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Investigation on the Hysteretic Behavior of NiTi Shape Memory Wires Actuated Under Quasi-Equilibrium and Dynamic Conditions

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The functional characterization of SMAs for actuation is typically performed by measuring the specimen deformation under constant load during a controlled thermal cycling across transformation temperatures. Under dynamic actuation, transformation temperatures different from those measured in quasi-equilibrium conditions have been observed. The aim of this work is to better investigate and understand these phenomena. Direct and indirect heating of shape memory wires under several loading conditions are examined in detail. According to the experimental results, the hypothesis is to consider the observed differences as an effect of the thermal cycling rate on the internal friction. However, the presented data seem do not fully confirm this idea. Further experiments will be carried out in order to directly measure the internal friction of the material under the same working conditions.

Keywords advanced characterization, nondestructive testing, titanium

1. Introduction

Despite SMA for actuation are more and more utilized in industrial applications, no standard testing specifications have been prescribed so far. Functional characterization is typically negotiated according to customer needs and manufacturer characterization facilities.

As far as wires are concerned, thermal cycling under constant load turns out to be a fundamental functional test (Ref 1). Preferably the test is carried out at several load values, for example at the operating load and at lower and higher loads. The test consists in loading a SMA wire with a constant tensile force and recording its length while increasing and decreasing its temperature across the transformation temperatures. The test, also referred to as *hysteresis test*, provides information about the strain, transformation temperatures and load dependence of transformation temperatures.

For practical reasons, the test is typically carried out in a climatic chamber by recording chamber temperature together with the wire length. Temperature rates are in this case very slow as thermal equilibrium must be ensured. As test conditions are different from those of most wire applications, where very fast wire heating is obtained by Joule effect, questions may arise about the suitability of this procedure.

In this article we investigate the effect of the temperature rate and heating method on the hysteresis test: in particular, thermal cycling tests carried out in climatic chamber are compared to those performed by SMAq, a patented instrument (Ref 2) where wire is heated by current flow. Besides, pulsed actuations are performed in climatic chamber at increasing chamber temperature, providing fast actuation information of the austenite-martensite (A-M) transformation. With the help of literature fundamental research results, physical interpretation of experiments will be provided.

2. Experimental Results

Hysteresis tests were performed on a hanging wire with a weight hooked at its bottom end in a climatic chamber. The chamber temperature was cycled across the transformation temperatures. The tests were carried on in a Weiss WK11-600 climatic chamber, performing thermal cycles between 15 and 170 °C at different temperature rates (0.3, 1, 5 and 10 °C/min); the temperature was measured by a PT100 thermocouple. Inside the chamber, four samples of 0.2 mm diameter SAES SmartFlex® wires ($Ni_{49}Ti_{51}$ at.%), 150 mm long, were constrained at the top end to a steel structure, so that four independent tests could be performed at the same time for a better reliability. A constant weight of 4.7 N (150 MPa) was applied to the bottom end of each wires and a position sensor measured the displacement (shortening) of the wire during the cycle. In order to compensate for the thermal deformation of the structure, the raw data were corrected by subtracting the displacement of a molybdenum wire, which has a low coefficient of thermal expansion. The acquisition of the signal was made by means of a SAES Field Interface, with the acquisition time set at 20 s. Both sensors were calibrated: the

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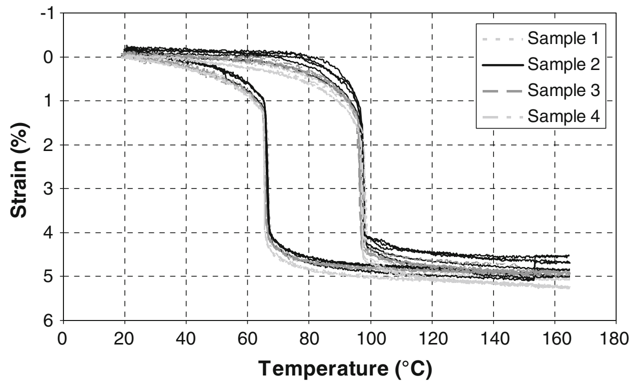

