VOL. 10, NO. 17, SEPTEMBER 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

EXPERIMENTAL STUDY ON TWO WAY SHAPE MEMORY EFFECT TRAINING PROCEDURE FOR NiTiNOL SHAPE MEMORY ALLOY

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ABSTRACT

This research describes training procedures for shape memory alloys (SMAs). SMAs are considered as a unique class of metal alloys that can recover apparent permanent strains when they are heated above a certain temperature. Shape Memory Effect (SME) is defined as the temperature driven response in SMA materials. The SME can be classified as either a One-way shape memory effect (OWSME) or a Two-way shape memory effect (TWSME). The TWSME response unfortunately requires repeated thermo-mechanical treatments known as "training" or "training cycles" before such a response is obtained. In this research work, the martensite deformation technique is used to train the SMA sample. Both the training procedure and the training jig was designed based on the bending mechanism procedure. The results obtained from the training process of SMA shows a great respond in SMA attack angle to their activation and de-activation temperatures. TWSME for SMA sample was successfully obtained in term of SMA sample attack angle value of 8˚ for SMA de-activation position and 39˚ for SMA activation position. Observations of spontaneous shape change as a result of the change in the sample temperatures were indications of the presence of TWSME in the SMA samples.

Keywords: Shape Memory Alloy, NiTiNOL, Two-Way Shape Memory and TWSME.

INTRODUCTION

Shape memory alloys (SMAs) materials are characterized by their ability of memorizing its original shape after deformation. If such alloys are plastically deformed at one temperature, they will completely recover to their original shape on being raised to a higher temperature. While recovering their shape the alloys they can produce a displacement or a force as a function of temperature. On the other words Shape memory alloys are the materials in which large deformation can be induced and recovered through temperature changes in a phenomenon called shape memory effect (SME) or stress changes which is called pseudo-elasticity (PE) [1]. The main features of such alloys that possess this shape memory property include: high force during shape change; large movement with small temperature change; a high permanent strength; simple application, because no special tools are required; many possible shapes and configurations; and easy to use just by heating.

First observations of shape memory behavior were reported in 1932 by Olander in his study of "rubber like effect" in samples of gold–cadmium [2]. Many researchers [1-4] reported the term "shape recovery" they were also working on gold–cadmium alloys. In 1962 Naval Ordnance Laboratory discovered shape memory effect in an alloy of nickel and titanium. He named it NiTiNOL for (Nickel–Titanium Naval Ordnance Laboratory) [3-4].

Shape memory alloys (SMAs) are a unique class of metal alloys that can recover apparent permanent strains when they are heated above a certain temperature. Shape memory alloys have two typical material characteristics, Shape Memory Effect (SME) and pseudo-elasticity (PE). SMAs can exist in a two different temperature dependent crystal structures shown in Figure-1, high temperature phase called austenite phase or parent phase (named after English metallurgist William Chandler Austen [5] and the low temperature phase, called martensite (named after German metallographer Adolf Martens [4].

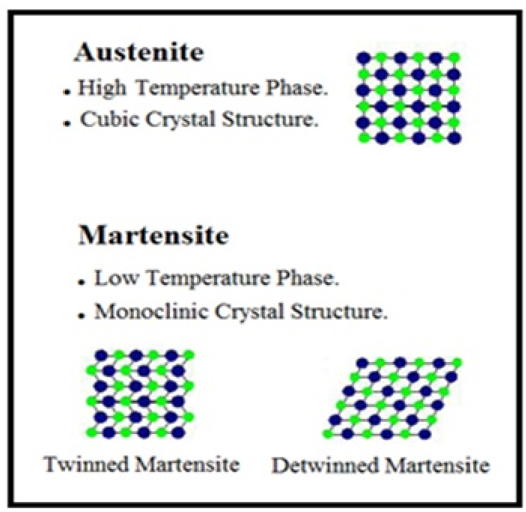

Figure-1. Different phases of a shape memory alloy (Texas A&M Smart Lab).

