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Low-to-high cycle fatigue properties of a NiTi shape memory alloy

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Abstract

Low-to-high cycle fatigue behavior of a pseudoelastic NiTi SMA was analyzed. The evolution of both global and local strain were captured during fatigue tests. Local strains were measured *in-situ* by the digital image correlation (DIC) technique. Significant differences were observed at the two scales, due to the localized nature of stress-induced transformations. Strain-life fatigue curves obtained from global and local strain measurements were compared. It was demonstrated that local phenomena play a very important role on the fatigue properties of pseudoelastic SMAs.

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1. Introduction

Nickel-titanium (NiTi) based shape memory alloys (SMAs) are increasingly used in several engineering and medical applications thanks their extraordinarily high strain recovery capabilities, namely shape memory effect (SME) and pseudoelastic effect (PE). These properties are due to a reversible crystallographic transformation between a parent phase, the body centered cubic austenite (B2), and a product one, the monoclinic (B19') martensite (Otsuka 2005). Phase transitions can be activated either by temperature or mechanical stresses through the so-called thermo-elastic martensitic transformation (TMT). As a consequence, cyclic thermo-mechanical loads usually involve repeated crystallographic transitions that significantly affect the fatigue damage phenomena, in terms of crack formation and propagation. This is of major concern because SMA components are typically subjected to cyclic loadings and, therefore, they are serious candidates for fatigue and fracture phenomena.

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Fatigue properties of SMAs were firstly investigated by (Melton 1979, Miyazaki 1986). Both structural and functional damage were observed during fatigue loadings, leading to premature failures and significant degradation of their shape recovery capabilities. At the crystallographic scale this is attributed to complex mechanisms, including the formation of stabilized martensite and local plasticity. Starting from these early works, several researches were carried out in last decades with the aim of analyzing both the functional and structural damage in pseudoelastic SMAs (Kang 2015). In most of these studies fatigue properties were analyzed by isothermal rotating-bending fatigue tests of SMA wires (Tobushi 1998, Tobushi 2000, Lagoudas 2009, Miyazaki 1999, Eggeler 2004, Bertacchini 2003, Rahim 2013, Figueredo 2009, Pelton 2013). However, in these tests the samples are not instrumented and, therefore, the evolution of strain amplitude and mean strain cannot be directly measured. To overcome this problem, instrumented axial tests were carried out (Scirè Mammano 2014, Casati 2012, Nemat-Nasser 2006, Kang 2012, Gall 1999, Sehitoglu 2001, Maletta 2012, Maletta 2014), and both structural and functional fatigue damage were captured. Multiaxial fatigue properties were also analyzed by combined axial and torsional loads (Runciman 2011), as well as by using special samples, such as the diamond-like specimens (Pelton 2011). However, in all these studies fatigue properties of SMAs were analyzed by global strain measurements and local effects, linked to stress-induced transformations, occurring by Louder's like bands, were not considered. As a consequence, special full field methods, such as the Digital Image Correlation (DIC) and Infrared thermography (IR), were recently used (Sgambitterra 2014, Sgambitterra 2015, Sgambitterra 2018, Maletta 2014, Maletta 2016, Alarcon 2017, Zheng 2017), with the attempt to capture localized transformation phenomena from the strain and temperature maps. These studies revealed the complexity of the mechanical response of such alloy, compared to most common engineering materials, requiring ad-hoc models to predict their fatigue crack initiation and propagation (Maletta, 2011). Furthermore, it was demonstrated that also nanoindentation method is able to provide information about local transformation phenomena and material damage (Sgambitterra 2015, Maletta 2017). These local effects were also confirmed by recent three-dimensional synchrotron x-ray diffraction analyses (Sedmák 2017).

In this work the effects of local and global strain on the low-to-high cycle fatigue (LCF-HCF) properties of a pseudoelastic NiTi alloy were analyzed. DIC technique was used to capture the strain distribution in a dog bone sample during pull-pull fatigue tests and systematic comparison between global and local strain distributions was made.

