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Experimental Investigation on Ni-Ti Shape Memory Alloy Samples

F. Casciati[1], S. Casciati [2], L. Faravelli[1], M. Vece[3]

1 *Professor, DICAr, University of Pavia, Pavia, Italy.*
E-mail: fabio@dipmec.unipv.it, lucia@dipmec.unipv.it
2 *Professor, DICAr, School of Architecture, University of Catania at Siracusa, Siracusa, Italy.*
E-mail: saracasciati@msn.com
3 *PhD Student, DICAr, University of Pavia, Pavia, Italy.*
E-mail: miche.vece@gmail.com

ABSTRACT
Shape memory alloys in their austenite form show a super-elastic behavior, which allows them to recover their undeformed shape once the mechanical stress is removed. The austenite-martensite transformation modifies the electrical resistivity of materials. This paper investigates the conductivity of Ni-Ti shape memory alloys, which present the complication of having a training process. The material properties are enhanced by loading-unloading cycles for same diameter specimens (2.46 mm) on a MTS hydraulic testing apparatus. Test results are here illustrated and discussed in order to provide a variability law for the electrical resistance of the alloy during the elongation.

KEYWORDS: *experiments, laboratory, SMA, electrical conductivity, mechanical properties*

1. INTRODUCTION

Shape memory alloys (SMA) are well known in literature [1-4], but its functional applications only developed in the last twenty years. The high cost, lack of clear understanding of the thermo-mechanical process and the inability to predict the behavior of shape memory alloys after several cycles of loading-unloading are the main reasons, which prevented from a faster diffusion [5-8]. Indeed, shape memory alloys (SMA) present different phenomena, which can be induced by changes in temperature and mechanical stress. For instance, all the effects such as one-way shape memory effect, two way shape memory effect, superelasticity and rubber-like behavior are characterized by modifications in crystalline structure of the SMA and also the austenite-martensite transformation modifies the electrical resistivity of materials. The electrical resistivity is one, among many others experimental techniques used to study these metallic alloys. It is used to measure the evolution of shape memory effect during ageing in parent phase and low temperature phase (martensitic stabilization). More recently, electrical resistivity measurement has been used to follow the thermomechanical shape memory behavior under applied load. The electrical resistivity is affected in this case by the strain, structural modifications, reorientation of martensite variants and by the introduction and rearrangement of defects. The knowledge of the electrical resistivity behavior during these events has special importance for technological applications. Indeed, it can be used to drive the material performance from electronic control. This paper investigates the conductivity of Ni-Ti shape memory alloy but also shows the complication of requiring a training process. The material properties are emphasized by tests on the universal testing machine and electrical resistivity measurements in Ni-Ti polycrystalline alloys confirm a linear variation as a function of strain. Finally, test results are here discussed in order to provide a variability law for the electrical resistance of the alloy during the elongation.

2. GOVERNING RELATIONS

During the test, the change in dimension of the wire occurs due to strain recovery and this factor has to be considered during the calculation of the resistivity, while the volume of the wire remains unaltered. Electrical resistivity measurements are carried out by recording the output voltage and strain at regular time intervals. This feature of the specimen is calculated using the Ohm's laws. The first one expresses the relationship between the electrical resistance R and the characteristic of the sample (length and section), as the second one shows the ratio between the potential difference V and the current intensity I:

$$\text{First law: } R = \rho \, \frac{l}{s} \qquad \text{Second law: } R = \frac{V}{I} \tag{2.1}$$

Recent papers [9-10] summarized the main features of the transformation of austenite into martensite in terms of electrical resistivity. One basic equation holds, the Ohm law, considering that a thermos-elastic martensitic transformation induces a negligible change of volume:

$$\frac{\Delta R_\varepsilon}{R_{\varepsilon_0}} = \frac{\Delta\rho_\varepsilon}{\rho_{\varepsilon_0}} - 2\varepsilon \tag{2.2}$$

In Eq. (2.2) ε denotes the current strain, while R is the electrical resistance and ρ is the electrical resis tivity. The suffix ε_0 denotes these properties in the initial state just before the test. Eq. (2.2) is applied to obtain the true electrical resistivity change by removing the contribution of geometrical alterations of the sample.