Numerous researchers have reported on the benefits of NiTiNOL compared to the other available SMA materials. Among them are [6-7], who reported on the advantages of NiTiNOL based on their high transformation strain, large actuation force, ductility, high strength and high resistance to corrosion and abrasion. These advantages however, can easily be out-weighted by the high material costs of NiTiNOL compared to the Cu- or Fe-based SMAs. Nonetheless, by improving existing manufacturing techniques or by introducing new techniques, the cost of NiTiNOL components could potentially be lowered. The viability of NiTiNOL devices or components can also result from using them in applications where cost is not the primary concern, eg. aerospace applications. The temperature driven response in SMA materials causes in shape memory effect (SME) which is defined as the phase transformation between the martensite phase at low temperatures, and the austenite phase at high temperatures, Illustration of the temperatures where martensite phase start (M_s), martensite phase finish (M_f), autenite phase start (A_s), and autenite phase finish (A_f) are shown in Figure-2 [4].

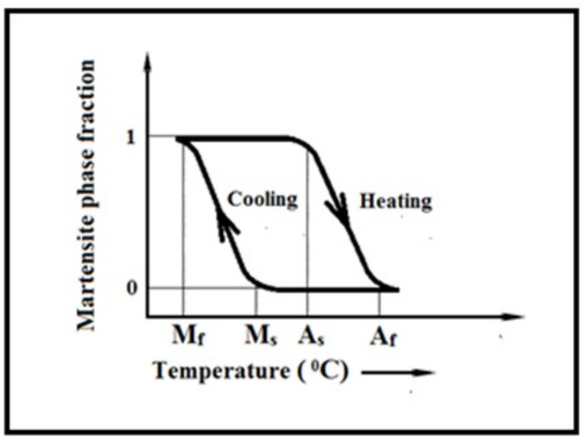

Figure-2. SMA materials transformation hysteresis curve and temperature [5].

The SME can be classified as either a One-way shape memory effect (OWSME) or a Two-way shape memory effect (TWSME). The One-way SME (OWSME) response is described as a reverse transformation process where the de-twin structures in its martensite phase transform to the parent phase structure in its austenite phase after heat is supplied. In other words, materials with OWSME characteristic can only remember its parent shape after heat is applied to its deforming shape. While in the tow-way SME (TWSME) response, the material has the ability to remember both its parent phase (austenite) and deformed phase (martensite) shapes through a spontaneous shape change mechanism. The essential difference between the OWSME and the TWSME is that the shape change which occurs in the latter is generated without external stresses. The TWSME response unfortunately is not an inherent property in SMAs and requires repeated thermo-mechanical treatments along specific loading path before such a response is obtained. The thermo-mechanical treatments are also known as “training” or “training cycles”, this training procedures are presented in details in the following sections.

LITERATURE REVIEW

The developments in the training procedures of SMA in recent years were mainly implemented to maximize of the strain magnitude, maintain reproducibility, and overcome stability issues of the TWSME response. In equiatomic NiTiNOL, the training procedures as reported by [8] are generally selected from the following options:

(a) Shape memory training.
(b) stress-induced martensite transformation training (pseudoelastic training).
(c) Thermal cycling training under constant stress.

Shape memory training involves repeated cycles of deforming the alloy which is already in its martensite phase and the recovery from the deformation by reverse transformation induced by heating under no stress [8]. In the case of pseudoelastic training, an external stress in introduced above the material’s austenite temperature (A_f), to induce martensitic transformation and the reverse transformation is allowed to proceed without the influence of an external stress [9]. Thermal cycling training involves subjecting the alloy to repeat thermal transformation cycles under influence of a constant external bias stress [10]. A comparison of the three above mention training procedures was carried out by [10] from which it was concluded that constant- stress thermal cycling was the most effective method in producing high TWSME strains.