2. Materials and methods

A commercial Ni-rich (50.8 at.% Ni–49.2 at.% Ti) NiTi alloy with pseudoelastic response at room temperature ($A_f = 287\text{ K}$) was analyzed. Figure 1.a reports the isothermal ($T = 298\text{ K}$) strain-controlled stress-strain curve of the alloy for a complete loading-unloading cycle, up to a maximum deformation $\varepsilon_{max}=8\%$, together with the values of the main mechanical parameters.

Dog bone samples were manufactured from NiTi sheets ($t = 1.5\text{ mm}$) by Electro Discharge Machining (EDM) and were subsequently electro polished to remove surface defects that represent preferred sites for fatigue crack formation. Pull-pull fatigue tests ($R = \sigma_{min}/\sigma_{max} \cong 0$) were carried out at room temperature ($T=298\text{ K}$), at a frequency $f=0.5\text{ Hz}$ and with a run-out of 10^6 cycles. Global strain over a gauge length of 10 mm were measured by an extensometer. A CCD Camera (Sony ICX 625 – Prosilica GT 2450, 2448×2050 pixels) with a proper optical magnification was used to capture images, during fatigue tests, to be used for DIC analyses.

Figure 1.b schematically shows the evolution of the stress-strain response of the material during fatigue cycling. In particular, marked ratcheting-like effects occur, mainly in the first 200 cycles (Maletta 2014), that is the material accumulates residual strain (ε_{res}) up to cyclic stabilization. As a consequence, each test is carried out in two steps: 1) Material stabilization, between increasing minimum strain (ε_{min}) and fixed maximum strain (ε_{max}), and 2) Constant strain amplitude fatigue tests, between fixed minimum ($\varepsilon_{min} = \varepsilon_{res}$) and maximum strain (ε_{max}). The LCF-HCF behaviour was investigated, with maximum deformation ranging from full elastic austenite ($\varepsilon_{max} < 1\%$) to stress-induced transformation ($1\% \leq \varepsilon_{max} \leq 6\%$) and to the elastic-plastic regime of oriented martensite ($\varepsilon_{max} > 6\%$), see Fig. 1.a.

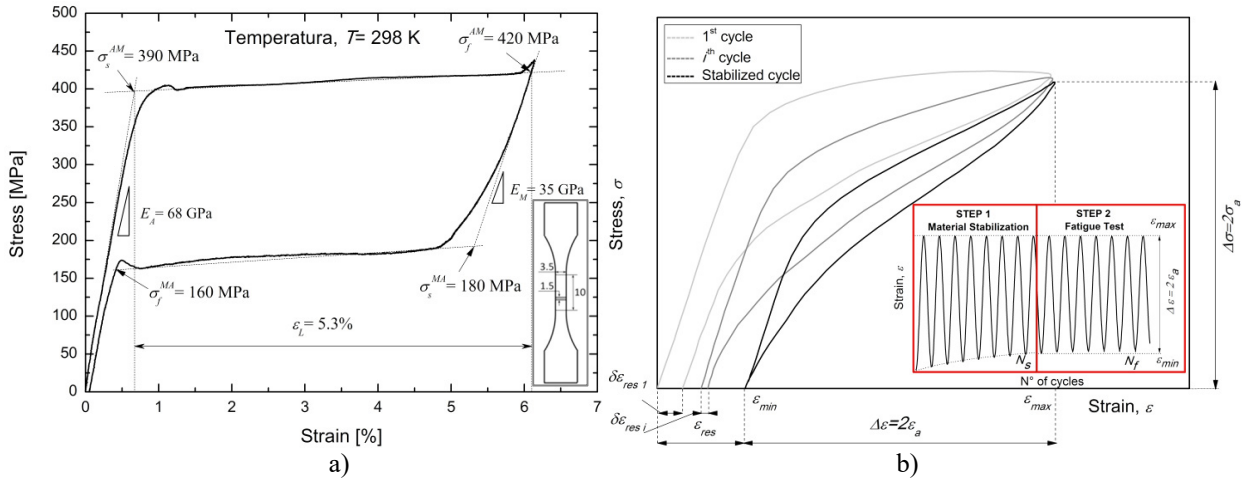


Figure 1: Stress strain curve of the alloy: a) Isothermal ($T = 298\text{ K}$) loading-unloading cycle; b) evolution of cyclic response during fatigue tests

3. Results and discussions

The evolution of the cyclic response, up to the material stabilization, in terms of residual and recovery strain (ϵ_{res} , ϵ_{rec}), was analyzed at both local and global scales, as shown in Fig 2.

