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Effect of strain rate on properties of superelastic NiTi thin wires

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Abstract

This study deals with the effect of strain rate on tensile and energy absorbing properties of superelastic NiTi thin wires. It also attempts to gain an understanding of the interplay of the ductile behavior, temperature and strain rate effects, energy storage and cycling. The wires are in austenite condition at room temperature and above. The strain rates imposed during testing range from 0.2 to 180%/min (i.e., 0.06–54 mm/min) corresponding to a frequency of 2.77×10^{-4} to 0.25 Hz for strain amplitudes of 6%. The corresponding frequency for 8% strain amplitude is 2.08×10^{-4} to 0.18 Hz. It is shown that NiTi SMAs exhibit ductility at both low and high strain rates. This is also true for the cold worked and heat treated conditions both below M_f and above A_f. During tensile testing the stress-induced martensite (SIM) plateau increases in length and translates upwards with increase in strain rate up to a certain value. Similarly, the onset of elastic yield stress also increases with strain rate. At high strain rates the SIM segment and elastically deformed SIM segment overlap. The SIM formation is not able to cope with the externally imposed higher strain rates. This is also the reason for the reduction of hysteresis loop at the high strain rates as observed in the cyclic tests.

The dissipated strain energy density (E_d) increases with increasing strain rate up to a certain value beyond which the E_d decreases. It is clear that the mean point of the superelastic loop shifts to the right and upwards (higher stress and higher strain region) for cyclic testing with increase in strain rates. However, it shifts to the right and downwards (lower stress/higher strain regime) for both the 6 and 8% strain amplitude cycling at constant strain rate. The stabilization of residual strain and E_d is based on the same underlying mechanism relating to SIM formation and occurs at the same numbers of cycles.

Keywords: Superelastic NiTi; Strain rate effects; Ductile behavior; Energy absorption

1. Introduction

NiTi shape memory alloys find their use in several areas such as aerospace, automobile, medical and others. This is because of their superior mechanical and functional properties compared to the other shape memory alloys. Amongst the several mechanical properties of these inherently ductile materials, the energy absorbing (damping) capacity makes them strong candidates for applications for which energy absorption is important. For these applications there is a need to understand the effect of strain rate on the energy absorption and related properties of these materials. Some efforts have been made in the past in this direction. Liu et al. [1] studied the effect of strain rate, strain amplitude and annealing condition on the martensite damping of NiTi shape memory alloy (SMA) wherein it was shown that these materials could withstand a high number of cycles without fracture under different stress modes within a large range of strain rates and at rather high strain amplitudes. DesRoches [2] investigated the strain rate effects by subjecting the NiTi SMA Wires and bars to loading frequencies of 0.025, 0.5 and 1.0 Hz at superelastic strain amplitude of 6%. Their results showed that as the test frequency increases the loading and unloading plateau stresses increase whereas the hysteresis and the hysteretic damping markedly decrease. Dolce and Cardone [3] studied the effect of loading frequency on the behavior of NiTi SMA wires in the austenite condition. They inferred that the mechanical behavior is affected when passing from very low frequency (less than or equal to 0.01 Hz) to the frequency range of 0.2–4 Hz. They recorded that when the strain rate is increased the hysteresis loops narrow and translate upwards, while the segments of the curve relevant to the phase transformation harden, thus, yielding an increase in the stress levels. The strain amplitude considered was again 6%. Brinson et al. [4] conducted in situ optical microscopy observations of NiTi SMA tensile behavior. During the loading sequences containing constant displacement holds

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Nomenclature

A_f	Austenite finish temperature
A_s	Austenite start temperature
J	Joules
M_d	Maximum temperature at which martensite occurs with the assistance of an external stress
M_f	Martensite finish temperature
M_s	Martensite start temperature
N	Newton

