Instabilities accelerate cyclic degradation: a macroscopic model of functional fatigue in shape memory alloys accounting for structure–material interplay

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KEYWORDS: *Shape memory alloys, Superelasticity, Functional fatigue, Propagating instabilities.*

Instabilities play a crucial role in stress-induced martensitic transformation in superelastic shape memory alloys (SMAs). Under tension-dominated loading, instabilities emerge as localized martensite bands, which, upon further loading, evolve into patterned interfaces (so-called macroscopic transformation fronts) separating austenite and martensite regions. The associated global mechanical response exhibits a stress drop followed by a stress plateau. The global stress that accompanies martensitic transformation is typically well below the plastic yield stress of the material. Nevertheless, as a results of cyclic forward–reverse transformation, the material accumulates irrecoverable strain and exhibits degradation of functional properties, notably reduction in the transformation stress and hysteresis loop area. This phenomenon is called functional fatigue and is generally attributed to the transformation-induced plasticity (TRIP). TRIP is inherently a multi-scale mechanism, operating across both the micro-scale and macro-scale levels [1]. Specifically, when phase transformation takes place within a grain, high strain incompatibilities and large local stresses are created near the austenite–twinned martensite interfaces, which promote dislocation slip. Upon cyclic transformation, slip accumulates and impedes the motion of phase interfaces, and thus gives rise to stabilized martensite that can no longer transform back to austenite. By a similar reasoning, transformation instabilities at the macro-scale level are expected to influence significantly the fatigue response of the material. Despite the longstanding recognition of this crucial aspect, its direct validation was provided only a few years ago in the experiments conducted by Zheng et al [2]. It was demonstrated that in view of the repetitive nucleation and propagation of the localized transformation, a rapid degradation of superelasticity occurs that accelerates the fatigue crack initiation and failure.

While existing models of functional fatigue are able to reproduce general degradation trends, they do not distinguish between homogeneous and localized transformation modes. To address this limitation, a novel macroscopic model of functional fatigue is developed in this work that integrates the effects of localized transformation into the fatigue constitutive description. The model adopts a gradient-enhanced formulation, in which the gradient of the martensite volume fraction is incorporated to represent the interfacial energy associated with the transformation front. The evolution law of fatigue-related variables is then enriched with the gradient effects so that the accelerating impact of localized transformation on the fatigue response is accounted for.

The resulting finite-element model is employed to investigate the impact of specimen thickness on the fatigue behavior of a straight NiTi specimen subjected to uniaxial tension with subloop deformation path. Experiments have shown that a thicker NiTi specimen develops a more diffuse transformation front, in contrast to a thin specimen with a sharp and more strongly branched front. Importantly, the latter exhibits a shorter fatigue life [3]. The developed model is capable of capturing morphology-dependent localization effects and their implications for the functional fatigue response.

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