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A shakedown analysis of high cycle fatigue of shape memory alloys

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ABSTRACT

Shape memory alloys (SMAs) are exploited in several innovative applications, experiencing up to millions of cycles, and thus requiring a fully understanding of material fatigue and fracture resistance. However, experimental and methodological descriptions of SMA cyclic response are still incomplete. Accordingly, the present paper aims to investigate the cyclic response of SMAs under macroscopic elastic shakedown and to propose a criterion for the high cycle fatigue of SMAs. A multiaxial criterion based on a multiscale analysis of the phase transformation between austenite and martensite and using the rigorous framework of standard generalized materials is proposed. The criterion is an extension of the Dang Van high cycle fatigue criterion to SMAs. The criterion is applied to uniaxial experimental data taken from the literature. It distinguishes run out from failure tests in the infinite lifetime regime. The analysis permits a novel insight into the development of a general multiaxial failure criterion for SMA materials and also suggests further experimental investigations to completely understand the fatigue behavior of SMAs under elastic shakedown.

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).

Shape memory effect and pseudoelasticity are successfully exploited in many fields, e.g., structural engineering, automotive, aerospace, micro-electromechanical, robotics, and biomedical industry [36,42]. In particular, a wide segment is covered by SMA actuation systems [50] and by innovative devices for the control of civil structures [1]. Within the biomedical industry, self-expandable vascular stents represent a considerable part of SMA applications for mini-invasive techniques [73]. The question of lifetime prediction and of the improvement of the alloys with respect to this aspect is a major topic in the field [15,35].

The rather complex micromechanical behavior of SMAs also induces unusual fracture and fatigue responses when compared with polycrystalline metallic alloys [47,78]. It has already been discussed, for instance by Tabanli et al. [86,87], that classical fatigue criteria cannot be directly applied, due to the uncertain role of the phase transformation under cyclically varying deformations and of the stress and/or thermally-induced microstructural evolution of the different phases [78]. Indeed, transformations between austenitic and martensitic phases, moving martensite interfaces, accumulation of dislocations are believed to play an important role in the fatigue lifetime of SMAs [6,69].

The prediction of crack initiation and growth under thermomechanical cyclic loading is an essential requirement for the design of novel SMA components [77], since fatigue failure has emerged as one of the main design issues [5,33]. As an example, SMA actuators are subjected to thermal cycling and are expected to undergo at least 10^4–10^5 cycles during their service life [38,84]. For SMA cables used as damping prevention in stay cable, suspension, and prestressed concrete bridges, fatigue life is usually taken into account considering the frequency range of vibration on real scale bridges, i.e. 5–20 Hz, and a number of working cycles up to $5 \cdot 10^6$ [49]. In the majority of the biomedical applications, stents are permanently implanted in the human body and experience millions of in vivo cycles due to blood pressure; stents should survive at least for 10 years without exhibiting failure, which translates into $4 \cdot 10^8$ service cycles [91].

For structures subjected to cyclic loading, the concept of shakedown represents a necessary condition for safety assessment [40].

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In case of elastoplastic structures, shakedown refers to a state in which plastic strains stabilize after a finite number of loading cycles, and therefore the structure undergoes only elastic or alternating plastic deformations. In particular, the shakedown analysis classifies the stress–strain response of the structure in three main categories: (i) *elastic shakedown* if the response is linear, (ii) *plastic shakedown* if the response exhibits a hysteretic loop, and (iii) *ratcheting* if the response is a non-closed path leading to increasing strains. Depending on this classification, in the fatigue diagram the corresponding shakedown regions are generally associated with the high and low cycle fatigue regimes [16]. The mechanical response of SMA structures under cyclic loading is more complex than the response of elastoplastic structures, due to the occurrence of phase transformation and plastic deformation, which can lead to different physical situations; see Feng and Sun [23] for details. As an example, let us consider two different cases of a SMA material subjected to cycling loading (at $T > A_f$, A_f being the austenite finish transformation temperature), according to the paths depicted in Fig. 1(a) and (b), which trigger different shakedown states within the SMA material:

1. The loading path in Fig. 1(a) consists first in loading (ABCDE) up to fully Martensite phase, then unloading (EFG), and finally cycling (GCDF) in the mixed Austenite–Martensite part of the diagram. The loading cycle GCDF exhibits a dissipative hysteretic loop where both forward and reverse phase transformations (Austenite–Martensite–Austenite) take place. In this case, the cyclic response is referred to as *alternating phase transformation* (this shakedown state with hysteretic loop is referred to as plastic shakedown in the case of elastoplastic structures).
2. The loading path in Fig. 1(b) consists first in loading (ABCD) up to fully Martensite phase, then unloading (DE), and finally elastic cycling (EC) in the mixed Austenite–Martensite part of the diagram. The loading cycle EC is linear with stabilized phase transformation. The response is referred to as *elastic shakedown*.
3. The loading path in Fig. 1(b) consists first in loading (ABCD) up to fully Martensite phase, then unloading (DE), and finally elastic cycling (FG) in the fully Martensite part of the diagram. The loading cycle FG is linear without phase transformation. The response is referred to as *elastic shakedown*.