One of effective methods of obtaining TWSME characteristics was reported by [11] where bending mechanisms were used instead of using mechanical tests (under constant stress). This technique is used to avoid shape recovery measurement errors associated with the thermal expansion of the SMA sample. In their reported research, two training procedures were proposed involving bending mechanisms: a martensite deformation technique and a constrained approach, in comparing the two techniques, Lahoz [11] found that the martensite deformation technique was more effective method of training NiTiNOL samples to achieve stable TWSME characteristics.

The relation between the number of cycles used to train the SMA and the improvements in TWSME characteristics was described by [12] as follow, the increase in the number of the training cycles means of stabilizing of the hysteresis response and saturating the inelastic strains in the material. An example relating the number of cycles to the TWSME response of a NiTiNOL wire sample under a constant load is shown in Figure-3. In this example, the TWSME response for NiTiNOL wire stabilized and recorded improvements in its strain rates after 50 cycles. The importance of the number of training cycles in a TWSME training procedure was emphasized by Wang *et al.* [13]. In their investigation on the TWSME response from a NiTi spring sample, a stable recovery rate was obtained after 50 training cycles.

VOL. 10, NO. 17, SEPTEMBER 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

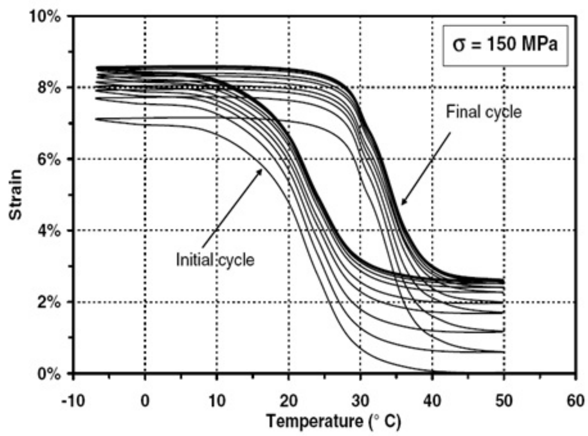

Figure-3. Thermal cyclic loading (50 cycles) of a NiTi shape memory alloy wire under constant load of 150 MPa [12].

METHODOLOGY

In the martensite deformation technique, the NiTiNOL sample is deformed round a cylinder and constrained in this position at room temperature. The sample is then unloaded, and its elastic recovery is position (2) recorded, as shown in the schematic diagram in Figure-4. By heating the sample above its A_f temperature, shape recovery is initiated and the sample shape returns close to its initial test position. The recorded angle θ_p denotes to the permanent deformation which the sample experience as a result of the training procedure. Finally, the sample is quenched in ice path, which triggers a martensite transformation and positions the sample at an angle θ_1 from its initial test position was recorded also. The difference between the θ_1 and θ_p is the TWSME angular range, θ_{tw}. This training procedure is repeated over a number of training cycles until the sample readily responds to its θ_{tw} range when operated between A_f and M_s (room temperature).

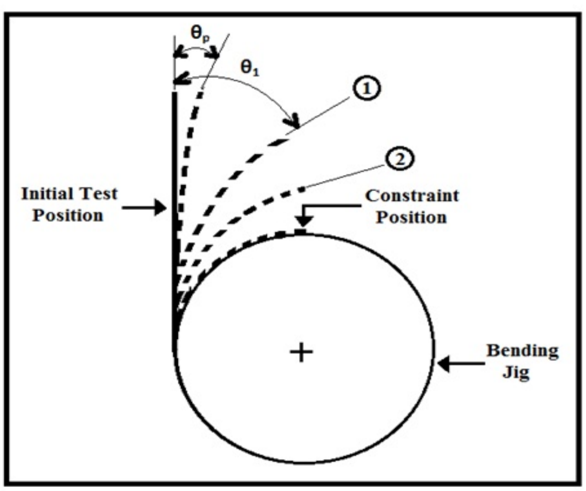

Figure-4. TWSME training procedure using a bending mechanism (adapted from Lahoz *et al.* 2002).

