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Effect of Current Pulses on Fatigue of Thin NiTi Wires for Shape Memory Actuators

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Shape memory alloys (SMA) are used in many technological applications, thanks to their unique properties: superelasticity and shape memory (SM) effect. Many efforts have been made to improve performance of SMA wires to utilize them as thermal actuators also for many thousands of cycles. Near-equiatomic nickel-titanium compound is the most used materials for SM actuators because of its high recoverable values of strain and good cycling stability, if compared to the other known SMA. In this study, the functional properties of NiTi thin wires (80 μm) thermally cycled under a constant load (200 MPa) were investigated. In particular, the effect of two heating conditions, carried out by a *step* and a *ramp* current pulses, on functional fatigue of SMA has been studied. By means of an experimental apparatus, thermomechanical cycling, thermal loop under constant load and actuation time (AT) tests were carried out to investigate the alteration and the trend of recovered strain, irreversible strain, characteristic temperatures, and ATs of the thin SM wires.

Keywords NiTi fatigue, shape memory actuators, shape memory alloys

1. Introduction

Shape memory alloys (SMA) exhibit unusual functional properties named pseudoelastic (PE) and shape memory (SM) effects which are the results of a thermoelastic reversible martensitic transformation induced in the material (Ref 1, 2). In particular, the SM consists in the capability of these alloys to recover a determined shape upon heating and it is exploited for the design of smart SM actuators (Ref 1, 3).

The nickel titanium system, also known as nitinol, is employed in most of the applications based on SM effect, thanks to its cycling stability and capability in recovering high values of strain (Ref 4). In NiTi, SM effect occurs by a martensitic transformation between a low-temperature monoclinic structure, B19′, called martensite (M) and a high-temperature body-centered cubic parent phase, B2, called austenite (A). This transition may occur in two steps in association with a trigonal phase, called R-phase (Ref 1). Ti-rich NiTi also has an excellent thermomechanical behaviour and a good ductility. Wires of few tens microns can be drawn to be employed as micro-actuators and sensors providing rapid actuation response (Ref 5). They are recently proposed to produce mechanical autofocus actuators, optical image stabilization devices for small cameras, linear actuators, and so on thanks to their high power/weight and power/size ratios (Ref 6). SMAs are carving out a niche in all the applications with very strict dimensions requirements.

Chemical composition and material processing strongly affect functional properties of NiTi since they involve significant changes in microstructure of semi-finished products (Ref 1, 7-11). The role of dislocations is particularly significant on characteristic transformation temperatures since they can hamper or favour the martensitic phase transformation (Ref 12, 13). Also precipitates can modify the SM properties of the material inducing lattice distortion and interacting with dislocations and changing chemical composition of the matrix (Ref 1, 14).

SMA employed as actuators are often subjected to thermal cycles under an external load. Such cycling originates crystallographic defects; in particular, it induces the formation of new dislocation networks and promotes the precipitation of nanoscale compounds, leading to a modification of functional characteristics of SMA. This phenomenon is called functional fatigue (Ref 15, 16). In order to prevent a drastic deterioration of the functional behavior of the material in operating condition some tailored thermomechanical processing (so-called training) are carried out on each device of SMA element. Through training, defects are intentionally introduced in crystal lattice in a right balance so as to get an acceptable fatigue response of the semi-finished product or of the final SM device (Ref 15).

Moreover, it is known that some operating parameters may affect the functional and the fatigue behavior (FB) of SM wires for actuators, for instance external applied load, maximum recovered strain and finally wire position (Ref 5). In order to promote martensite shrinking to high-temperature austenitic phase, SM actuators are often heated by Joule effect with a consequent recovering of the imposed deformation. The time spent for this operation is named actuation time (AT). Then, the current is switched off and the material is cooled by natural air convection to room temperature. This lapse of time is called reset time. Although several SM devices were developed and

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many papers are available in the open literature on this subject, there is not a clear evidence of the effect of the Joule heating parameters on functional fatigue.

This study was aimed to study the influence of electrical heating conditions performed by different waveforms on functional fatigue of 80 μm NiTi wires for SM actuators. *Ramp* and *step* pulses revealed to strongly affect the cycling behaviour of SMAs leading to different results in terms of irreversible strain, transformation temperatures, strain recovering, and ATs.