It should be pointed out that for the scopes of the present study, other cyclic loading paths for SMAs will be not handled. These paths include: cyclic loading in the fully austenitic (elastic shakedown) and fully martensitic phases (plastic shakedown). Given these different possible fatigue conditions, in order to prevent premature failure of SMA structures, it becomes necessary to verify whether they will shakedown elastically or by alternating phase transformation, or will fail by alternating plasticity or ratcheting.

Several experimental investigations and fatigue methodologies have analyzed both SMA structural fatigue (component failure) and functional fatigue (the evolution of shape memory effect and pseudoelasticity under repeated thermo-mechanical cycles); see Robertson et al. [78] as review article.

Experimental investigations are generally coupled with observations to track the nucleation and evolution of martensite and austenite during mechanically unstable regimes with the final aim of characterizing the material fatigue response on a microscopic and even macroscopic level [11,17,27,28,39,41,51,69,89,96]. Experimental observations have also inspired a series of fatigue approaches aimed to estimate the lifetime, as a macroscopic crack initiation criterion. Most of the studies focus on stress- or strain-life SMA fatigue approaches for different types of uniaxial tensile loading, e.g., [30,37,48,70,94], while only few focus on the torsional fatigue loading of SMAs, e.g., [76,79].

Concerning available failure criteria, although uniaxial ones may fail to accurately predict the lifetime of devices under multiaxial loading conditions, only few multiaxial fatigue criteria exist for SMAs. It is worth mentioning the works by Moumni et al. [55,56] and Morin et al. [54] who firstly proposed an energy approach, where the dissipated energy of the pseudoelastic hysteresis cycle was used as a parameter for lifetime estimation. Recently, Hartl et al. [32] proposed a constitutive model describing SMA behavior undergoing a large number of cycles, coupled with a continuum theory which includes an internal damage evolving into final failure. These approaches focus on the cyclic alternating phase transformation behavior of SMAs. Only few works have been proposed to extend the shakedown theorems for elasto-plastic materials to SMA structures, see, e.g., [23,66–68,74,95]. To the authors' knowledge, no works address the fatigue analysis of SMA elastic shakedown, even though such a loading condition is very frequent in various applications [78].

Motivated by the above considerations, the present paper focuses on the cyclic response of SMAs, under the elastic shakedown regime, and proposes a multiaxial criterion for the high cycle fatigue of SMAs. The derivation starts from the following considerations: such criterion should (i) predict high cycle fatigue crack initiation; (ii) be based on a multiscale analysis taking into account the complexity of the phase transformation between austenite and martensite; (iii) be multiaxial.

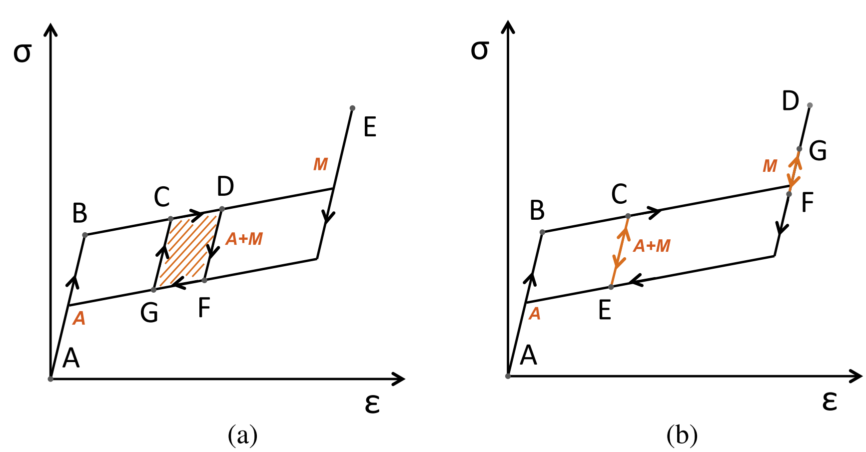

Fig. 1. Two examples of SMA response under cyclic loading at $T > A_f$. (a) The loading path consists in loading (ABCDE) up to fully Martensite phase (M), then unloading (EFG), and finally cycling (GCDF) in the mixed Austenite–Martensite part of the diagram (A + M phases). The loading cycle GCDF denotes alternating phase transformation. (b) The loading path consists in loading (ABCD) up to fully Martensite phase (M), then unloading (DE), and finally elastic cycling in the mixed Austenite–Martensite (A + M phases) or in the fully Martensite (M) part of the diagram (EC or FG, respectively). The loading cycles EC and FG denote elastic shakedown conditions.