Fig. 1 Hysteresis curves of samples 1-4 at 150 MPa and 1 °C/min temperature rate

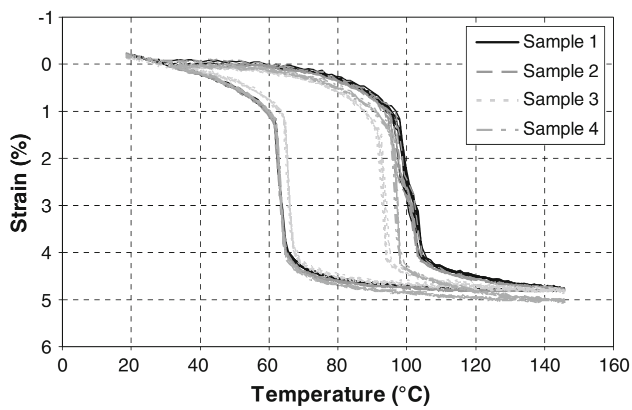

Fig. 2 Hysteresis curves of samples 1-4 at 150 MPa and 5 °C/min temperature rate

PT100 in an oven with a reference thermocouple, at different temperatures, while the displacement sensor with standard blocks of certified thickness at room temperature.

In Fig. 1 the tests output for a 0.2 mm SmartFlex® wire under constant stress of 150 MPa are displayed. The temperature rate is 1 °C/min: this is the highest temperature rate providing sufficient measurement reproducibility. As shown in Fig. 2, in fact, at higher temperature rates (5 °C/min), the differences of the four samples hysteresis curves indicate bad temperature homogeneity inside the chamber. Curves obtained at the rate of 1 °C/min will be considered as reference later in the discussion.

For comparison with the previous tests, thermal cycling at constant load is performed by means of the instrument SMAq whose hardware and functionalities can be found in Ref 2. Here a brief instrument description is presented.

The most important component of SMAq is a linear motor with a peak force of 430 N and a continuous force of 220 N. The motor is equipped with an absolute linear optical encoder (Heidenhain LC) with a resolution of ± 2 μm over a wire length up to 240 mm and controlled by the driver Control Technique Unidrive SP, which features a position repeatability of ± 1 μm. SMA wires having a maximum diameter of 0.5 mm are horizontally restrained between a first clamp located on the moving element of the linear motor and a second clamp located on a tension load cell (Laumas SA) featuring an accuracy of $\pm 0.02\%$ and a repeatability of 0.01%. The linear motor can be

