Behavior of NiTi Wires for Dampers and Actuators in Extreme Conditions

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Abstract

Shape memory alloys are considered smart materials because of their singular thermo-mechanical properties, due to a thermoelastic martensitic transformation, enabling possible uses as actuators (because of mechanical recovery induced from temperature changes) and as dampers (because of hysteresis). NiTi wires for dampers in Civil Engineering had been characterized and tested in facilities. Guaranteed performance needs to know behavior during fatigue life and knowledge of effects in the event of extreme conditions, as eventual overstraining. In this work, we check the possibilities to absorb mechanical energy on the fatigue life depending on stress level and explore the consequences of overstraining the material during installation, the possibilities of partial healing by moderate heating, and some effects of over-stressing the wires. The mechanical energy absorbed by the unit weight of damper wire might be very high during its lifetime if maximum stresses remain relatively low allowing high fatigue life. We show also some results on NiTi wire working as an actuator. The lifetime mechanical work performed by an actuator wire can be very high if applied stresses are limited. The overstraining produces relevant "residual" deformation, which can be to some extent reversed by moderate heating at zero stress. The reason for the observed characteristics seems to be that when external high stresses are applied to an NiTi wire, it undergoes some plastic deformation, leaving a distribution of internal stresses that alter the shape and position of the macroscopic stress-strain transformation path.

Keywords

creep and stress rupture
failure analysis
intermetallics
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Introduction

Shape memory alloys are considered smart materials because of their singular thermo-mechanical properties, due to a thermoelastic martensitic transformation between metastable phases, enabling possible uses as actuators (because of mechanical strain recovery induced from temperature changes) and as dampers (because of hysteresis on the mechanical transformation) (Ref 1). Many applications of SMA need a controlled reproducibility and a careful evaluation of the fatigue life under thermal and mechanical actions (Ref 2).

Among the applications of SMA, NiTi wires for dampers in Civil Engineering have been characterized and tested in facilities, where they showed good performance in damping of cables, enabling a reduction of the steady oscillation amplitude to 50%, and a considerable shortening of the time to decrease the oscillation after a force impulse (Ref 3-5). The reliable performance of SMA dampers needs a known life time in terms of fatigue, both structural and functional (Ref 6). The increase in fatigue life might be obtained by a reduction of working stresses (and strains). In these conditions, damping is reduced as energy absorbed per mechanical cycle is lower. However, life performance might imply a larger amount of vibration energy absorbed due to the higher number of cycles possible. The effects of maintaining the NiTi alloy at different temperatures near room temperature have been previously investigated (Ref 7, 8). Temperature effects on cycling have been characterized, aiming at damping applications (Ref 9), and the effects of size or wire diameter and frequency of cycling on damping behavior have been also characterized (Ref 10).

In this work, we explore the changes in stress-strain cycle shape for the damper (pseudoelastic NiTi) wire, the hysteresis energy, the total mechanical energy absorbed during the lifetime, the consequences of overstraining the material, for instance during installation, and the possibilities of partial healing by moderate heating. We show also some results on NiTi wire working as an actuator (martensitic at room temperature). There is some performance as an actuator at high stresses, with limited strain recovery, high non-recoverable strain, shorter fatigue life to fracture, and reduced total work (in the life time) that can be obtained from the actuator.

Experimental

Three kinds of NiTi wires have been studied: First one, pseudoelastic wires of 2.46 mm diameter (from Special Metals—actually Memry corp., a division of SAES Getters, Italy), with composition of 55.95 wt.% Ni and balance in Ti, intended for use as dampers in civil engineering. The tensile forces to mechanically transform the wires are in the 3 kN traction range at room temperature.

Second one is the thinner pseudoelastic wires, 0.5 mm diameter (from Special Metals—actually Memry corp., a division of SAES Getters, Italy), with forces to mechanically transform the wire in the 100 N traction range at room temperature. For this wire and the previous one, the furnisher indicates that the nominal composition was Ni 55.95 and 55.92 wt.% with balance in Ti, and the nominal transformation temperatures (As, austenite start) were similar, 243 and 248/247 K.

