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Effect of the amplitude of the training stress on the fatigue lifetime of NiTi shape memory alloys

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ABSTRACT

This paper presents a mechanical training process that allows enhancing resistance to low cycle fatigue of shape memory alloys. To this end, three training stresses were tested (0–509.6 MPa, 0–637.0 MPa, 0–764.3 MPa); for each case, NiTi wires were first subjected to the corresponding load during first 20 cycles, and then tested to failure under strain-controlled fatigue loading. Results show that fatigue lifetime is training-dependent in the sense that specimens with higher training stresses present a better fatigue lifetime. Indeed, for sufficiently high training stress, fatigue lifetime can be 10 times extended.

The unique property of pseudoelastic shape memory alloys (SMAs) is their ability to accommodate large strains as a result of stress induced solid-solid martensitic phase transformation. This special property promotes their use in a variety of applications ranging from biomedical to space industries, where durability requirement is a critical issue. In many of these applications, SMAs are subjected to cyclic loading. As a consequence, they are serious candidate for fatigue and fracture. However, this issue is still challenging because fatigue lifetime of SMAs is strongly dependent on factors related to phase transformation, such as grain size [1], temperature [2], localized phase transformation [3–5], and thermomechanical coupling [6–9]. In order to improve the fatigue resistance, SMAs are usually submitted to complex thermomechanical treatments to obtain better material parameters (grain size, phase transformation temperatures, large transformation strain, etc.).

When subjected to cyclic pseudoelastic loading, SMAs present residual deformations mainly due to transformation induced plasticity (TRIP) [10–13]: during stress induced phase transformation, high local stresses, caused by the unmatched deformation near the austenite-martensite interfaces, assist the dislocation slip. Hence, plastic deformation occurs although the macro-stress is lower than the plastic yield strength. Upon cyclic loading, the residual deformations get saturated and the mechanical response of SMAs reaches a stabilized state after some few cycles [14–16]. Therefore, SMAs always need to be trained for several cycles in order to stabilize their mechanical behavior before being utilized for practical applications. It has been experimentally shown that large pre-strains significantly reduce the fatigue lifetime of Nitinol wires during the fully reversed rotary bending fatigue tests which induce both tensile and compressive residual stresses [17]. However, the detailed mechanism of the influence of the residual stresses fields introduced by the training loads on the fatigue lifetime of SMAs is still unclear.

In this paper, we report tensile fatigue tests on pseudoelastic NiTi SMA wires with a diameter of 1 mm (50.8 at % Ni, obtained from Xi'an Saite Metal Materials Development Co. Ltd., China). The phase transformation temperatures of the material are measured using a differential scanning calorimeter (DSC) and valued as follows: $M_s = -77^\circ$ C, $M_f = -110^\circ$ C, $A_s = -31^\circ$ C, $A_f = -15^\circ$ C. The experiments were carried out using the Bose Electroforce 3510-AT fatigue test machine at room temperature ($25 \pm 1^\circ$ C); two pairs of aided grips were used to hold the SMA wire in place so that the specimen does not break at the contact point under low cycle fatigue loading (details about the experiment setup for fatigue tests can be found in the authors' previous work [6]). The tests were classified into three groups according to the amplitudes of the training stresses during first 20 cycles (0.04 Hz; stress control): *Case* I: 0–509.6 MPa, *Case* II: 0–637.0 MPa and *Case* III: 0–764.3 MPa; the specimens in each group were subsequently submitted to the same fatigue loading (0.2 Hz, strain control, $\varepsilon_{min} = 0$, ε_{max} ranging from 2.5% to 6.1%) until failure. Each test was repeated at least twice.

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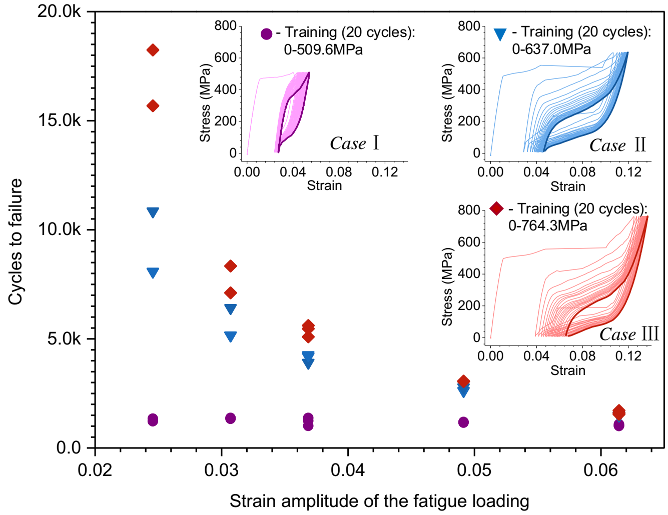

Fig. 1. $N-\varepsilon$ curves, loading ratio = 0; $0 \leftrightarrow \varepsilon_{max}$.