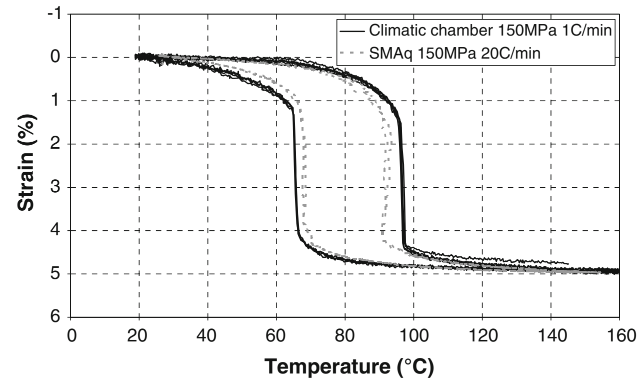

Fig. 3 Comparison between climatic chamber and SMAq thermal cycling at 150 MPa

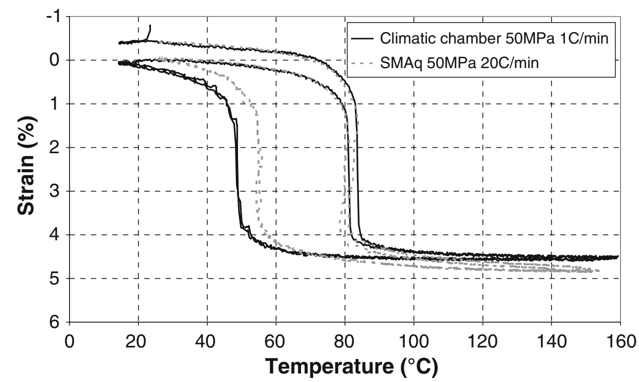

Fig. 4 Comparison between climatic chamber and SMAq thermal cycling at 50 MPa

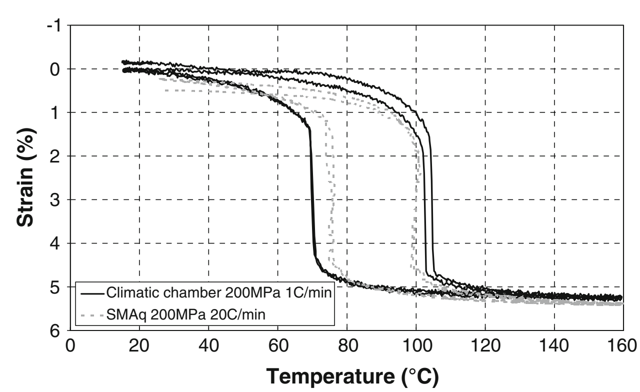

Fig. 5 Comparison between climatic chamber and SMAq thermal cycling at 200 MPa

closed-loop controlled through a feedback from the load cell or through a feedback from the linear optical encoder with an overall frequency response of 20 kHz. An infrared camera (Jenoptik VarioCAM), with a resolution of 320×240 pixels and a frequency response of 50 Hz over the spectral range 7.5-14 μm, allows for non-contact measurements of the wire temperature between -40 °C and $+1200$ °C.

Comparison of climatic chamber and SMAq curves at different loads are reported in Fig. 3-5: the SMAq curves hysteresis width is systematically lower than that measured in the climatic chamber.

3. Discussion

The small discrepancies between the results obtained by the different measuring systems must be ascribed to the different heating methods. Two possible explanations have been initially guessed. As a first hypothesis, it was supposed that the differences observed in the hysteresis curves could be related to the heating conditions which, in case of fast actuation, may generate inhomogeneity in the temperature profile of the wire during thermal cycling, especially on SMAq where the ambient is at room temperature and the wire is heated at a temperature above A_f. In order to assess the core temperature versus periphery temperature difference during the SMAq cycling, a thermal 2D simulation has been carried out. The material parameters reported in Table 1 have been utilized for the time dependent computation.

The free convection film coefficient of a horizontal infinite cylinder has been calculated according to Ref 3. In Fig. 6 simulation results are shown: the temperature difference during the whole time history remains below 0.05 °C. According to the calculation, the temperature inside the wire is practically homogeneous.

The second and more reasonable hypothesis is to consider the observed differences as an effect of the thermal cycling rate on the internal friction. In the case of the hysteresis test carried out in a climatic chamber, the conventional ramp up and down is very slow (1 °C/min). On the other hand, by Joule effect on SMAq the heating and cooling rates are higher (more than 20 °C/min). As measured by Yoshida et al. (Ref 4) several internal friction peaks have been observed during the phase transformation. The behavior of these peaks is, however, very complicated since it depends on experimental parameters such as the frequency, the amplitude and the heating or cooling rate, as well as on the composition of the sample and the history of the heat treatment (Ref 5-7). Sugimoto et al. (Ref 8) found the relation between the appearance of the internal friction peaks and Ni/Ti ratio. According to them when the ratio is smaller than 1 the transformation to martensite occurs at a single stage and the spectrum shows very low internal friction in the parent phase and very high in the martensite. In this case a sharp peak is typically observed just below the M_s and A_s transition temperatures. Associated with the internal friction peak a

Table 1 Material parameters for time dependent computation

Parameter	Value
Wire diameter	0.2 mm
A_s	90 °C
A_f	110 °C
M_s	70 °C
M_f	50 °C
Resistivity	90 μΩ cm
C_p	400 J/kg/K
Density	6450 kg/m^3
Thermal conductivity martensite	8.6 W/mK
Thermal conductivity austenite	18 W/mK
Emissivity	0.3

remarkable depression of the rigidity is observed. Also, the cycling rate (frequency) plays an important role on internal friction. By decreasing frequency the internal friction typically increases.

On the basis of these considerations we may suppose that the martensitic transformation at very low rates, like in a climatic chamber, can increase the internal friction. This effect is more evident under heating and cooling at the beginning of the direct and reverse transformation, confirming the Yoshida observations. In fact, looking at the typical hysteresis curve at 1 °C/min in the climatic chamber, it is evident that the hysteresis is larger and the course of the martensitic transformation is much steeper than that collected on SMAq by faster heating and cooling.

In order to confirm the effect of heating rate on the properties of the transformation, a special test has been carried out in the climatic chamber. The same setup described before (climatic chamber, position sensor, PT100 thermocouple) was used. In this case, the chamber temperature was set at different constant values, ranging from 25 to 85 °C, and the wire was actuated by an electrical current with an external Delta Elektronika power unit (0-30 V, 0-5 A). The current pulse duration was set to 3 s for all actuations; the current was varied according to the chamber temperature in order to achieve a 160 °C peak temperature. The displacement was recorded with a National Instrument logger that allows a very fast acquisition (in this case 0.01 s). In Fig. 7, the sequence of actuation cycles at increasing room temperature is shown.