Third one is a 0.6-mm-diameter wire from AMT, in martensitic state at room temperature, intended for use as an actuator, with temperature to stress-free retransform the wire to austenite state of 325 K (as measured by DSC).

The pseudoelastic NiTi wires of 2.46 mm diameter were tested for fatigue, cycled in MTS hydraulic testing machine in strain control, at frequencies up to 4 Hz. The mechanically cycled samples in fatigue tests had previously performed a "training" of 100 cycles to 8% strain, at 100 s per cycle, to stabilize the behavior, as the first cycles show strong evolution on the shape of force-displacement (or stress-strain) graph with the number of cycle.

The pseudoelastic NiTi wire of 0.5 mm diameter was cycled with a home-made straining machine, computer controlled, enabling a DC current on the sample (to heat the sample when needed), permitting more than 100-cm-long samples. The stepper motor and the mechanics used allowed only slow cycles (600 s per cycle and lower speed were possible). The wire was checked for overstraining effects.

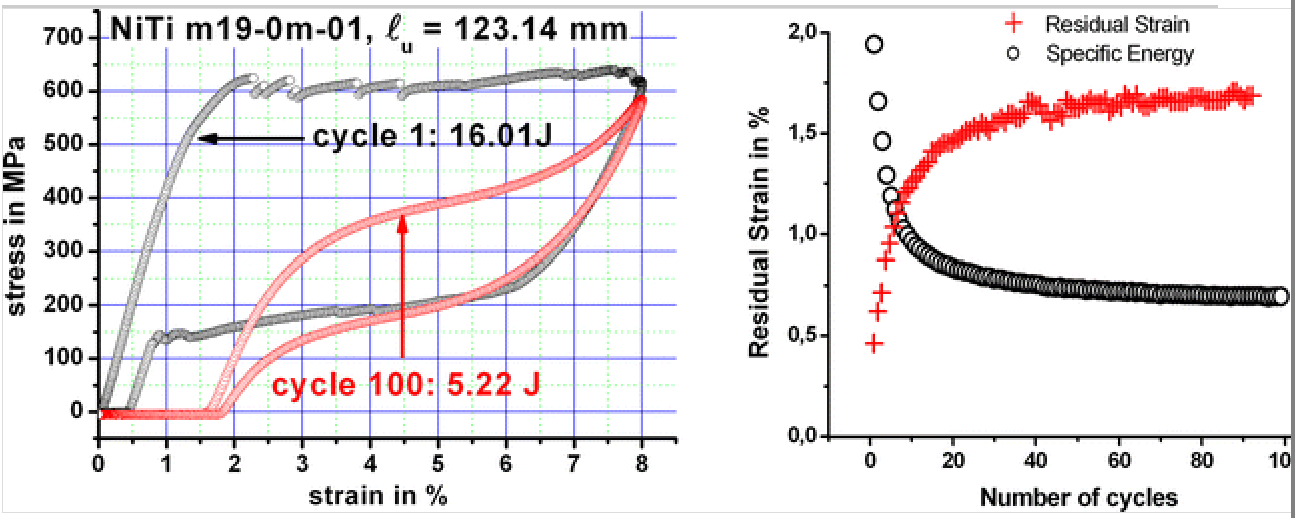
The 0.6-mm-diameter wire was thermally cycled at constant stress and low speed (suspended weight) by a home-made device controlled with a computer, switching DC current through the wire (heating the wire up to 120 °C over room temperature), with a 100-s period (50 s on and 50 s off), and measuring voltage across the wire to detect the failure.