3. EXPERIMENTAL PROCEDURE

In order to check the material conductivity, the sample needs to be isolated inside the machine. Then, the electrical resistivity measurements are carried out by the following method: a constant electrical current pass through the sample ends (600 mA) and two electrodes are placed respectively one (negative) at the top of the sample and the other (positive) for different lengths providing the measurement of the voltage signal, as shown in Figure 1.

Figure 3.1 Representation of electrical resistance measurement

The voltage signal is recorder for three point within the electrodes:

$$\frac{1}{4}\, l_u = 40\ mm \tag{3.1}$$

$$\frac{1}{3}\, l_u = 53\ mm \tag{3.2}$$

$$\frac{1}{4} - 2\left(\frac{1}{4} - \frac{1}{3}\right) l_u = 67\ mm \tag{3.3}$$

where l_u is the effective length of the sample. These values are doubled when repeating the voltage measurement for respectively 80, 106, and 133 mm. In this way, the dependence of voltage by the distance between the electrodes is demonstrated. A graphical representation of the measurements is given in Figure 3.2.

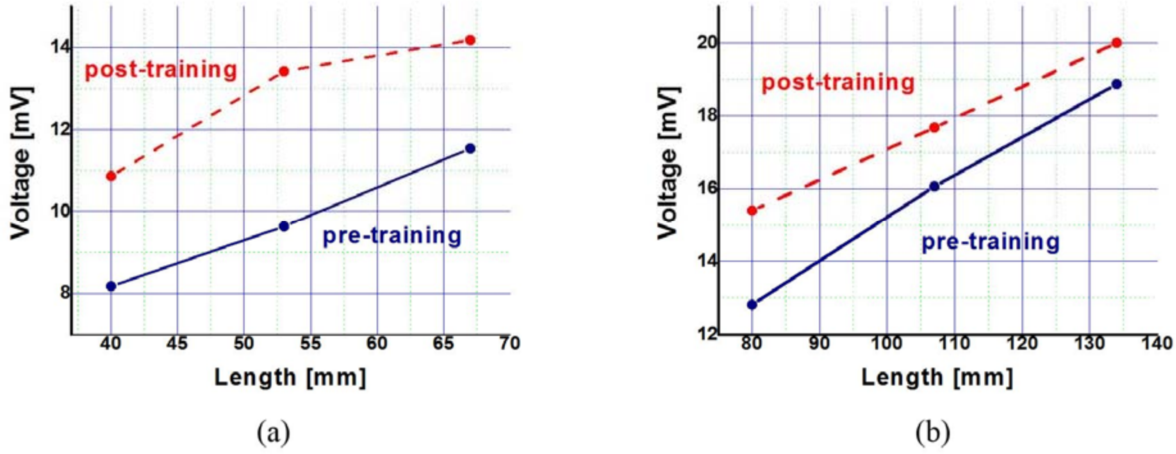


Figure 3.2 Voltage measurement before (a) and after training process (b)

Finally, Tables 3.1 and 3.2 show the results before and after the training for a specimen of SMA mounting on the MTS apparatus (Mini Bionix II).

