A TWO SCALES ANALYSIS OF THE FATIGUE OF SHAPE MEMORY ALLOYS

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Abstract

Shape memory alloys (SMAs) are employed in innovative applications experiencing millions of cycles during their lifetime. The existing failure criteria are purely phenomenological based on macroscopic experimental results and ignore their complex microstructure. The proposed paper presents a two-scale fatigue criterion based on the elastic shakedown of the austenitic and martensitic grains of the Dang Van - Papadopoulos class. The underlying assumptions and predictions are discussed on a series of novel experiments and compared with results from literature.

1 Introduction

Shape memory alloys (SMAs) possess unique properties, known as shape memory effect and pseudoelasticity. These properties result from reversible diffusionless solid-solid transformations (known as martensitic transformations) between a relatively ordered parent phase, called austenite (A), and a less ordered product phase, called martensite (M). Their peculiar properties are successfully exploited in many fields, ranging from structural engineering, to robotics or biomedical industry. In particular, a wide segment is covered by SMA actuation systems, innovative devices for the control of civil structures and self-expandable vascular stents.

The rather complex micromechanical behavior of SMAs also induces unusual fracture and fatigue responses when compared with standard polycrystalline metallic alloys. It has already been discussed, in several papers, that classical fatigue criteria cannot be directly applied due to the uncertain role of the phase transformation under cyclically varying deformations and the stress and/or thermally-induced microstructural evolution of the different phases. Transformations between austenitic and martensitic phases, moving martensite interfaces, and accumulation of dislocations are believed to play an important role in the fatigue lifetime of SMAs.

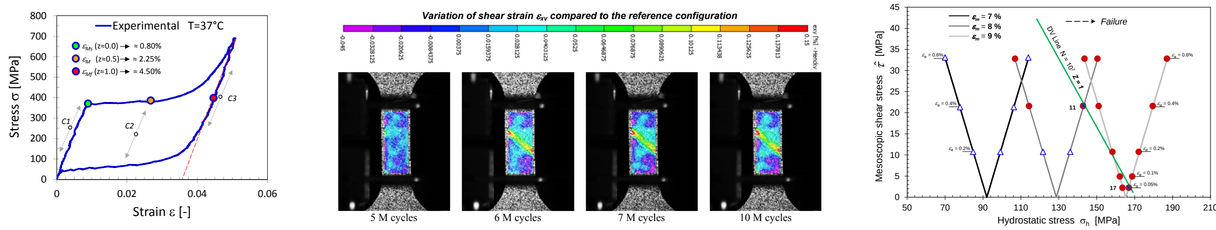
The novelty of the present predictive fatigue failure methodology for cyclic loading of SMAs is based on a shakedown analysis performed at different scales of the materials [3, 4, 5]. The results rely on recent mathematical and theoretical advancements on shakedown theorems [6] and constitutive models for SMAs [2]. The proposed fatigue criterion (i) predicts high cycle fatigue crack initiation; (ii) is based on a multiscale analysis taking into account the complexity of the phase transformation between austenite and martensite and (iii) preserves the multiaxial character of the phenomena.

The papers presents (a) the fatigue criterion based a thermodynamical consistent framework using shakedown concepts and (b) the analysis of novel fatigue results of the research group and from literature [7, 8]. The experimental results of the group permit to evaluate the micromechanical assumptions of the theoretical deduction from evolution of macroscopic strain and the local distribution of phases in the microstructure. The experimental are completed with results from literature to asses the lifetime prediction capability of the proposed criterion.

2 Theory

Assuming a small strain regime, the initial configuration of the local SMA material state is described by the total strain $\boldsymbol{\epsilon}$, the temperature θ, and an internal variable $\boldsymbol{\alpha}$. The variable α represents the inelastic strain and can include the description of several physical phenomena characterizing SMA behavior, ranging from permanent plasticity and phase transformations, up to void generation and fracture. A series of constitutive models, as for example [2], can be cast in the framework of standard generalized materials. As such we have a direct estimation of the shakedown state under cyclic loading, due to the recent results by Peigney [6].

The proposed fatigue criterion aims to predict the onset on infinite lifetime for polycrystalline SMAs. It starts from the experimental observation that, in high cycle fatigue, only few grains of the material undergo inelastic strains, whilst most of the material remains elastic. Furthermore, the elastic cycles described at the scale of the structure or of the crystalline



(a) (b) (c)

Figure 1: High cycle experimental data on SMAs: (a) position of applied cycles compared with the constitutive law in the stress-strain space (b) evolution of the shear strain map during cycling at $x \times 10^6$ cycles and (c) a typical Dang Van fatigue diagram resulting from available experimental data from literature[7, 8].

grains of the polycrystal can be characterized by using the shakedown concepts [6]. Moreover the idea of a weak, inelastic element embedded in an elastic matrix represented by two springs was initially proposed by Orowan in 1939 and it is a key element in the development of the Dang Van-Papadopuolos fatigue criteria [5].

Starting from this observation a proposed *Dang Van (DV) fatigue criterion for SMAs* (see for extended details [1]) can be defined as:

Dang Van (DV) fatigue criterion for SMAs. *A structure subjected to cyclic loading has an infinite lifetime expressed as an elastic shakedown state at both macroscopic and mesoscopic scale, if and only if:*

$$\max_{t>t_0}\{\hat{\tau}(\mathbf{x},t) + a(\alpha(\mathbf{x}))\hat{\sigma}_h(\mathbf{x},t)\} \leq b(\alpha(\mathbf{x})) \tag{1}$$

for all points $\mathbf{x}$ *of the structure. If the condition* (1) *is not respected in a point, fatigue crack will initiate and the structure will have a finite lifetime.*

Here, $\hat{\tau}$ and $\hat{\sigma}_h$ are expressed in terms of the instantaneous position of stress with respect to the smallest hypersphere encompassing the stress path for large times and represent a norm of the deviatoric and hydrostatic part respectively.

3 Experiments and Results

The group has performed a series of high cycle fatigue experiments on plain and notched dog-bone specimens of commercial Nitinol offered by the courtesy of `www.memry.com`. The specimens have been submitted to cyclic tensile loading on stress-strain path as presented in Figure 1(a) in a temperature controlled environment. The strain field on the complete surface of the specimens has been recorded at different moments of the lifetime using digital image correlation reported in Figure 1(b). The plain specimens run out without failure at $\approx 10^7$ cycles. Notched specimens present a stress concentration and recorded lifetimes have been much smaller and will not be discussed in the abstract for brevity. At the grain scale, further observations will analyze using SEM the evolution of the microstructure, i.e. phase change, in the failure region and the evolution of the local strain fields as displayed in Figure 1(b). The lifetime can now be analyzed using the proposed Dang Van-type fatigue criterion as depicted in Figure 1(c). This diagram here shows that the proposed criterion is also capable to distinguish correctly failure in data coming from literature [7, 8].

4 Conclusions and Perspectives

This paper has investigated the elastic shakedown behavior of SMA materials and has presented the extension of the DV high cycle fatigue criterion to SMAs and opens a novel way to analyze the onset of damage for materials involving phase change. The analysis also open a realm of new questions ranging from additional insight into microscopic deformation and damage mechanisms at the phase boundaries to innovative methods for the fast identification of fatigue limits, such as infrared thermography measurements.

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