shape memory alloy (SMA) or ''smart alloy'' was first discovered by Arne Ölander in 1932. A shape-memory alloy (SMA, smart metal, memory metal, memory alloy, muscle wire, smart alloy) is an alloy that "remembers" its original shape and that when deformed returns to its pre-deformed shape when heated. 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 robotics and automotive, aerospace and biomedical industries. The two main types of shape-memory alloys are copper-nickel-aluminum and nickel-titanium alloys but SMAs can also be created by alloying zinc, copper, gold and iron.

Since now we've discussed the shape memory alloys, among them we will be discussing about one of the nickel-titanium alloys called NITINOL. NITINOL (Nickel Titanium Naval Ordinance Laboratory), is a metal alloy of nickel and titanium, where the two elements are present in roughly equal atomic percentages e.g. Nitinol 55. NITINOL alloys exhibit two closely related and unique properties: shape memory effect (SME) and super-elasticity. Shape memory is the ability of NITINOL to undergo deformation at one temperature, then recover its original, undeformed shape upon heating above its "transformation temperature". Superelasticity occurs at a narrow temperature range just above its transformation temperature; in this case, no heating is necessary to cause the undeformed shape to recover, and the material exhibits enormous elasticity, some 10-30 times that of ordinary metal.

II. Nitinol Phases and Transformations

Nitinol's unusual properties are derived from a reversible solid-state phase transformation known as a martensitic transformation, between two different martensite crystal phases. [3] Practically, SMAs can exist in two different phases with three different crystal structures (i.e. twinned martensite, detwinned martensite and austenite) and six possible transformations (see Fig. 1). The austenite structure is stable at high temperature, and the martensite structure is stable at lower temperatures. When a SMA is heated, it begins to transform from martensite into the austenite phase. The austenite-start-temperature (As) is the temperature where this transformation starts and the austenite-finish-temperature (Af) is the temperature where this transformation is complete. Once a SMA is heated beyond as it begins to contract and transform into the austenite structure, i.e. to recover into its original form. This transformation is possible even under high applied loads, and therefore, results in high actuation energy densities. During the cooling process, the transformation starts to revert to the martensite at martensite start-temperature (Ms) and is complete when it reaches the martensite-finish-temperature (Mf) (Fig. 2). The highest temperature at which martensite can no longer be stress induced is called Md, and above this temperature the SMA is permanently deformed like any ordinary metallic material .Crucial to Nitinol properties are two key aspects of this phase transformation. First is that the transformation is "reversible", meaning that heating above the transformation temperature will revert the crystal structure to the simpler austenite phase. The second key point is that the transformation in both directions is instantaneous.

Martensite's crystal structure (known as a monoclinic) has the unique ability to undergo limited deformation in some ways without breaking atomic bonds. This type of deformation is known as twinning, which consists of the rearrangement of atomic planes without causing slip, or permanent deformation.

The alloy training temperature is 500°C. That is when we want a particular shape for the given alloy, the alloy is forcefully held in the needed different shape in its martensite phase then it's heated at around 500°C. When this happens the alloy remembers this current shape as its original shape. Since the alloy is still in austenite phase, it's suddenly kept in cold water so that it changes back to the martensite phase quickly. Thus at the normal room temperature at its martensite phase the alloy gains and memorizes its new shape.

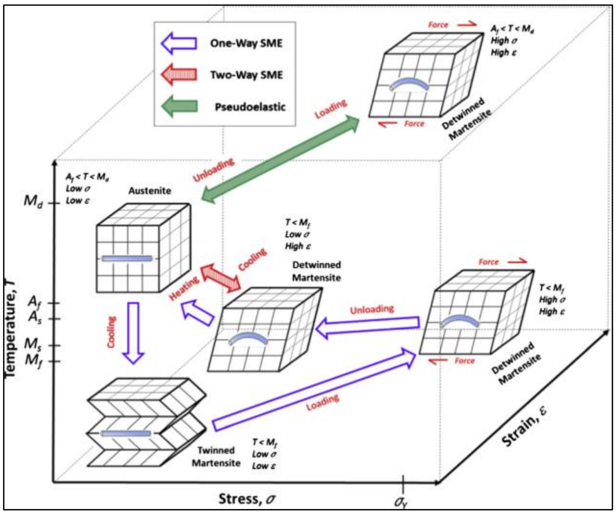

Fig. 1: SMA phases and crystal structures [3]

