Interaction of instabilities and functional degradation in shape memory alloys: a macroscopic modeling study

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Abstract

Instabilities play a crucial role in stress-induced martensitic transformations in polycrystalline shape memory alloys (SMAs). Under tension-dominated loading, instabilities often manifest as localized martensite bands, which, with continued loading, evolve into patterned interfaces that separate the austenite and martensite domains. The localized martensitic transformation is inherently a multiscale phenomenon that appears at both the micro (grain) and macro (specimen) levels. At each level, pronounced strain incompatibilities are induced within the interface regions, which, in turn, give rise to large local stresses. Microscopically, localized interfaces are known to be the main source of microstructural defects, such as dislocations and locked-in martensite (1). On the other hand, macroscopic localization can accelerate the degradation of the functional properties and significantly impact the functional/structural fatigue behavior under cyclic loading (2). In this work, we aim to elucidate the interplay between macroscopic strain localization (structural-level inhomogeneities) and the functional degradation of SMAs. To this end, a macroscopic model of functional fatigue is developed, integrating two key capabilities: the ability to capture the functional degradation, which is incorporated into the materials' constitutive relations, and the ability to capture transformation localization, which is incorporated by adopting a softening-like response combined with the enhancement of the free energy function with gradient terms. The phenomenon of return-point memory observed during the subloop deformation of a partially-transformed NiTi specimen is a clear manifestation of the structure-material (localization-fatigue) interaction and is analyzed as an illustrating example (3). Subsequently, the analysis is extended to explore the low-cycle fatigue behavior of NiTi tubes characterized by cyclic localized transformation.

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