2. Experimental Part

2.1 Material

A $Ni_{49}Ti_{51}$ (at.%) ingot (of about 5 kg) was produced using a vacuum induction melting furnace (Balzers VSG10) under a controlled argon atmosphere. The ingot was hot forged, hot rolled, and finally cold drawn down to 80 μm in diameter with 47% final cold deformation degree. A straight annealing at 400 °C for 1200 s + WQ was carried out and the wire were cut into samples of 100 mm in length. The specimens were not etched before testing; hence, they were covered by a brown and thin TiO_2 layer. Detailed thermomechanical process of the manufactured wire is reported in Ref. 11.

2.2 Experimental Setup

Each specimen of thin wire was vertically positioned and constrained to the system structure by an upper clamp. It was axially loaded by a weight hanging from it by a lower clamp. The clamps were connected to a power source which was controlled by a NI Labview program to heat the wire by Joule effect. This routine permits to set the shape of the electrical pulses and allows a fast control mode of wire deformation: the current was switched off when the sample recovers a certain displacement value indicated by operator (ε_l = 3%). The displacement was measured by a linear voltage differential transducer (LVDT Macro Sensors HSTA 750-125) and the experimental apparatus was placed in a thermostatic chamber (Angelantoni, mod. SU250). The specimens were electrical heated imposing two different current waveforms: *ramp* and *step* as depicted in Fig. 1 and a thermomechanical cycling up to n_c of 5×10^5 cycles, under constant stress of 200 MPa and at limited recovered strain value of 3 % was carried out. The cycling parameters were chosen on the base of previous results on operating conditions of 80 μm wire and resumed in the following:

- Applied external stress, σ = 200 MPa.
- Limited recoverable strain ε_l = 3%.
- Cooling time, t_{OFF} = 1.5 s.
- Maximum current, I_{MAX} = 0.19 A (only for *step* pulse).
- Current increment rate, k = 0.4 A/s (only for ramp pulse).

For both step and ramp pulses, SMA functional properties were tested and compared in term of:

- FB: fatigue behaviour by current heating.The minimum and maximum wire deformations values were measured and plotted as a function on N of cycle. Thermomechanical cycles (n = 50,000) were carried out at constant applied load (200 MPa) and limited strain (3%).
- TL: thermal loop by thermostatic chamber heating/cooling.The evolution of the transformation temperatures, thermal hysteresis, and maximum recoverable strains were analyzed and strain/temperature curves were plotted after 1, 50, 500, 5000, 50,000 cycles. TLs were performed in a temperature range between 193 and 343 K with a heating/cooling rate of 0.038 K/s, so it is to be considered a quasi-static test. The applied constant load was 0.91 N, corresponding to a stress of 200 MPa.
- AT: actuation time by single current heating.In order to study the AT evolution the strain values were detected