By plotting the asymptotic displacement of the wire at the cooling cycle versus testing chamber temperature, a cooling

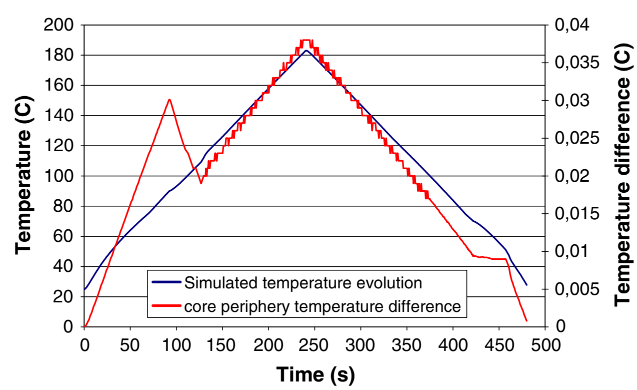

Fig. 6 Core temperature vs. periphery temperature simulation

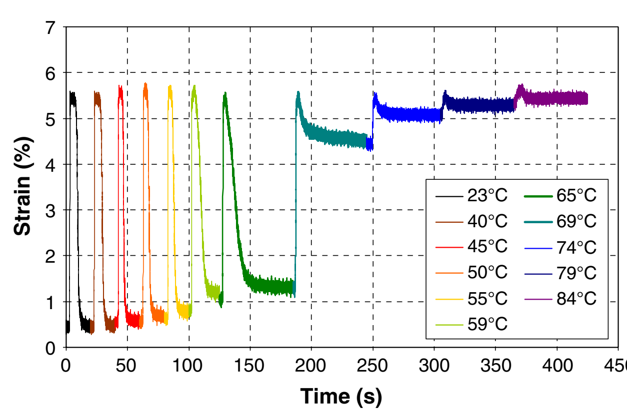

Fig. 7 Wire deformation at increasing ambient temperature

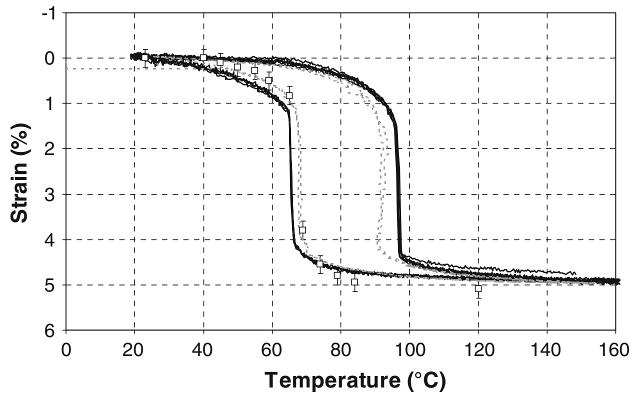

Fig. 8 The cooling branch of hysteresis reconstructed by collecting asymptotic deformation of fast actuations vs. SMAq and climatic chamber results

branch of the hysteresis curve can be constructed and compared to SMAq and climatic chamber, as shown in Fig. 8. The collected points do not overlap the climatic chamber curve, but seem to better match the SMAq hysteresis curve, thus confirming the above discussed hypothesis. However, further experiments should be carried out in order to definitely prove the temperature rate dependence of internal friction.

4. Conclusions

Thermal cycling at constant load, also known as hysteresis test, is a fundamental functional characterization of SMA wires for actuation. In this paper, two different experimental approaches for measuring the hysteresis curve of SMA wires have been compared and discussed. The first one has been carried out in a climatic chamber by submitting the material to a very slow thermal cycling across the transformation temperatures, so that quasi-equilibrium conditions may be attained. The second consists in a faster cycling of the material by Joule effect on SMAq.

On the basis of the experimental results, slight differences in the hysteresis width have been measured. In particular, we observed that in the case of high heating rates, the hysteresis curve becomes narrower with a reduction of A_s and an increase of M_s transformation temperatures. These results have been confirmed by performing pulsed actuations in climatic chamber at increasing chamber (ambient) temperatures. This behavior could be related to the internal frictions generated during the martensitic transformation. As measured by Yoshida et al. the internal friction in NiTi is strongly affected by the composition, thermo-mechanical history and thermal cycling rates. At very low rates, like in a climatic chamber, the internal friction can increase. This effect is more evident under heating and cooling at the beginning of the direct and reverse transformation, confirming the Yoshida observations. This possible hypothesis is not fully supported by the presented data. Further experiments must be carried out in order to directly measure the internal friction of the material.

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