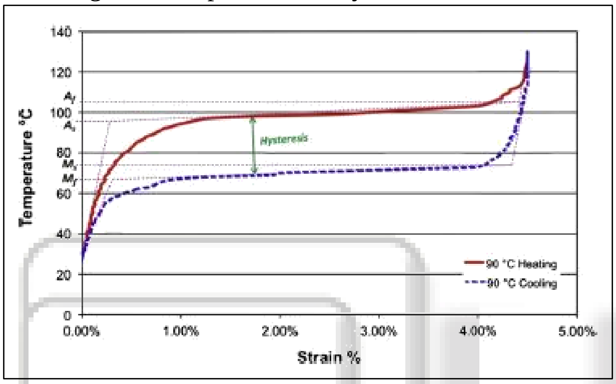

Fig. 2: Ni-Ti SMA phase transformation [3]

III. NITINOL SUPERELASTICITY AND SHAPE MEMORY

A. Superelasticity

Superelasticity, sometimes called pseudoelasticity, is an elastic (reversible) response to an applied stress, caused by a phase transformation between the austenitic and martensitic phases of a crystal. It is exhibited in shape memory alloys. Pseudoelasticity is from the reversible motion of domain boundaries during the phase transformation, rather than just bond stretching or the introduction of defects in the crystal lattice (thus it is not true superelasticity but rather psuedoelasticity). Even if the domain boundaries do become pinned, they may be reversed through heating. Thus, a pseudoelastic material may return to its previous shape (hence, shape memory) after the removal of even relatively high applied strains.

B. Shape memory

As discussed earlier the shape memory is that property which "remembers" its original shape and that when deformed returns to its pre-deformed shape when heated. NITINOL based SMAs are preferable for most applications due to their stability, practicability and so is the most vastly used shape memory alloy in majority fields. Transition temperature is 20-50°C, that is once when the alloy is deformed at around this temperature the alloy remembers and starts regaining its original shape repairing its deformed crystal structure.

(Figure 3b) suggests that austenite to martensite transformation may be exclusively thermal-driven due to the fact that test temperature lay exactly within the temperature range previewed to the structural transition of such alloy. Each Ni-Ti alloy depicts a specific range of temperature for the phase transformation. The superelastic wires used in the scope of this study were austenitic active with As = –15 ± 5 °C whereas the thermally active wire was martensitic active with As = +30 ± 5 °C. Based on (Figure 3a), the superelastic wire was originally austenitic. In this case, it can be seen that the transformation to martensite is stress-induced and reversed upon unloading.

[2] Below figure represents the stress-strain plots of NITINOL material as received and 1-month used 0.016 inch Ni-Ti wires. a) superelastic (As = –15 ± 5 °C); and b) thermal activated wires (As = 30 ± 5 °C).

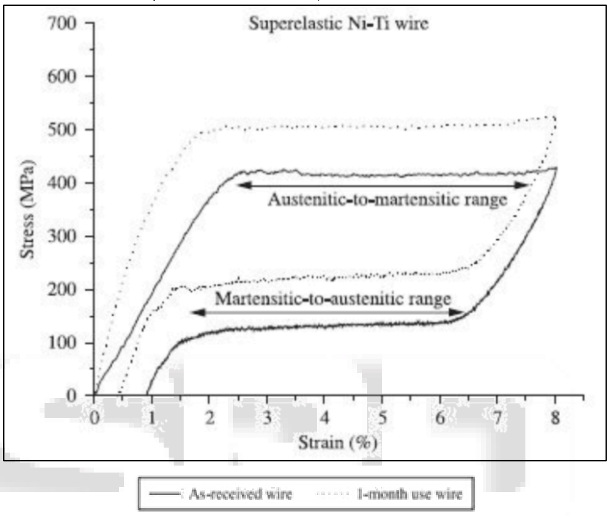

Fig. 3(a): Superelastic wires [2]