Table 3.1 Test results on wires before the training process

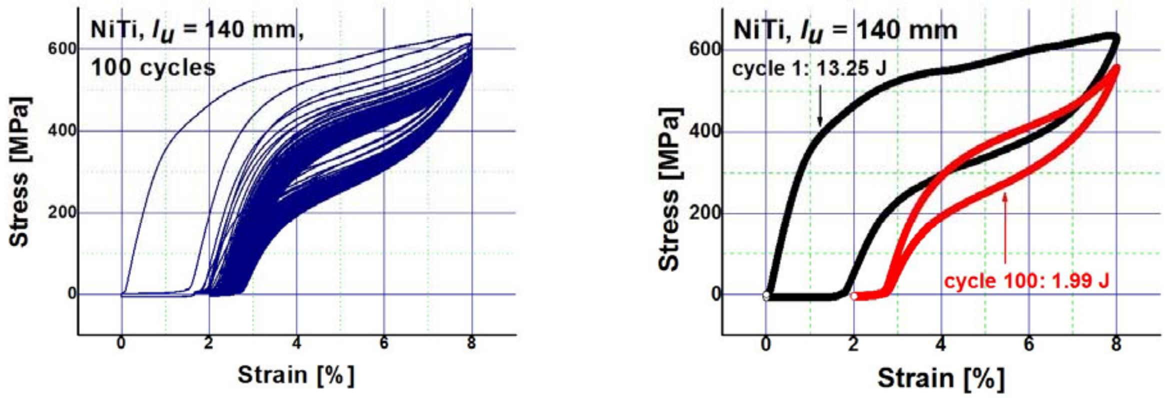
Length [m]	Voltage [V]	R [Ohm]	ρ [Ohm · m]
0.040	0.0082	0.01361	1.61·10-6
0.053	0.0096	0.01601	1.43·10-6
0.067	0.0115	0.01972	1.40·10-6
0.080	0.0128	0.02168	1.29·10-6
0.107	0.0161	0.02697	1.21·10-6
0.134	0.0189	0.02412	1.20·10-6

Table 3.2 Test results on wires after the training process

Length [m]	Voltage [V]	R [Ohm]	ρ [Ohm · m]
0.040	0.0109	0.01825	2.07·10-6
0.053	0.0134	0.02233	2.00·10-6
0.067	0.0145	0.02412	1.80·10-6
0.080	0.0156	0.02608	1.65·10-6
0.107	0.0180	0.02999	1.34·10-6
0.134	0.0205	0.03417	1.22·10-6

4. PROPERTIES OF THE AVAILABLE ALLOY SPECIMENS

The behavior of shape memory alloys consists of two main phases, depending on the ambient temperature. Indeed, it is worth noting that at high temperatures, the alloys are in their austenitic phase, while at low temperatures they are in the martensitic phase. Moreover, this material shows a phase transformation when subjected to thermal or mechanical loading - unloading and its superelastic behavior allows the alloy to recover its undeformed shape once the mechanical stress is removed. Figure 4.1 shows the stress–strain relationship for a cyclic training (100 cycles) on a Ni-Ti specimen of length 140 mm and diameter 2.46 mm, carried out up to a maximum strain of 8%.



(a) (b)

Figure 4.1 Behavior of the 100 first cycles (a) and frictional energy for cycles 1 and 100 (b)

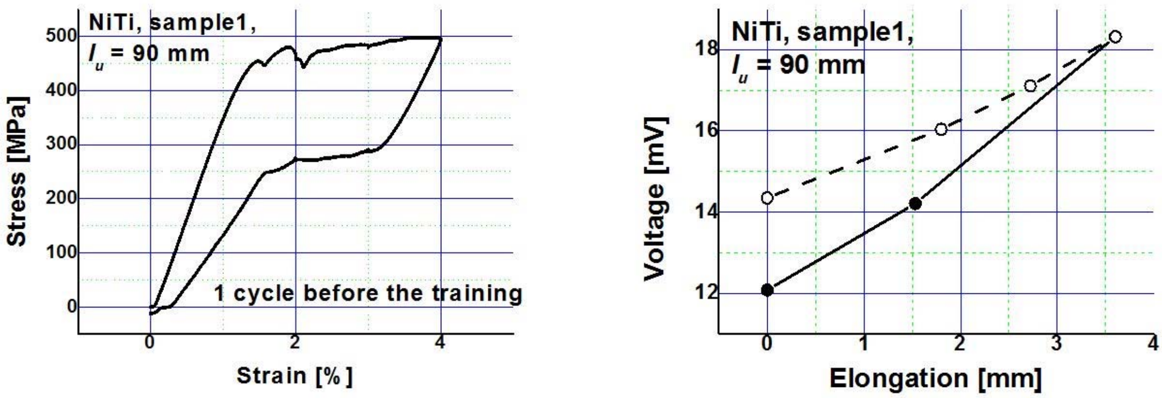
Hundred sinusoidal cycles at 0.01 Hz produce an increase of length, which is associate to the maximal stress, i.e. near 600 MPa, and to their cycling rate. Increasing the cycling rates, the sample temperature increases under the action of the dissipation associated to hysteresis and subsequently, the SMA creep increases. Another cause of this phenomenon, which characterizes the shape memory alloy behavior, can be represented by the increase of the external temperature which helps to increase the maximal stress and so the accumulate deformation.