Results and Discussion

The mechanical cycles presented an "S-shaped" appearance for the 2.46-mm-diameter wire after the "training" procedure. The "residual" or "permanent" deformation ("creep") situated near 1.6-1.9% from the initial dimension. The specific energy absorbed by the wire, defined as mechanical work absorbed on cycling, or the integral of force by increment of displacement for a complete cycle, per unit mass of wire, decreased on cycling during the "training" to stabilize the properties, similarly to the increase of the "residual" accumulated strain, showing both an approach to a stable state in a little more than 20 cycles (see Fig. 1). We used 100 cycles of "training" for the pseudoelastic wire for dampers.

Fig. 1

Left: Cycles 1 and 100 on the "training" of pseudoelastic NiTi wire (2.46 mm diameter). Right: Specific energy absorbed per cycle (in J/kg) and accumulated residual (permanent) strain for NiTi wire of 2.46 mm diameter, 100 cycles to 8% strain at 100 s per cycle (“training” or stabilization of properties procedure)



Structural Fatigue and Dissipated Energy in Damper

In the references, data can be found concerning mechanical fatigue of NiTi with relative high dispersion (Ref 11 - 15). The initial state of the material influences strongly fatigue performance, and SMAs are in general very sensitive to previous thermo-mechanical treatments. Fatigue failure comes many times from a surface defect inducing crack growth, and this means that fatigue has to be studied for concrete applications, with the correct samples, as the state of the material might present size effects on fatigue (Ref 16). Frequency effects are also relevant for functional fatigue (Ref 10). The maximum stress appears to be the representative variable to describe the life to fracture (Ref 2). The results show that the Basquin law (Ref 17 , 18) gives a practical approach to the fatigue life for the 2.46-mm-diameter wire. For this wire, the relationship of the number of cycles to failure Nf to maximum applied stress could be approached as follows: maximum stress (in MPa) = 170 + Nf$^{-0.4}$ (Ref 2).

For the 2.46-mm-diameter wire with S-shaped, stabilized stress-strain cycles at room temperature, the energy dissipated per mechanical cycle starts to be appreciable at near 0.8% maximum strain from the residual strain, with some 16 J/kg of absorbed energy per cycle on NiTi wire. The energy dissipated per cycle evolves in a near parabolic form by increasing the strain. At 2.25% maximum strain, the energy per cycle amounts to 115 J/kg, and at maximum strain to fully transform, the energy dissipated per cycle reaches near 1.4 kJ/kg. It has to be noted that the initial cycle had larger absorbed energy, near 4 kJ/kg, but the value changes strongly during the first cycles, making it difficult to apply for a reliable design if many cycles have to be done.

It has to be noted that a damper wire (NiTi wire of 2.46 mm diameter), working at 0.8% maximum strain (stress under 200 MPa), has a fatigue life (to fracture) in the 4×10^6 cycles range (Ref 2), so 64 MJ/kg of mechanical work (vibration energy) can be absorbed in the lifetime. However, if the wire is made to work in the 2.25% maximum strain, life would be some 40,000 cycles (Ref 2), and absorbed energy in the lifetime results as 4.6 MJ/kg. In the 8% strain regime, the average work absorbed per cycle will be some 1400 J/kg, but the life extends to some 2000 cycles (Ref 2), and the total work absorbed would be 2.8 MJ/kg.

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Functional Fatigue of Actuator

The 0.6-mm-diameter wire was thermally cycled at constant load, at low frequency (0.01 Hz), heating it by an electric current. The thermally cycled wires accumulated residual (“permanent”) deformation, especially during the first 20 cycles (Fig. 2). The residual deformation was some 4.5% at 528 MPa in traction, and the actuator could recover 2.3% strain by heating. The residual deformation was more than 5% at high stresses (near 800 MPa), with recovery of near 1.5% strain (Fig. 3). At very low stresses, the phase change is not mechanically driven to full transformation, so recovery strain increases by increasing stress (see Fig. 3 left, up to 100-150 MPa). At higher stresses, plastic strain starts to develop and recovery strain does not increase more than some 4%, see Fig. 3 left, stresses from 150 to 350 MPa. At still higher stresses, the plasticity starts to dominate and recovery goes down (Fig. 3 left, above 350 MPa).