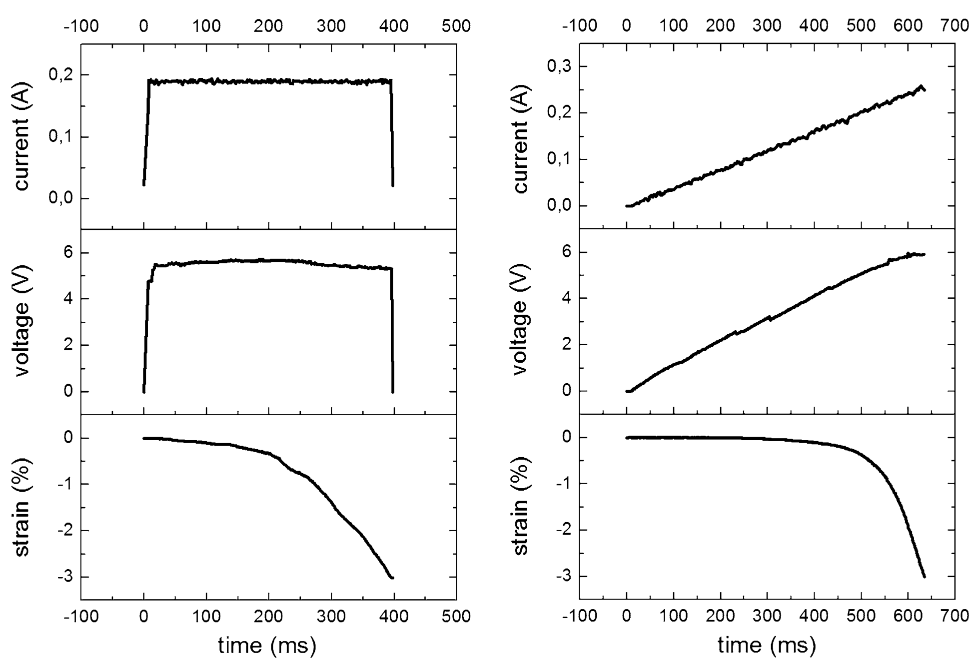

Fig. 1 Current, voltage, and strain versus time for *step* current pulse (left) and *ramp* current pulse (right)

during single current pulse after 1, 50, 500, 5000, and 50,000 thermomechanical cycles

3. Results and Discussion

3.1 Current Pulses

Figure 1 depicts the trend of the strain, voltage, and current in time domain of two wires under 200 MPa at first thermomechanical cycle. The sample heated by *step* current pulse (0.19 A) takes about 400 ms to reach the imposed strain value of 3%. Of course, the voltage measured across the wire does not follow the same flat behavior since the phase transition causes a change in resistivity of the specimen. The wire heated by ramp current pulse (k = 0.4 A/s) takes 623 ms to reach the same 3% of strain value, so at the first thermomechanical cycle it takes about 65% more than the one heated by *step* pulse.

The electrical energy (input) is estimated integrating the curve of electrical power in the time interval

$$E_e = \int_0^{t_{\varepsilon=3\%}} i(t)v(t)\,dt,$$

where $t_{\varepsilon=3\%}$ is the time taken by the wire to recover the 3% of strain, $i(t)$ and $v(t)$ are, respectively, the current and the voltage as function of the time.

The mechanical work (output) is calculated as follows:

$$L_m = F * \varepsilon * l,$$

where F is the applied load, ε is the strain, and l is the length of specimen, while the actuator efficiency, η, is given by

$$\eta = \frac{L_m}{E_e}.$$

Ramp and *step* pulses were designed to spend, at first cycle, the same electrical energy to heat wire until it recovers the 3% of the deformation imposed by constant load (E_e = 0.33 J). Since the value of mechanical work is a constant in common to all the tests (L_m = 0.0027 J), at the first cycle *ramp* and *step* heating mode have also the same efficiency (in percent, 0.91).

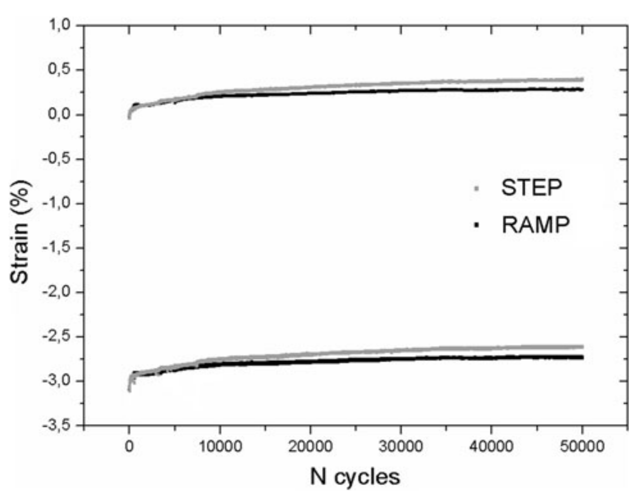

Fig. 2 FB—minimum/maximum strain versus n_c; step and ramp pulses comparison

3.2 FB by Electrical Heating

Figure 2 shows the maximum and minimum strain as a function of the number of cycles. During cycling the wires accumulate irreversible strain. In particular, the *ramp* pulse led to a more stable trend compared to the *step* one. After 5×10^5 cycles, the wire heated by ramp current stored the 0.28% of irreversible strain, while the one heated by *step* pulse stored the 0.40%. Moreover, plastic deformation is largely accumulated during the first thermomechanical cycles. After 10^5 cycles, the wire underwent to a ramp pulse cycling accumulated 0.21%, while the one cycled by *step* pulse accumulated the 0.25%.

Plastic deformation is an inevitable phenomenon which is inherent to the martensitic transformation mechanism (Ref 12, 13), so it is a necessary problem to handle in actuators design. In this sense, *ramp* heating condition better results than *step* mode.