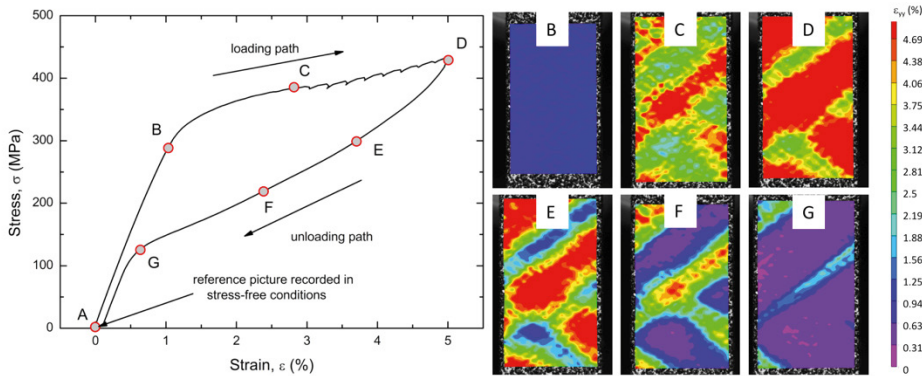


Figure 2: Stress-strain curve at the first loading cycle for $\epsilon_{max} = 5\%$: global response vs local strain distribution

The figure reports the cyclic stress-strain curve at the first loading cycle for a maximum deformation $\epsilon_{max} = 5\%$. The DIC strain maps in the gauge length of the specimen, obtained in different points of the stress-strain curve, are also illustrated. Marked local effects were observed in both loading and unloading transformation paths, due to both direct (B2-B19') and reverse (B19'-B2) stress-induced transformations (Maletta 2017) that occur through Louder's-like transformation bands. It was found that fatigue failure always occurs within the transformation bands, where local damage and irreversibility are linked to the formation of stabilized martensite and plastic deformations.

Figures 3 shows the evolution of the global and local strain amplitude (ϵ_a), after material stabilization, as a function of the maximum applied strain (ϵ_{max}), and a marked difference at the two scales is highlighted. In fact, global strain amplitude shows a monotonic increasing trend, with maximum values around 1.9%, whereas local strain exhibits an almost flat trend just beyond the initiation of the stress-induced transformation plateau ($\bar{\epsilon}_{max} \geq 2\%$), with values around 2%. This is due to the early saturation of stress-induced transformations in the transformation band, as illustrated in Fig. 2.

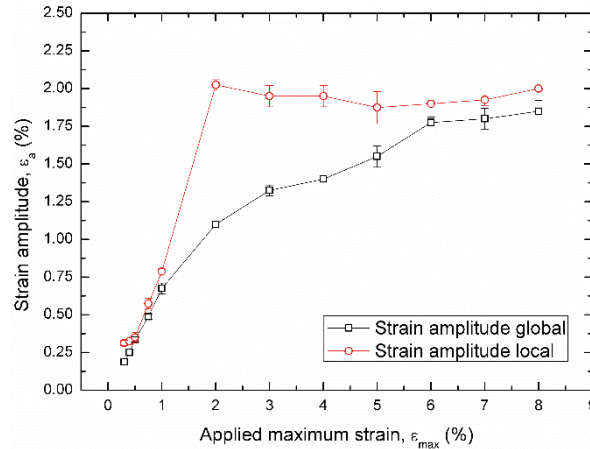


Figure 3: Strain amplitude (ε_a) at the global and local scales as a function of the maximum applied strain (ε_{max})

Figure 4 shows the effects of global and local strain on the strain-life curves ($\varepsilon_a - N_f$) in the whole LCF-HCF regime. In particular, in Fig. 4.a and 4.b fatigue life data are plotted as a function of the global and local strain amplitudes, respectively.