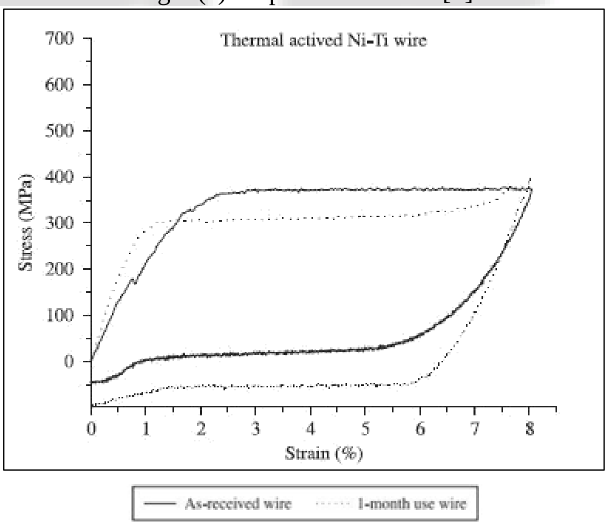

Fig. 3(b): Thermally activated wires [2]

IV. MANUFATURING AND TRAINING OF NITINOL

A. Manufacturing process

Nitinol is exceedingly difficult to make, due to the exceptionally tight compositional control required, and the tremendous reactivity of titanium. Every atom of titanium that combines with oxygen or carbon is an atom that is robbed from the NiTi lattice, thus shifting the composition and making the transformation temperature that much lower. Shape setting or training is accomplished by constraining the Nitinol element on a mandrel or fixture of the desired shape and applying an appropriate heat treatment. As said earlier Nitinol is exceedingly difficult to make due to the tremendous reactivity of the titanium atoms. Because of this high reactivity, the alloy is melted in vacuum based manufacturing processes. Majorly only two types of manufacturing processes are used:

1) Vacuum arc re-melting (VAR)
2) Vacuum induction melting (VIM)

B. *Training of Nitinol*

Training is method which helps inducing a memory of the shape required in the Nitinol alloy. As said it is accomplished by constraining the Nitinol element on a mandrel or fixture of the desired shape and applying an appropriate heat treatment. The heat treatment parameters chosen to set both the shape and the properties of the part are critical, and usually need to be determined experimentally for each desired part's requirements. In general, temperatures as low as 400 ℃. and times as short as 1-2 minutes can set the shape, but generally one uses a temperature closer to 500 ℃. and times over 5 minutes

V. Nitinol Properties

A. *Chemical Composition [2]*

Element	Weight %
Nickel	55.79
Titanium	43.98
Oxygen	0.05 max
Carbon	0.05 max
Mn,Si,Cr,Co,Mo,W,V	< 0.01
Nb, Al, Zr, Cu, Ta, Hf	< 0.01
Ag, Pb, Bi, Ca, Mg, Sn, Cd	< 0.01
Zn, Sb, Sr, Na, As, Be, Ba	< 0.01
Fe	< 0.5
B	< 0.001

B. *Physical Properties [1 3]*

Property	Value
Density (kg/m^3)	6450-6500
Melting point (℃)	1310
Electrical Resistivity (μΩcm)	76-80(approx)
Sp. Heat Capacity (J/kgK)	836.8
Thermal Conductivity (W/mK)	8.6-10
Ultimate Tensile Strength (Mpa)	895-1900
Young’s Modulus (GPa)	28–41(approx)
Yield's Strength (MPa)	70-140
Elongation (%)	60

VI. Conclusion

An alloy of such calibre can be widely used in mechanical and medical fields. Its typical shape memory and superelastic properties are the major reason for its wide use. On studying the types of Nitinol we come to understand that Superelastic Ni-Ti wires exhibited higher load stress values than thermally activated wires. Since it also have elongation of 60% more than that of any other simple metal, it can absorb more strain and has a reversible stress-strain curve. Even the manufacturing process show that such special material could only be manufactured in vacuum and needs special methods called training to change the shape of the material. Currently since the material is still under development and research, the extent of its exploitation towards different applications is still limited. But with such research, lies more opportunities towards greater applications.

References

[1] William J. Buehler and Fredrick E. Wang, "A Summary of recent research on the NITINOL alloys and their potential application in Ocean Engineering", Ocean Engg. Vol. 1, pp. 105-120, July 1967.
[2] Kathia Maria Fosenca de Brittoa, José Eduardo Spinellib*, Antonio Eduardo Martinellic, Rubens Maribondo do Nascimentoc, "The effect of Residence Time on the tensile properties of Superelastic and Thermal Activated Ni-Ti Orthodontic wires", Material Research, 14(3) pp 423-427, June 2011.
[3] Jaronie Mohd Jani, Martin Leary, Aleksandar Subic, Mark A. Gibson, "A reiview of shape memory alloy research, applications and opportunities " Materials and Design 56, pp 1078–1113, November 2013.