3.3 TL by Thermostatic Chamber Heating/Cooling

In Fig. 3, the results obtained by TL are shown. Both the graphs show that the cycling involves a reduction of the capability of the material to recover the imposed deformation. In particular, at the first thermomechanical cycle the wire

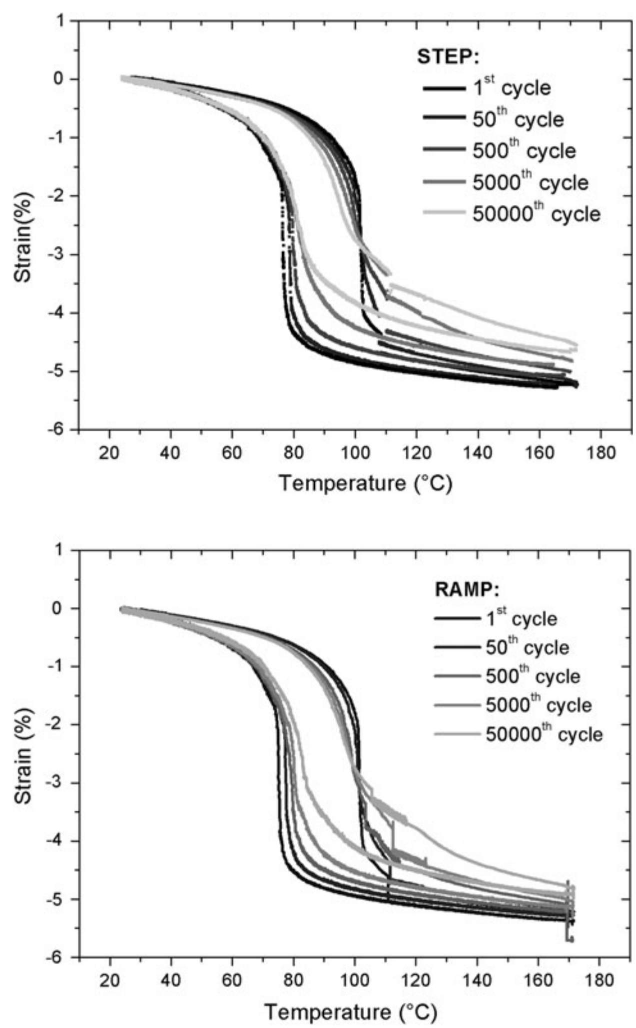

Fig. 3 TL results. Wires cycled by *step* pulse (up) and by *ramp* pulse (down)

recovers 5.35% of deformation, while after 5×10^5 cycles, the specimens cycled by *ramp* pulse recovers the 4.9% while the one cycled by step pulse recovers the 4.6%.

Also an alteration of transformation temperatures is well noticeable from these curves. In both the cases there is a reducing of thermal hysteresis between cooling and heating branches.

Different current pulses lead to different thermal hysteresis behaviors that are particularly appreciated for *N* cycles over than 5000 (Fig. 3).

3.4 AT and Efficiencies

The effects of cycling are observable by not only quasi-static tests (Fig. 3) but also dynamic tests (Fig. 4a), which represent the behavior of SM wires in using conditions.

Figure 4(a) describes the strain evolution in time domain of the wires heated by the two different current pulses. Basically, they show the times required by the wires to recover the 3% of deformation, hence the ATs.

At the first cycle the two heating modes were designed to have the same efficiency (0.91%) but the AT is 400 ms by step current pulse while it is 623 ms by *ramp*.

However, after 5×10^3 cycles the wire heated by step pulse employs 618 ms, so 218 ms more than the time employed at the first cycle. In contrast, the *ramp* pulse leads to an increase of just 22 ms. After 5×10^4 cycles the AT related to the wire heated by step is even higher than the one related to wire heated by *ramp*. This behavior leads to a drastic decrease of the step heating method efficiency (from 0.91 to 0.55%), vice versa the efficiency of the *ramp* heating method does not change so much (from 0.91 to 0.75%) (Fig. 4b).

The AT is a very important characteristic for the technological application and it is a criterion for the selection of the right type of actuator for the specific device.

Then, the waveform of the electrical impulse revealed a fundamental parameter to set to achieve good performance in terms of functional fatigue of the wires subjected to thermo-mechanical cycling. The *ramp* current pulse leads to a more steady behavior in terms of ATs compared to the one related to step pulse.