Fig. 1 gives the results of $\varepsilon - N$ curves for each of the three groups and clearly shows that the fatigue lifetime of SMAs is strongly dependent on the training stress:

- Larger amplitude of the training stress during the first 20 cycles obviously extends the fatigue lifetime of SMAs. The lowest lifetime corresponds to *Case* I, for which the training stress during first 20 cycles is not high enough to complete the phase transformation. When the training stress is sufficiently high to complete the phase transformation, fatigue lifetime increases (*Case* II); the longest lifetime is obtained in *Case* III, in which the SMA wire is overloaded after the phase transformation being completed. For the sake of clarity, this effect hereinafter is referred to as *training stress effect*.
- *Training stress effect* depends on the amplitude of the subsequent fatigue loading. The *training stress effect* is significant when the strain amplitude of the subsequent fatigue loading is small (see Fig. 1; for the minimum strain amplitude 0–2.5%, the fatigue lifetime in *Case* III increases by more than 10 times compared to *Case* I). When the strain amplitude of the fatigue load increases, the *training stress effect* weakens and nearly vanishes when the strain amplitude reaches 0–6.1%.

Fig. 2 provides an explanation of how the residual internal stress field assists the forward phase transformation in a material RVE (Representative Volume Element) in which $\boldsymbol{\Sigma}$ and $\boldsymbol{E}$ are macroscopic stress and strain, $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$ are the corresponding local responses at mesoscopic scale: according to TRIP theory, dislocations are created during forward phase transformation and when the applied load is completely removed, dislocations remain and result in a residual internal stress field $\boldsymbol{\sigma}_r$. During subsequent cycles, the internal stress, which is of the same kind of the applied stress as pointed out by Ref. [18], assists the nucleation of martensite variants, leading to a significant reduction in the yield stress required to trigger the forward phase transformation (Fig. 2b). As a consequence, the yield transformation surface shrinks during subsequent cycles [18,19]. In region A (Fig. 2a; close to the dislocations), the amplitude of the local residual stress is high and therefore a reduction in the yield stress of the phase transformation occurs. Furthermore, the residual stress field has a gradient in its strength [18,20,21] in such a way that when the phase transformation propagates from region A to region B the amplitude of the internal stress reduces (see Fig. 2b, the magnitude of $\boldsymbol{\sigma}_r^A$ is larger than the magnitude of $\boldsymbol{\sigma}_r^B$). As a consequence, in order to continue the forward phase transformation, the macro-stress must be increased (see Fig. 2c) resulting in a higher slope of phase transformation plateau. Furthermore, since the fatigue loading is strain-controlled, the macro-stress-strain response of the trained SMAs necessarily lies under the response of the virgin SMAs. In fact, since the phase transformation is triggered at lower yield stress, it induces a macroscopic stress relaxation phenomenon resulting in a reduction of the amplitude of the fatigue stresses and an increase of the fatigue lifetime.

As shown above, the residual local stress ($\boldsymbol{\sigma}_r$) field plays an important role in the fatigue of SMAs. Due to the complicated microsctructure, it is very difficult to evaluate it at the mesoscopic scale. Nevertheless, if one considers the RVE as a structure (Fig. 2a), it is clear that a higher amplitude of the macroscopic stress $\Delta(\boldsymbol{\Sigma})$ will result in a lower fatigue lifetime [7,22]. Furthermore, tensile pre-deformation creates compressive residual stresses on the surface of polycrystalline SMA samples [17,23], which naturally improve the subsequent fatigue resistance because the crack opening is prevented.

The previous analysis allows to give a physical interpretation of the *training stress effect* as follows: as shown in Fig. 1, from *Case* I to *Case* III, the higher TRIP is triggered in the training step, the more dislocations remain after unloading (see Fig. 1). As a consequence the residual strain after the training process increases from *Case* I to *Case* III. Fig. 3 gives a schematic comparison between the stresses required to trigger the same fraction of phase transformation

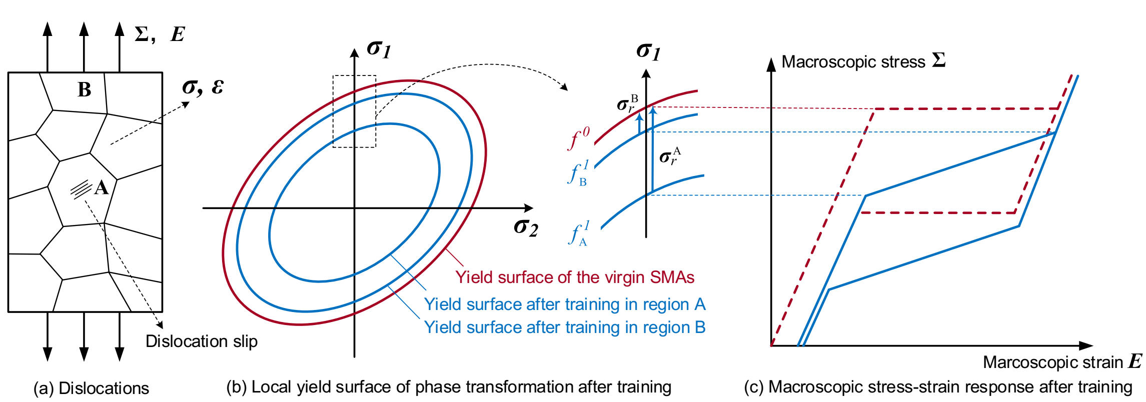

Fig. 2. The residual stress induced by dislocation slip can assist the phase transformation, where $\boldsymbol{\Sigma}$ and $\boldsymbol{E}$ are macro-stress and strain; $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$ are the corresponding local responses; $\boldsymbol{\sigma}_r^A$ and $\boldsymbol{\sigma}_r^B$ are local residual internal stresses in region A and region B respectively, f^0 is the yield surface of the virgin SMA and f_A^1 and f_B^1 are yield surfaces during a subsequent cycle corresponding to region A and region B respectively.