Fig. 2

Strain for 0.6-mm-diameter NiTi wire thermally cycled at a constant traction stress of 528 MPa

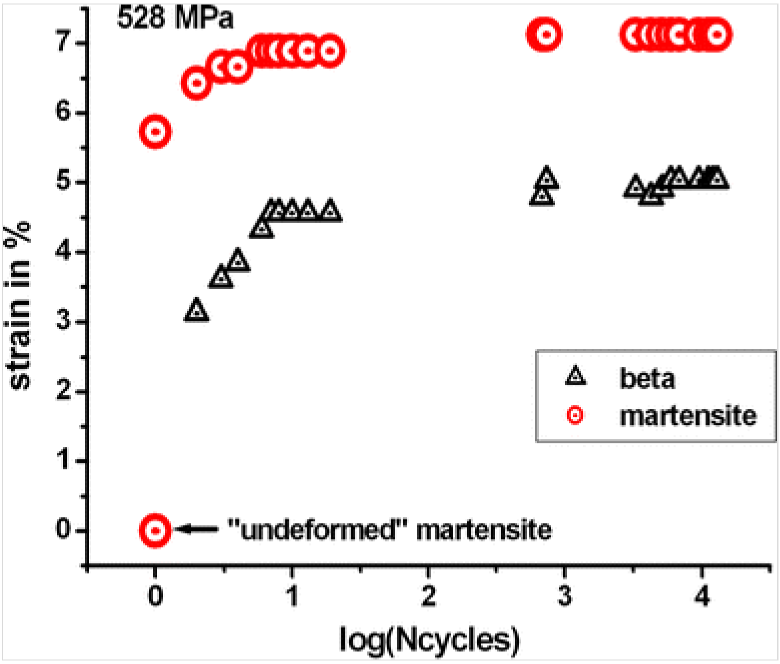
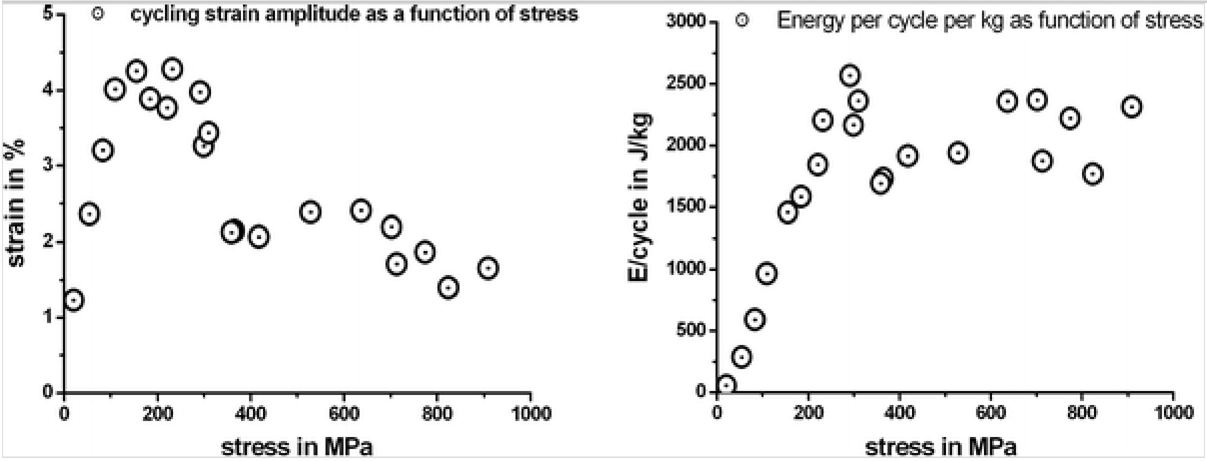


Fig. 3

Left, recovered strain on cycling, after the first cycles, for NiTi wire of 0.6 mm diameter, as a function of constant applied stress. Right, energy (work) per cycle as a function of constant applied stress, for NiTi wire of 0.6 mm diameter



AQ2

The strong initial evolution of the residual (permanent) strain produces that the wire has to be “trained” by more than some 20 initial cycles to be used later as an actuator with reduced changes during the lifetime, a similar effect that the one found by mechanically cycling the pseudoelastic wire.

