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Contribution to Shape Memory Alloys Actuated Systems Design

Even it has been recognized that Shape Memory Alloys have a significant potential for deployment actuators, the number of applications of SMA-based actuators to the present day is still quite small, due to the need of deep understanding of the thermomechanical behavior of SMA. SMAs offer attractive potentials such as: reversible strains of several percent, generation of high recovery stresses and high power / weight ratios. This paper tries to provide an overview of the shape memory functions. A table with property values for different properties of shape memory alloys is also included.

Keywords: Shape memory, modelling, actuation, thermo mechanical transfer, Nitinol

1. Introduction

Shape Memory Alloys consist of a group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure. Some examples of these alloys are 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.

Basically, SMAs are functional materials. They are more important for what they do (as an action) than for what they are (as a material). Shape-memory materials recover their original induced shape when they exceed a transition temperature (a narrow temperature band, not a single point) between a low-temperature phase and a high-temperature phase. The occurrence of these unique properties is originated from a molecular rearrangement related to a solid state phase variation. This is possible due to a solid-state phase change between martensite and austenite, occurring in the SMA. The initial values of these four variables are also strongly affected by the alloy's composition.

The Shape Memory Effect occurs due to a temperature and stress dependent shift in the material's crystalline structure between two different phases called martensite and austenite. Martensite, the low temperature phase, is relatively soft whereas Austenite, the high temperature phase, is relatively hard.

2. Nitinol functionality

Martensite is relatively soft and easily deformed phase of SMAs, existing at lower temperatures, whereas austenite, the stronger phase of SMAs, befalls at higher temperatures. The studies are carried out on NiTi alloy (49.8% titanium) wires, having as transformation temperatures: austenite start temperature A_s= 25,5^0 C, austenite finish temperature A_f= 46,5^0 C, martensite start temperature M_s = 10^0 C and martensite finish temperature M_f = -14,5^0 C, measured by laser thermal imagers. NiTi alloy primary wire at cold work state was annealed at a temperature between 400 ^{0} C and 650^0 C for 0.5–2 hours in order to regulate the phase transformation temperature of the SMA.

It is demonstrated that a treatment solution at 650^0 C / 60 min and ageing treatment at 380^0 C / 100 min yields an M_s at about 14^0 C, while ageing treatment at 480^0 C / 100 min yields an M_s at about 20^0 C. The variation is consistent with the formation of lenticular Ti_3Ni_4 precipitates. When the specimen is annealed lower than 400^0 C, the Ti_3Ni_4 precipitate particle is fine and the dispersion density is high, so the precipitate Ti_3Ni_4 has great coherence with the matrix. However, when annealed at a higher temperature than 400^0 C, the precipitate Ti_3Ni_4 increases and the low dispersion density destroys the coherence between Ti_3Ni_4 and the matrix.

NiTi senses changes in the ambient temperature and is able to convert its shape to a preprogrammed structure. While NiTi is soft and easily deformable in its lower temperature form (martensite), it resumes its original shape and rigidity when heated to its higher temperature form (austenite). This is called the one-way shape memory effect. The presence of permanent deformation, related to plastic strains or to the residual martensite variants occurring during the material training, allows reversible spontaneous shape change to be obtained during cooling and heating processes without application of any external stress, which is known as the two-way memory effect.

The NiTi (49.8% titanium) wires with a diameter of 2 mm, after a solution treatment at 650^0 C / 60 min. and ageing treatment at 480^0 C / 100 min. followed by air-cooling, were used to train two-way memory effect spring. The detailed training process of two-way memory effect was schematically shown in Figure 1 with the following procedures:

1) The TiNi wires were wound on a cylindrical jig, and then annealed at 500^0 C for 30 min. followed by air-cooling.

2) The springs were annealed at 350 - 450^0 C for 1 hour when the springs were constrained at the frame.

3) The constrained springs were thermo-mechanically trained for several cycles, at a temperature of 58^0 C (in a martensitic state) before relaxing the force

and again heating up to 100 - 300^0 C, a temperature slightly higher than the austenite finished temperature (A_f).

The thermo-mechanical training on two-way memory effect was related to the variation of internal stress fields and the distribution of dislocation, as well as the states of parent phase related to shape and dispersal degree of precipitates Ti_3Ni_4 (Sraiman et al., 1992). The aging precipitates in the early stage of precipitation have coherent interfaces with matrixes, which introduce sites of internal stress and serve to control the martensite preference.

The sites of the internal stress can be dislocations induced by deformation, stable stress-induced martensite and precipitates. This dislocation structure creates an anisotropic stress field in the matrix, which governs the transformation of martensite into variants of preferential orientations in relation to the deformation adopted in the training procedure, thus resulting in a macroscopic shape variation during subsequent thermal transformation cycles. At lower annealing temperatures, the dislocation density and strength of materials at the austenite state were very high, prohibiting the reorientation of the martensite phase, with a weak two-way memory effect.