they observed stress relaxation. The magnitude of the stress relaxation decreased with decreasing strain rates. The stress relaxation was attributed to the latent heat released in the specimen during the transformation. Li et al. [5] inferred that the pseudo elastic behavior is influenced by both ambient temperature and loading frequency. Nasser and Guo [6] found that the superelastic behavior of these materials have stronger sensitivity to temperature than to strain rate. Humbeeck and Delaey [7] inferred that for Cu-Zn-Al crystal the change in hysteresis as a function of strain rate could be attributed to heating and cooling of the sample due to exothermic character of the beta-martensite transformation and the reverse endothermic transformation. The observations of Adharapurapu et al. [8] illustrate a complex interplay of test temperature, stress state and martensite type that lead to an asymmetry in compression vs. tension response of NiTi SMA in quasi-static and dynamic loading conditions. Tobushi and Shimeno [9] studied the influence of strain rate on the deformation property of NiTi SMAs. They concluded that the martensitic transformation stress and recoverable strain energy density is dependant on the strain rate in a certain range. In a similar work Lin and Tobushi [10] inferred that at strain rates higher than 10%/min the martensitic transformation stress and dissipated work increase with increase in strain rate. But the reverse transformation stress and strain energy decreased. They also observed that at strain rates lower than 2%/min the characteristic values associated with the martensitic transformation did not depend on the strain rate.

There is certainly a strong interdependence of the ductility, temperature and strain rate that affect the tensile and energy absorbing (cyclic properties) behavior of NiTi SMAs. The interplay of the ductile behavior, temperature, energy storage, and strain rate effects and cycling needs a much better understanding. A comprehensive study of the effect of a wide range of strain rates on the various parameters of tensile testing up to failure as well as the energy absorbing or damping properties of NiTi superelastic SMAs is not available in the literature. It is very important that for the proper design of superelastic SMA-based devices such a study should be carried out to elucidate the following: (a) comparison of energy storage capacity of NiTi SMAs vis-a-vis conventional materials. (b) The stress levels at different strains (as a function of the strain rate) in the elastic region. (c) Effect of temperature and strain rate on ductility. (d) The strain rates at which the energy dissipation is optimum. (e) Cyclic loading effects. The present effort aims to systematically study the effect of a range of strain rates and temperature on the tensile behavior, energy absorption and related properties. The tensile testing is backed by limited fractographic studies of the gross features. The strain rates during testing range from 0.2 to 180%/min (i.e., 0.06–54 mm/min) corresponding to a frequency of 2.77×10^{-4} to 0.25 Hz for strain amplitude of 6% and 2.08×10^{-4} to 0.18 Hz for strain amplitude of 8%, respectively.

2. Material and specimen details

The material used for the study was 0.6 mm superelastic NiTi SMA in the wire form. The nominal chemical composition of the wire was Ni = 54.3% and Ti = 45%. The cold worked material was heat treated for 15 min at 500 °C. The transformation temperatures of the heat treated material obtained from the DSC tests were as follows:

$$M_f = 6.8\,^{\circ}\mathrm{C};\quad M_s = 12.5\,^{\circ}\mathrm{C};\quad A_s = 11.9\,^{\circ}\mathrm{C}\quad \text{and}$$
$$A_f = 17.7\,^{\circ}\mathrm{C}.$$

The length of the wire used for the testing was 30 mm. Only for the comparison of energy storage with a helical tensile spring a length of 100 mm was used (to ensure stiffness matching). The specimens were straight with uniform cross-section.

3. Experimental details

The tensile and cyclic testing was done using a Tinius Olsen H 10 KT computer controlled tensile testing machine. The specimen was secured in the wedge type of grips by mechanical fastening. The following four types of experiments were conducted on the NiTi wires:

1. Tensile tests up to failure for different strain rates from 0.2 to 180%/min (i.e., 0.06–54 mm/min) at room temperature (27 °C).
2. Fractographic studies on cold worked and a few selected heat treated specimens after tensile testing under the following condition:
   (a) at different temperatures, i.e., −50, 25 and 100 °C (at a fixed strain rate of 2%/min (0.6 mm/min)).
   (b) at low (0.2%/min (0.06 mm/min)) and high (180%/min (54 mm/min)) strain rates at room temperature.
3. Cyclic tests for fixed strain amplitude of 6 and 8% carried out:
   (a) at different strain rates from 0.2 to 180%/min (i.e., 0.06–54 mm/min).
   (b) up to 100 cycles for a strain rate of 30%/min (9 mm/min).
4. Tensile test up to failure at different temperatures, viz.; −50, +25 and +100 °C at a constant strain rate of 2%/min (0.6 mm/min).

It is to be noted that type 1, 2 and 4 tests are up to failure and type 3 are cyclic tests.

4. Shape memory alloy

Shape memory alloys are materials that have the unique ability to recover their original shape after undergoing large