The actuator wires had some performance at high applied stress; they were able to partially recover shape. However, an increased residual strain develops, higher with higher stress. This makes the wires more difficult to use, as recovery strain might be lower than residual deformation induced by stress.

Around 1.3% of strain could be recovered by heating wires at high stresses (near 800 MPa), with relatively short fatigue life (fracture in less than 2000 cycles). In this case, the residual strain was as high as more than 5% after 20 cycles.

The mechanical energy (work) the actuator can give on a retransformation cycle (by heating) increases from zero to near 250 MPa of applied stress, giving some 2.5 kJ/kg. Then, plasticity effects produce a near-constant specific energy the actuator can give per cycle, up to the higher stresses, around 2 kJ/kg, as the stress increases produce more irrecoverable (plastic) strain.

Also, it has to be noted that an actuator wire (NiTi wire of 0.6 mm diameter), working at 500 MPa, can perform some 2000 J/kg of mechanical work per cycle (see Fig. 3 right), and its fatigue life is in the 10^4 cycles to fracture, so some 20 MJ/kg of work can be obtained. However, if the wire is made to work in the slightly less than 100 MPa stress, the work per cycle will be much lower, some 600 J/kg (see Fig. 3 right), but the life extends to more than 40~~,~~0000 cycles, and the total work would be much higher, more than 240 MJ/kg.

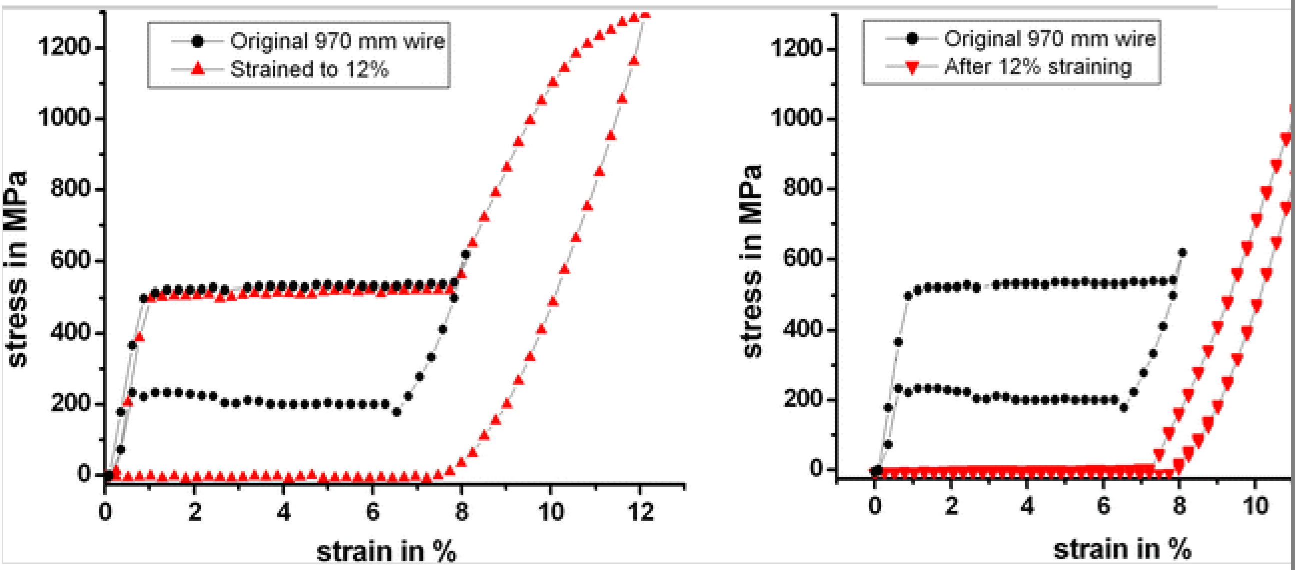
Then, the wires could be used for damping with large number of working cycles, or for actuators, if the applied stresses are limited to under 100-200 MPa. In this case, the absorbed energy per cycle in damping, or the actuator energy (work) per cycle, is much smaller than in a few cycles of action, but the accumulated energy, taking into account the number of cycles, can be much higher than at larger stresses and strains. The mechanical energy absorbed by the unit weight of wire (or the work done by the actuator wire) might be very high during its lifetime if maximum stresses remain relatively low allowing high fatigue life.