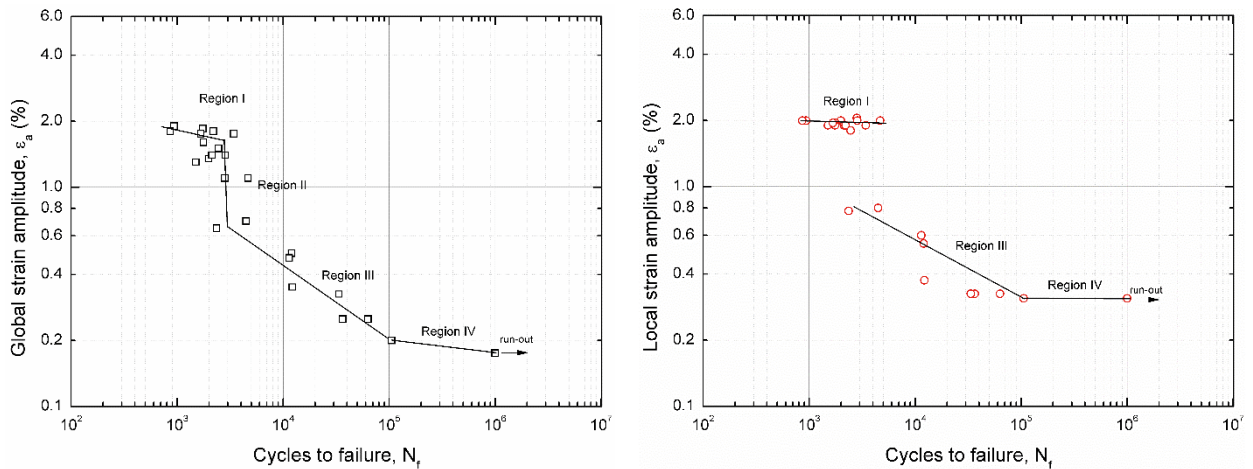


Figure 4: Low to high cycle strain-life curves ($\varepsilon_a - N_f$): a) global strain and b) local strain

Four different regions are highlighted in Fig. 4.a, as also observed in previous studies (Pelton 2013): Region I ($N_f < 3 * 10^3$) defining the LCF behavior of oriented stress-induced martensite (M), Region II ($N_f \approx 3 * 10^3$) corresponding to the transformation plateau, Region III ($3 * 10^3 < N_f < 10^5$) representing the LCF-HCF behavior of predominantly elastic austenite (A) and Region IV ($N_f > 10^5$) for the lowest value of strain amplitude. Region II corresponds to a maximum strain range $\varepsilon_{max} = 2\% - 6\%$ and fatigue life seems to be unaffected by the strain amplitude (Melton 1979, Figueiredo 2009, Pelton 2013). This latter represents the region where local deformation saturates in the transformation bands. The trend appears significantly different when plotting fatigue life data as a function of the local strain amplitude (Fig. 4.b). In fact, region II vanishes, as local strain amplitudes in such region are almost constant ($\varepsilon_a \approx 2\%$), as shown in Fig. 3. This result is consistent with the physics of the problem, as just two distinct finite fatigue regions are observed, linked to the two crystallographic phases of the material. Region I represents the LCF behavior of martensite and region III defines the LCF-HCF behavior of austenite.

4. Conclusions

It was found that localized stress-induced transformations play a very important role on both functional and structural fatigue damage of pseudoelastic SMAs. Systematic comparison between the global and local cyclic response revealed the origin of the unusual Z-shaped strain-life fatigue trend reported in the literature. It was demonstrated that it is actually an apparent phenomenon linked to the mismatch between global and local response of the material.

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