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Effect of Impact-Induced Strain on the Stress-Induced Martensitic Transformation of Superelastic NiTi Shape-Memory Alloy Wires

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The stress-induced martensitic (SIM) transformation of NiTi shape-memory alloy wires has been studied as a function of the maximum strain induced during tensile deformation at impact and quasi-static strain rates. The SIM transformation stresses are higher at impact than at quasi-static strain rates. Only the lower plateau strength is sensitive to the maximum strain achieved during transformation when this is higher than necessary to complete the SIM transformation. For the same maximum strain achieved, the deformation energy (E_d) and recoverable strain energy (E_r) are greater at impact than at quasi-static strain rates, and the dissipated energy (W_d) is slightly lower at impact, reaching values close to those obtained at quasi-static strain rates.

Keywords impact, mechanical testing, NiTi, polymer matrix composites, shape-memory alloys

1. Introduction

Due to its high damping capacity, the superelastic (SE) property of shape-memory alloys (SMAs) in the form of wires has been required to be used as reinforcement in composite materials for improving damage resistance and damage tolerance (Ref 1) or as components for seismic protection devices (Ref 2). The effects of the maximum strain achieved during the stress-induced martensitic (SIM) transformation at quasi-static loading strain rates on the SE property is known in terms of transformation stresses (Ref 3, 4) or dissipated and recoverable strain energy (Ref 4). Nevertheless, the fate of these features when the loading occurs at higher strain rates, that is, at impact strain rates, is unknown. The aim of this work is to study the effect of the maximum strain achieved during an impact event on the SIM transformation of SE-NiTi-SMA wires.

2. Experimental Procedure

For the experimental tests carried out in this work, a NiTi-SMA (56 wt.% nickel) has been selected. This is a commercially available alloy in the form of wire, 0.5 mm in diameter (ref. NT09), purchased from AMT n.v. Herk-de-Stad, Belgium. The austenitic finish temperature (A_f), determined by tensile tests carried out at different temperatures, is about 240 K; hence, this alloy is in the austenitic phase at room temperature and shows SE behavior under stress. These specimens have been subjected to a loading-unloading cycle at impact strain rates, achieving different maximum strains.

Instrumented tensile impact tests have been carried out to obtain the stress-strain curves at impact strain rates (of the order of 10 s^{-1}), with different energies to obtain the different maximum strains not only for incomplete, but also for complete SIM transformations (from 1% until failure occurs 11%). The experimental technique is described in detail in Ref 5. The sample is fixed between a mobile and a fixed grip. An impactor hits the mobile grip and the tensile force is transmitted to the sample. The force during the deformation is measured at the fixed grip by a piezoelectric sensor and the stress is calculated by dividing the impact force curve by the initial section of the wire. The displacement is calculated as the integration of the deformation velocity measured during the impact test with laser-based noncontacting measurement equipment and the strain is obtained by dividing this displacement by the initial length of the sample. Moreover, quasi-static tensile tests (at strain rates of 10^{-4} s^{-1}) for the same maximum strains have also been carried out to facilitate comparison of the results at low and high strain rates. These tests have been carried out in a uniaxial screw-driven testing machine Instron 4206. Displacement-controlled tension tests have been conducted by monitoring the force with a 50-kN load cell and measuring the strain by the crosshead displacement. Both quasi-static and impact experiments have been carried out at room temperature.

3. Results and Discussion

3.1 SE Stress-Strain Response Based on the Maximum Induced Strain

The SE behavior of NiTi is shown in Fig. 1 for different loading-unloading cycles in which different maximum strains