Overstraining Effects and Recovery

We have also studied the stress-strain behavior after an overstraining of an NiTi pseudoelastic wire. Preliminary observations with the 2.46-mm-diameter NiTi wire showed that the “trained” pseudoelastic wires (that had been cycled 100 times at 0.01 Hz at room temperature) could recover around half of the residual deformation appeared on cycling at room temperature by heating to 100 °C at zero stress. Some specific observations were later done. Figure 4 indicates the stress-strain trajectory for non-trained, 0.5-mm-diameter pseudoelastic NiTi wire. These wires were able to withstand one-time strains around 15% and maximum stresses near 1300 MPa (Ref 5).

Fig. 4

Stress-strain trajectories at room temperature for 0.5-mm-diameter wire showing the effect of overstraining on the functional performance as a damper. Left, original cycle (full circles) and overstraining to 12% (up triangles). Right, original cycle (full circles) compared to cycle after overstraining (down triangles)



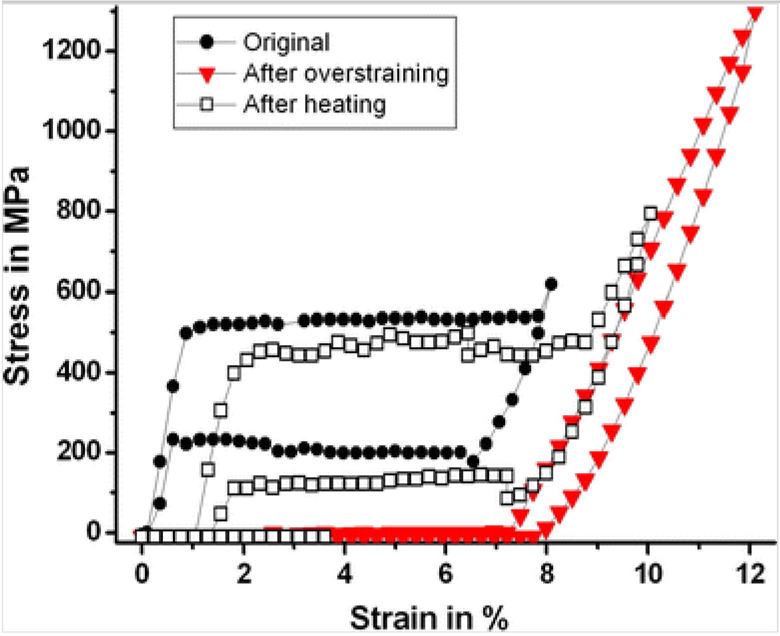
The initial cycle in Fig. 4 left showed an absorbed mechanical energy of 3.6 kJ/kg per cycle at 8% maximum strain. If the wire is strained to 12%, the area of the first straining cycle increases strongly (Fig. 4, left), but recovery force ceases at around 6.5% strain (residual strain). A later cycle (Fig. 4, right) shows a very different appearance in stress-strain coordinates as referred to the initial cycle, but the new cycle is still able to absorb near 1.9 kJ/kg per cycle, if it is strained to 12% from the initial starting situation (Ref 19).