Since the training procedures were carried out in-situ, the functionality of these devices was also tested during the training cycles. The transformation temperatures and activation angles at their activated and de-activated positions were the parameters used to asses the functionality of the SMA device. The sample preparations involve heat treating the samples while constraining them to their activated positions. The heat treatment was carried out in a 1200 ˚C (max) furnace manufactured by CARBOLITE at specific temperatures and time intervals as indicated by heat treatment curve in Figure-5. After heat treatment, the martensite deformation training procedure was carried as discussed before. The training cycles were repeated for 50 times and the activated and deactivated positions were measured after each cycle.

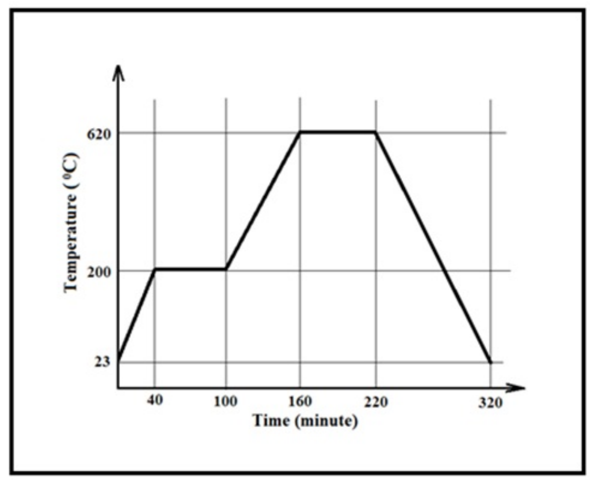

Figure 5. Heat treatment curve for SMA samples.

EXPERIMENTAL SETUP

Two-way SME training procedure was carried out based on the martensite deformation training procedure for the SMA sample show in Figure-6. both the training procedure and the training jig which was designed based on the bending mechanism procedure, were suggested by Lahoz *et al.* (2002). The training cycles were carried out between a high temperature (100 ˚C) and a low temperature (0 ˚C) set point for total of 50 cycles. The two-way training procedure was carried out in-situ and involved the samples being deformed by external stress in their martensite phase and later heated to their austenite phase to recover their high temperature phase. An illustration of the steps involved in the two-way training procedure of the SMA samples is shown in the Figure-7. The training cycle is initiated when the sample is placed in an ice-bath and deformed by external force to a $\alpha = 0˚$ position. The samples is then removed from the ice-bath and heated up to its high temperature set point where it is expected to be fully activated. The sample is then allowed to cool down from step III to step I to room temperature. It is at this room temperature when the SMA sample attains a new angle of attack, close to its deformed position. As

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the training process is repeated, the angle of attack in step I will closely approach to 0˚ while the activation angle in step III is expected to drop slightly below its original 45˚ angle. Illustration of the jigs that used to train the SMA samples and training steps pictures are shown in Figure-8. and Figure-9.

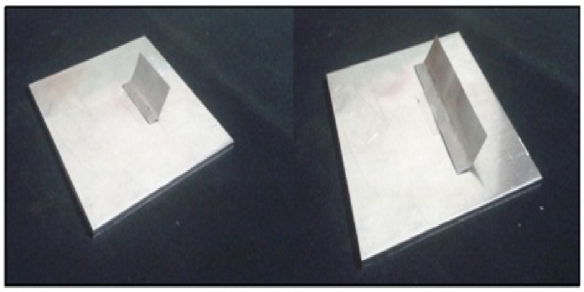

Figure-6. Illustration of the samples of SMA.

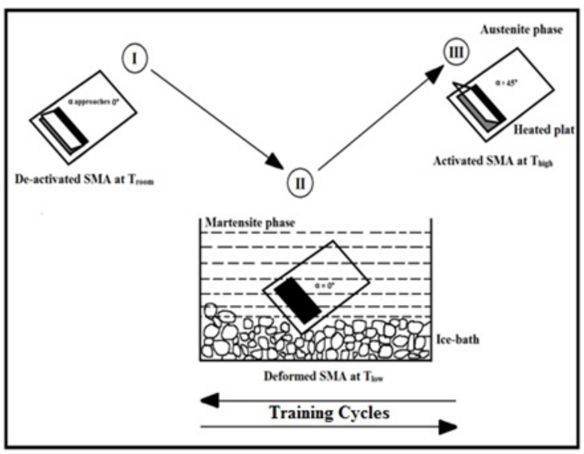

Figure-7. SMA training procedure.