5. RESULTS AND DISCUSSIONS

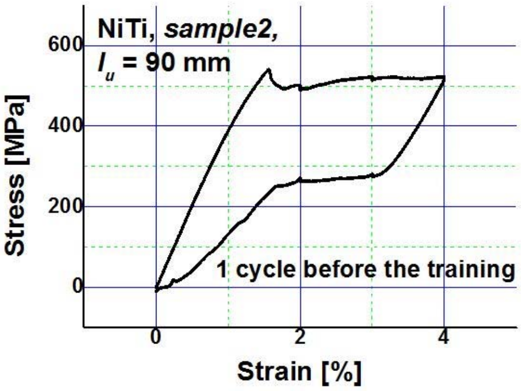
Several specimens of NiTi alloy of the same diameter (2.46 mm) are studied. They are all supplied by Memry Corp. (Bethel CT, USA), a division of SAES Getters (Italy), previously named Special Metals Corp. (New Hartford, New York, USA). According to the supplier's certificates, the A_s temperature is about 248/247 K. The furnisher certificate also indicated that the nominal wire composition was 55.95 and 55.92 wt % of Ni balance Ti. The composition includes other minor components such as 270 ppm of C, 234 ppm of O and reduced quantities (under 0.01 wt %) of more than 25 elements (Si, Cr, Co, Mo, W, Nb, Al, Ba, H, and Fe). The electrical resistance measurements are carried out at half of the effective length (90 mm) and are obtained in the following environment:

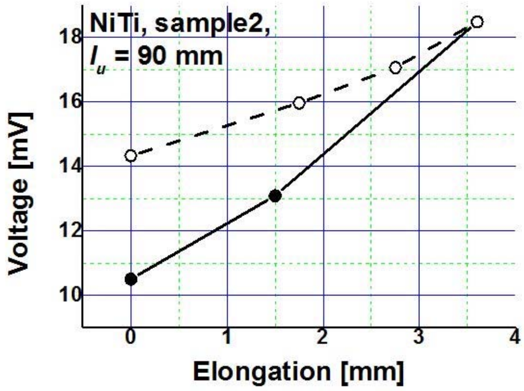
a) two points of connection with a power supply capable of a current of 600 mA are employed,
b) two electrodes internal to the previous two points of alimentation are used to measure the voltage difference. This four-point probe setup allows measuring the electrical resistance of the specimen in a way that is insensitive to the contact resistances of the probes themselves, and
c) strain is then introduced by the MTS universal testing machine (MiniBionix II) and the alterations in the voltage readings are recorded.

Figure 5.1 shows the behavior of the material during the first loading-unloading cycle up to 4% of strain at 0.03 Hz (a-c) and the recorded voltage during the elongation of the sample before the training process (b-d).



(a) (b)