This shows that, on the one hand, even with a strong change on properties, the wire has still some of its functional performance as a damper. For instance, it might be able to absorb about one half of the mechanical energy per cycle it was designed to absorb at 8% maximum strain, if it is strained to 12% maximum strain. On the other hand, it will not be able to re-center a structure or absorb energy at lower deformations after an overstraining, because of the high residual strain.

Further on, if the wire is heated to 100 °C with zero load, it recovers partly from the previous overstrain. The resulting mechanical cycle at room temperature (empty squares), compared with the initial cycle (full circles) and the cycle performed after straining to 12% (down triangles), is shown in Fig. 5. The healing after heating to 100 °C is partial, a residual deformation of more than 1% exists, and the cycle after the heating has lower stresses (both transformation and retransformation plateaus) than the initial cycle, and also a larger residual strain develops during the cycling.

Fig. 5

Partial recovery (healing) of NiTi wire after heating to 100 °C. Full circles, original (as furnished) wire. Inverted triangles, cycle after overstraining to 12%. Empty squares, cycle after heating the wire to 100 °C



The reason for the observed characteristics seems to be that when high external stresses are applied to a pseudoelastic NiTi wire, it undergoes some plastic deformation, producing a non-uniform distribution of internal stresses that alter the shape and position of the macroscopic stress-strain transformation path and leaves some martensite at room temperature, part of this martensite with relatively low stresses (the high macroscopic stress is to a certain extent supported by other parts of the material, with higher-than-average stresses). Then, the wire might recover some length (partial shape memory effect) by moderate heating, as the part of martensite with lower stresses retransforms to parent phase, redistributing internal stresses and giving some change in macroscopic strain.

Conclusions

NiTi wires (2.46 mm diameter) could be used for damping in civil engineering. A large number of working cycles can be supported, if the applied stresses are limited to under 100-200 MPa, with reduced performance per cycle (some 16 J/kg/cycle of mechanical energy transformed to thermal energy), but with large life performance and a larger amount of total energy (work) absorbed, up to 64 MJ/kg, compared with the use of higher stresses (in the magnitude of 5 MJ/kg). Thin NiTi wires (0.6 mm diameter) could also be used for actuators, with long life and larger total mechanical work output during lifetime if maximum stresses are restricted to around 100 MPa.

An overstraining of the wires changes strongly the behavior in stress-strain; the wires conserve some possibility to absorb mechanical energy, but a residual deformation develops and fatigue life (to fracture) is shortened. Then, for application as a damper in civil engineering, it is necessary to adapt the length of the wires to the maximum expected deformation with relatively reduced stress, taking into account design life, or the performance will be strongly reduced with respect to the total energy absorbed by the NiTi wires in the lifetime.

The NiTi actuator wires (0.6 mm diameter) could recover shape partially under high stresses, even with moderate temperature increases (1.4% recovery with stresses near 800 MPa), but in this case large residual deformation appears (higher than 3% in 20 cycles) and fatigue life (to fracture) is shortened, making it difficult to profit the partial shape recovery.

The results indicate that when high external stresses are applied to an NiTi wire, it undergoes some plastic deformation, leaving non-uniform internal stresses that alter the shape and position of the macroscopic stress-strain transformation path. Then, the wire might recover some length (partial shape memory effect) by moderate heating even at high stresses, because part of the martensite would be at reduced stresses, and temperature could produce some partial retransformation. The change of the hysteresis cycle induced by the high stresses applied justifies the observed performance. The partial healing observed by heating the wire with residual deformation by cycling or by overstraining should be due to retransformation of the martensite part at reduced stresses, producing a re-distribution of internal stresses and a reduction of residual strain.

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