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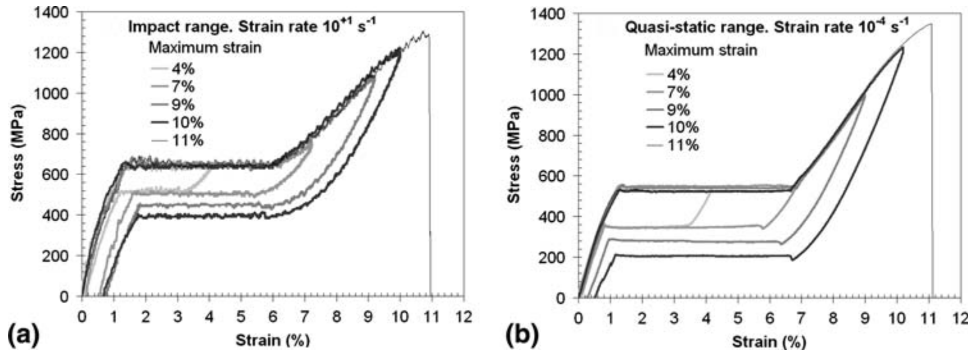

Fig. 1 Stress-strain response of NiTi obtained for different maximum strains. (a) At impact strain rates and (b) At quasi-static strain rates

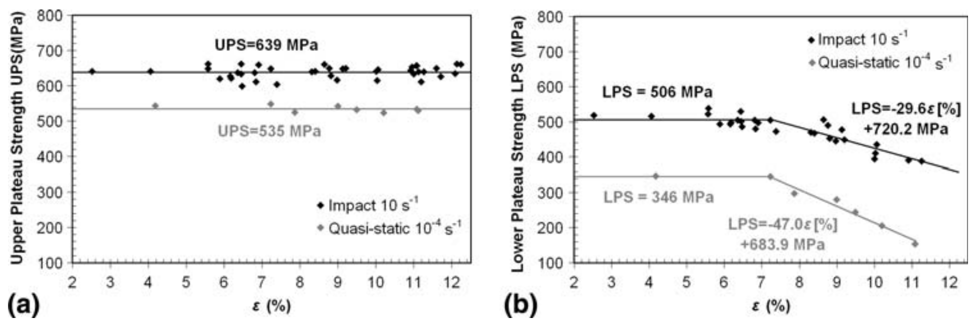

Fig. 2 Plateau strength as function of the maximum strain achieved during deformation of NiTi. (a) UPS and (b) LPS

are achieved. With the aim of studying and comparing the SIM transformation stresses as a function of the maximum strain achieved during deformation, it has been used for each test a specimen without any previous deformation. This avoids any accumulation of defects which are favorable for the following transformations, leading to a decreasing of the transformation stresses. The waved response shown in the impact curves is due to local oscillations in the stress-strain curve associated with the dynamic response of the impact test, which are superimposed on the mean response of the material.

Experiments carried out at impact strain rates are shown in Fig. 1(a), and in Fig. 1(b) tests at quasi-static strain rates are shown. In both cases, the appearance of plateau zones indicates that SIM transformation is observed during deformation, yielding incomplete transformations (4% of maximum strain), complete SIM transformations (7%), complete transformations and elastic deformation of the martensitic phase (9%), and failure of specimens (11%). The residual plastic strain in impact loaded specimens is slightly higher at impact than at quasi-static strain rates (Fig. 1). This may be attributed in part due to higher stresses developed during the impact tests, that generates more defects and causes more plastic deformation, but also due to a very small slippage of the specimen at the grips, difficult to avoid due to the dynamic nature of the impact experiment.

3.2 The Effect of Maximum Strain Achieved on the Transformation Stresses

The upper plateau strength (UPS), measured as the forward transformation stress at 3% strain during the loading process, and the lower plateau strength (LPS), measured as the reverse transformation stress at 2.5% strain during unloading are plotted as functions of the maximum strain achieved during deformation (Fig. 2). The local oscillations observed in the impact stress-strain curves, Fig. 1, contribute to a higher scatter data points at impact than at quasi-static strain rates in Fig. 2.