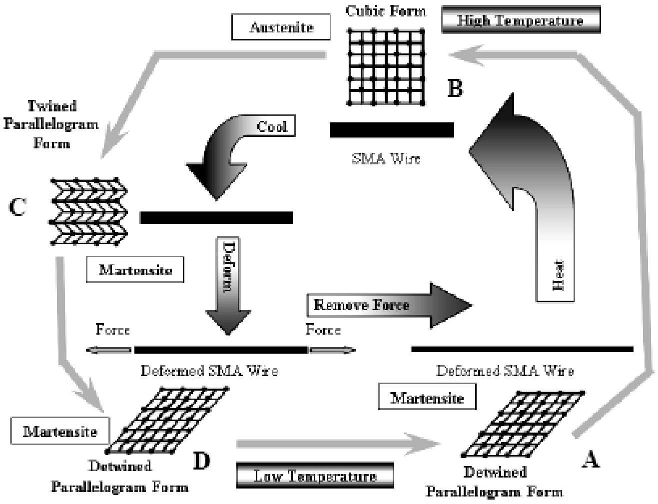

Figure 1. Phase transformations in an SMA wire spring actuator

Increasing the annealing temperature, the dislocation density and the strength of austenite decreased. After deformation, the reorientation of martensite occurred, which led to the variation of internal stress fields in the matrix. Therefore, increasing the annealing temperature, the shape memory recovery rate also increased.

The special properties of shape memory alloys result from phase transformations between martensite and austenite in their crystal structure.

The Figure 1 below illustrates phase transformations in an SMA wire spring actuator. Assuming that the SMA wire is initially at a low temperature and is in its martensite state (point A), upon heating to a transformation temperature (90^0 C), the SMA wire will experience a phase transformation to the cubic stronger austenite and the spring wire will contract in its length (point B). During this phase transformation, the SMA generates an extremely large force when encountering resistances or realizes a significant dimension change when being unrestricted. After cooling, the SMA wire will transfer from austenite to the weaker martensite phase (point C), in this stage the crystal structure of the SMA has in a twinned parallelogram form. In general, its strength in terms of Young's Modulus in martensite is 3-7 times less that in austenite. When an external tension force is applied to the spring, the wire can be easily stretched (point D). During this process, the twinned martensite becomes the detwinned martensite upon applying the external force. When the external force is removed, the wire remains in its deformed shape (point A) until it is heated again.

2. Shape Memory Actuators using the memory effect.

Most industrial applications of Shape Memory Alloys (SMA) have been used for on/off applications such as cooling circuit valves, fire detection systems, clamping devices and many others.

Commercial on/off applications are available in very small sizes such as the miniature actuator of A.M.T. [1] for loads up to 1N and with an activation time of 0.1 sec. On the other hand one can also find truss actuators and Shape Memory Actuated Cylinders (SMACs) for loads up to 400 N [2]. Ni-Ti SMAs have a larger electrical resistance, and allow much higher working stresses and strains. Recently, a lot of research efforts have been directed towards continuous position and force control of shape memory actuators [3]. SMAs offer important advantages in actuation mechanisms, as summarized below:

1. Simplicity, compactness, and safety of the mechanism:

The actuator can be reduced to a single SMA element, i.e. an electrically activated SMA wire. The stroke and force can be easily modified by the selection of the SMA element, e.g. SMA wire vs. SMA spring. Additional parts such as reduction gears are not required. Hence, the use of SMAs can result in a simplified, more compact and more reliable device.

2. Creation of clean, silent, spark-free and zero gravity working conditions:

Since friction is absent in activated SMA elements, the production of dust particles can be avoided. Conversely, a dusty environment has no influence on the action of SMA elements. Since there are also no additional vibrating parts, the activation is nearly noiseless. The acoustic emission created by the martensitic transformation can only be detected by very sensitive detectors. While no high-voltage or electrical switches are required, SMA actuators can work completely spark-free allowing them to operate in highly inflammable environments. SMA actuators can be controlled in such a way that accelerations of the order of only a few microns are generated.

3. High power/weight (or power/volume) ratio:

K. Ikuta [4] compared all types of actuating technologies (from small DC motors to gas turbines). He concluded that SMA actuators offer the highest power to weight ratio at low levels of weight (below 100 grams.

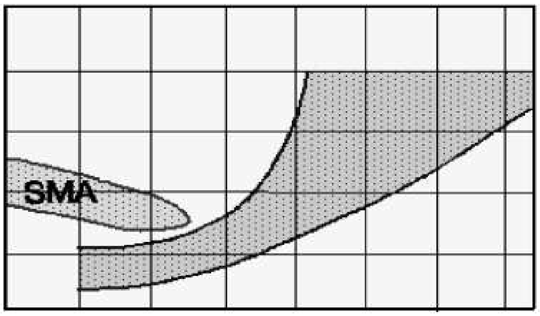

Figure 2. Schematic representation of the locus of SMA-actuators in a power density vs. weight diagram

This means that shape memory alloys are extremely attractive in micro-actuator technology. Therefore, SMA-actuators became a very important design tool in the important and rapidly growing field of micro-actuation. Examples of prototypes have been already described by Ikuta [5] and Walker [6]. Brite project has been approved for the development of remote controlled micro-actuators for medical applications [7]. Additional advantages of Ni-Ti SMAs are the excellent corrosion resistance and biocompatibility.

4. Conclusion

SMA materials can be formed into almost any shaped actuator imaginable. All that is needed is a heat treatment process to define the actuators dimensional configuration in the austenite (actuated) phase. Some shapes that have been used are cantilever beams, wires, springs, ribbon, strip, sheet, and tubing. Although a SMA actuator could be designed such that it applies a force in three dimensions (depending on which direction it was deformed from the memory configuration), the great majority of SMA actuators apply a one directional tensile force and cannot directly apply a compressive force.

The functional properties of shape memory alloys offer unique opportunities in many fields of industrial activities. At present, most commercial successes are related to the use of superelasticity in biomedical applications. In near future many new commercial successes can be expected in various domains and especially in microactuator technology and in smart materials developments. Important to notice is that the design of shape memory applications always require a specific approach, completely different from the design with structural materials.

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