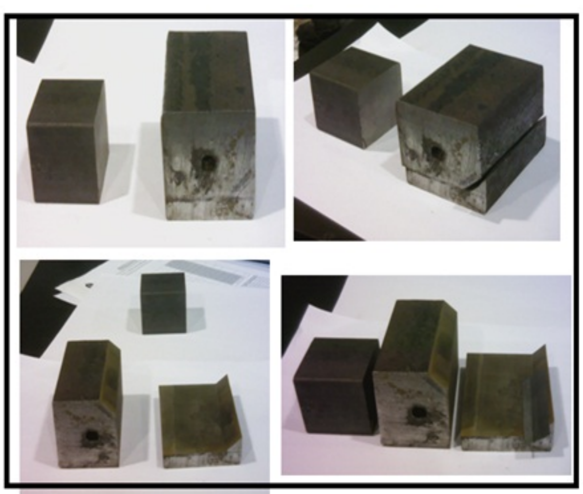

Figure-8. Illustration of the jigs that are used to train the SMA samples.

Figure-9. Illustration of the training steps of the SMA samples.

RESULTS AND DISCUSSION

The effect of the number of training cycles on the improvements to the TWSME response were determined from the measured angles of attack for the activated and de-activated positions in shown in Figure-10.

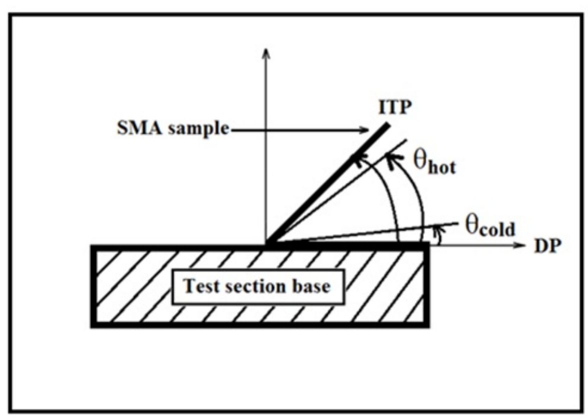

Figure-10. The angle of attack measurements to determine TWSME response.

The angle of attack at the initial test position (ITP) was 45˚ and the deformed position (DP), the SMA sample was held by external stress to an angle of 0˚. Both the hot (ϴhot) and cold (ϴcold) were measured when the sample spontaneously changed shapes (without external stress) in their respective phases for each training cycle and are shown in Table-1.

Table-1. Process parameters and their levels.

Material	ITP	DP	T_{hot}	T_{cold}	Training cycles	Θ_{hot}	Θ_{cold}
NiTiNOL thin sheet	45°	0°	100°C	55°C	1	43°	11.5°
					2	43°	11.5°
					3	42°	11.5°
					4	42°	10.5°
					5	41°	10°
					6	41°	10°
					7	41°	9.5°
					8	40°	9.5°
					9	40°	9°
					10	40°	9°
					11	39°	8°
					12	39°	8°
					13	39°	8°
					14	39°	8°
					15	39°	8°

CONCLUSIONS

TWSME for SMA sample was successfully obtained from the training procedures. Observations of spontaneous shape change as a result of the change in the sample temperatures were indications of the presence of TWSME in the SMA samples. The functionality for the SMA device was also observed from their response to the high and low temperature. The information provided form the measured data suggests a stabilized TWSME response after 11 training cycles and the relevant hot and cold position angles of 39° and 8° respectively.

ACKNOWLEDGEMENTS

The authors would like to convey their gratitude to Universiti Teknologi PETRONAS for providing laboratory facilities and financial assistance to this research project.

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