The UPS is around 20% higher at impact than at quasi-static strain rates (Fig. 2a) as a result of the self-heating process, which is due to the exothermic character of the forward SIM transformation. The LPS is also higher at impact but depends mainly on the maximum deformation achieved until the unloading process starts (Fig. 2b). At strains lower than 7%, when the SIM transformation is not complete, the LPS remains constant and is strain independent. However, when the impact energy is sufficient for completing the SIM transformation, at strains higher than 7%, this trend changes and the reverse SIM transformation stress diminishes linearly as the strain increases. This may be attributed to the high stresses generated during the loading process, which generates internal stresses that are favorable for reverse SIM transformation, similar to the stress reduction that occurs while cycling SE-NiTi (Ref 6, 7). In the present work, a similar trend has been found at quasi-static strain rates, with the difference that the stresses at impact are higher, and the rate at which the LPS decreases with strain is lower at impact strain rates (Fig. 2b). The quasi-static results shown here match well with those observed in reviewed literature (Ref 3, 4).

3.3 The Effect of Maximum Strain Attained on the Deformation, Dissipated and Recoverable Energies

The deformation energy (E_{d}), the energy required to deform the material until the maximum strain, obtained as the integration of the force during loading along the deformation

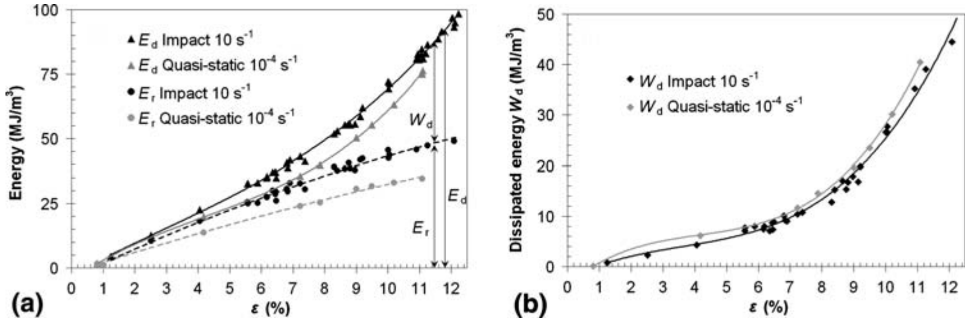

Fig. 3 Significant energies as function of the maximum strain achieved during deformation of NiTi. (a) Deformation energy (E_d) and recoverable strain energy (E_r). (b) Dissipated energy (W_d)

of the sample from zero to the maximum strain; and the recoverable strain energy (E_r), the energy recovered during unloading from the maximum strain until the zero stress state, as the integration of the force during unloading along the deformation of the sample from the maximum strain to zero, are plotted as function of the maximum strain achieved during deformation (Fig. 3a).

Each test is represented in the graph with its respective mark, and the superimposed smooth line shows the average tendency. Results from the impact tests show that E_d and E_r increase with the maximum strain reached and are higher at impact than at quasi-static strain rates, with average higher values at impact of 7.8 and 11 MJ/m^3 of SIM transformed material, respectively. Similarly, the dissipated energy (W_d), the difference between E_d and E_r, is plotted as a function of the maximum strain (Fig. 3b). W_d also increases throughout the strain range studied, but the value is slightly lower at impact strain rates. For the same maximum strain attained, the average difference between the impact and quasi-static values of W_d is 3.2 MJ/m^3 of SIM transformed material. This implies similar values of W_d at impact and at quasi-static strain rates for complete SIM transformations. Nevertheless, the difference may be higher in relative terms for incomplete SIM transformations.

4. Conclusions

This study addresses the effect of the maximum strain achieved at impact strain rates, compared with quasi-static strain rates, on the SE behavior of NiTi in terms of stress-induced martensitic transformation stresses; and deformation, recoverable and dissipated energies. The results are summarized as follows:

1. The UPS is higher at impact than at quasi-static strain rates because of self-heating due to the exothermic character of the forward SIM transformation.
2. The LPS is also higher at impact and depends on the maximum strain achieved during deformation. For strains lower than that necessary for completing the SIM transformation, LPS remains constant. Nevertheless, for higher values of strain, LPS diminishes linearly as the strain increases.
3. Deformation energy (E_d), recoverable strain energy (E_r), and dissipated energy (W_d) increase as the maximum strain achieved during deformation becomes greater.
4. E_d and E_r are higher at impact than at quasi-static strain rates, but W_d is lower. For the latter parameter, the results of the quasi-static and impact states are similar.

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