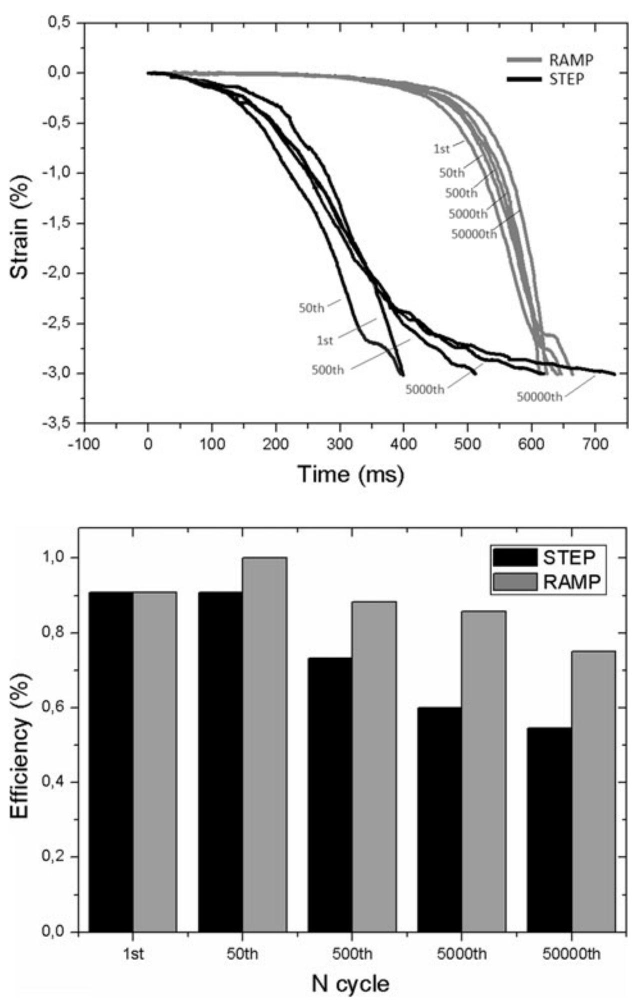

Fig. 4 AT curves (up) and efficiencies (down)

4. Conclusion

Thermal cycling under constant load performed by electric heating (FC) tests, TL under constant load performed by thermostatic chamber tests, and AT test performed by electric heating was carried out on 80 μm NiTi wires by means of an experimental apparatus. *Ramp* and *step* current pulses were chosen to heat the SM wires of 100 mm in length with the same electrical efficiency at the first thermomechanical cycle. Functional properties of SMA specimens were severely affected by different electrical heating methods:

- During thermal cycling under constant load the wires accumulate irreversible strain: after 5×10^5 cycles, the wire heated by *ramp* current stored the 0.28% of irreversible strain, while the one heated by step pulse stored the 0.40%, so the *ramp* pulse led to a more stable cycling behavior.
- Thermal cycling under constant load involves a reduction of the capability of the material to recover the imposed deformation: at the first thermomechanical cycle the wire recovers the 5.35% of deformation, while after 5×10^5 cycles the specimens cycled by *ramp* pulse recovers the 4.9% while the one cycled by step pulse recovers the 4.6%.
- Thermal cycling under constant load implies drastic alterations of characteristic transformation temperature of the SM samples: a reducing of thermal hysteresis between cooling and heating branches is well noticeable.
- The two heating methods, designed to have an efficiency of the 0.91%, implies an AT of 400 ms for the wire heated by step and 623 ms for the one heated by *ramp* current pulse at the first thermomechanical cycle. The change of transformation temperature involved by cycling leads to the alteration of ATs. Step pulse influences much more the ATs than the *ramp*. After 5E5 cycles, the AT related to the wire heated by step becomes even higher than the one related to wire heated by *ramp*. This behavior leads to a strong decrease of the step heating efficiency (from 0.91 to 0.55%), vice versa the efficiency of the *ramp* heating does not change so much (from 0.91 to 0.75%).

Finally, this experimental work shows that *ramp* current pulse leads to a more steady behavior compared to the one related to step pulse. Then, to get suitable performance for the specific technological application in terms of functional fatigue, the heating condition of SM wires subjected to thermomechanical cycling must be carefully designed.

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