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On the Fracture Response of Shape Memory Alloy Actuators

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Abstract

In this paper, the effect of global thermo-mechanically-induced phase transformation on the driving force for crack growth in polycrystalline shape memory alloys is analyzed in an infinite center-cracked plate subjected to thermal actuation under isobaric, plane strain, mode I loading. Finite element calculations are carried out to determine the mechanical fields near the static crack and the crack-tip energy release rate using the virtual crack closure technique. Analysis of the static crack shows that, as compared to constant mechanical loading, the energy release rate during cooling increases by approximately an order of magnitude. This increase is attributed to the stress redistribution at the crack-tip induced by global phase transformation during cooling. Crack growth during actuation is assumed to occur when the crack-tip energy release rate reaches a material specific critical value. Fracture toughening behavior is observed during crack growth and is mainly associated with the energy dissipated by the progressively occurring phase transformation close to the moving crack tip. Lastly, the effect of crack configuration on fracture toughness enhancement in the large-scale transformation problem is studied. Numerical results for static cracks in compact tensile and three-point bending SMA specimens are reported and a comparison of fracture toughening during thermal actuation in the semi-infinite crack configuration with the compact tensile and three-point bending geometries is presented.

Introduction

Shape Memory Alloys (SMAs) are a class of inter-metallic materials that are capable of recovering large, apparently permanent strains when subjected to the appropriate thermal and/or mechanical inputs. These materials can be plastically deformed at some relatively low temperature, and upon exposure to some higher temperature, they return to their shape prior to deformation. The physical mechanism that drives this shape recovery is a reversible diffussionless solid-to-solid transformation between the alloy's austenite and martensite phases. SMA actuators take advantage of this property to provide a significant amount of actuation within an extremely small envelope volume. SMA actuators are therefore used as an alternative to electromagnetic actuators (like piezoelectric actuators) when a small volume and/or large force and stroke are required and thermodynamic efficiency is not important [10, 18, 15]. A few notable applications of SMA actuators include DARPA's Smart Wing program, NASA's Smart Aircraft and Marine Propulsion System demonstration (SAMPSON) and the Boeing variable geometry chevron.

During their life-cycle SMA actuators are typically subjected to hundreds of thousands of themomechanical loading cycles, and as such, their fatigue response and ultimate failure behavior has become a topic of significant scientific interest. Cracks form in SMA actuators owing to thermally-induced transformation fatigue and the effective use of SMAs in actuators requires an understanding of their fracture and actuation-fatigue-crack growth properties under thermal loading. As such, the study of fracture and actuation-fatigue-crack-growth properties of SMAs is an area of ongoing scientific research. Currently, the bulk of numerical and experimental research focuses mostly on the fracture response of SMAs during purely mechanical loading at nominally constant temperatures [14, 16, 7, 8, 6, 2, 1, 4, 3]. In these studies, crack-tip stress induced martensitic transformation is identified as the primary reason behind the experimentally observed phenomenon of stable crack growth under monotonically increasing load or displacement conditions.

As an initial attempt to understand the fracture behavior of SMAs under actuation, this paper mainly discusses the effect of thermo-mechanically-induced global phase transformation on the driving force for crack growth of a static crack in an infinite center-cracked SMA plate under plane-strain mode-I constant applied loading. The thermo-mechanical loading path used in the analysis is an idealization of typical loading paths that utilize SMAs as actuators subject to constant external mechanical loading under temperature variations, and is referred as isobaric. The driving force for crack growth is identified to be the crack-tip energy release rate, which is calculated using the Virtual Crack Growth Technique (VCCT). Next, crack *growth* during thermal actuation in SMAs is numerically investigated for the same crack configuration and thermo-mechanical loading path as described above. Furthermore, the authors also discuss the effect of crack configuration on the fracture toughness enhancement during cooling subjected to a similar thermomechanical loading path. Herein, the authors also attempt to understand the interplay between the increase in the driving force for crack growth during cooling and the energy dissipation caused by further transformation in material regions close to the advancing crack tip.

The paper is organized as follows: In section 2, the thermomechanical SMA constitutive material model that simulates the material behavior is given. In section 3, formulation of the boundary value problem and solution methodology using finite element analysis for global thermo-mechanically induced phase transformation in an infinite center cracked SMA specimen ("infinite medium" specimen) is described. Section 4 contains a brief review of the key results to draw a connection between results from analysis of the static crack and crack growth. A subsection is dedicated to numerical results pertaining to static crack in two additional crack configurations, *viz.* compact tension and three-point bending specimens with empirically calculated thermo-mechanical parameters and a comparison is made with numerical results from infinite medium specimen with the same material parameters. Finally, some of the key findings of this work are concluded and summarized in the end.