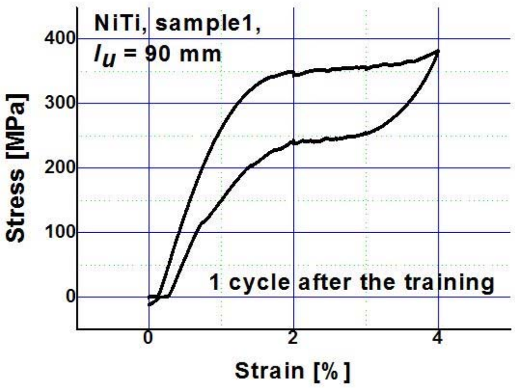


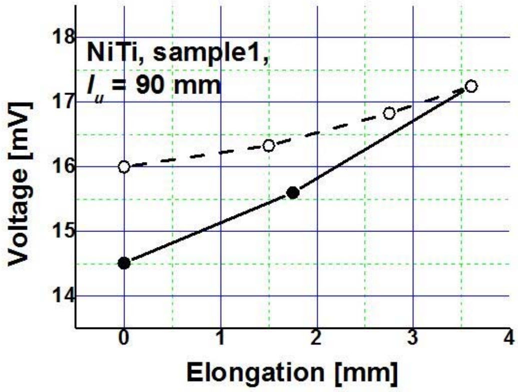


(c) (d)

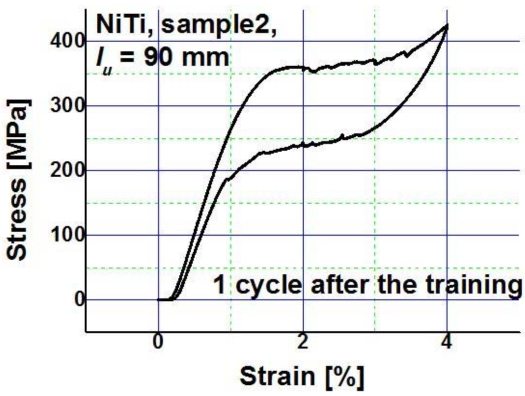
Figure 5.1 Hysteretic behavior before the training process (a-c) and elongation versus voltage (b-d)

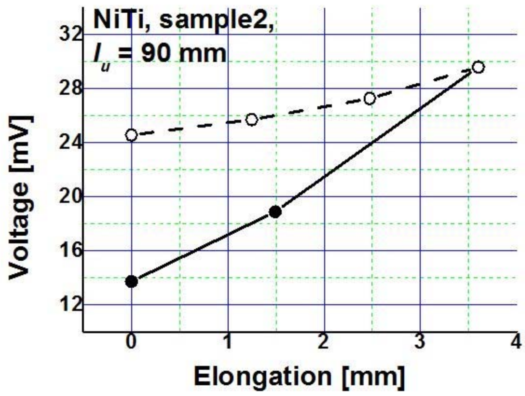
Once the mechanical training is ended, a new loading-unloading cycle equal to the previous is carried out, in order to record the changes in the sample and the voltage of the wire after the training process. In Figure 5.2, the hysteretic behavior of the material (a-c) and its voltage during the elongation (b-d) are shown through a two-dimensional representation.





(a) (b)





(c) (d)

Figure 5.2 Hysteretic behavior after the training process (a-c) and elongation versus voltage (b-d)

The martensite produced in the loading step (until to 4% of elongation) provides the higher voltage value detected after the unloading. After the training, the last value of voltage is reached in the starting point of the loading step, but a lower value of stress is detected. The loading phase is always represented by a continue line, while the unloading step produces the result summarized by a dashed line. It is possible to conclude that the shift to the right, from the virgin (non-linear) relation between elongation and voltage, gives evidence of the maximum elongation achieved, thanks to the martensite produced along the process.

6. CONCLUSIONS

Martensite and austenite phases of the investigated Ni-Ti shape memory alloy offer a different electrical resistivity and, in this paper, several specimens are tested in order to employ this property in smart composites with a self-diagnostic function.
The tests are carried out to highlight the conductivity of the alloy phases (austenite and martensite) before and after the training process. The results are reported and discussed, but several investigation steps should be further developed as: (i) the influence of the training features on the fatigue life of the alloy, (ii) the dependence of the physical phenomenon on the temperature, and (iii) design motivations pro and con the use of un-deformed or pre-stressed wires in SMA components.
As a result of the experimental campaign carried out in this paper, a significant accumulation of martensite during the training is noticed which reduces the self-diagnostic ability of some specimens. It should be emphasized that the production process of multi-crystalline elements could avoid some of the reported drawbacks.

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