Journal of the Mechanics and Physics of Solids 89 (2016) 255–271

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

journal homepage: www.elsevier.com/locate/jmps

On the driving force for crack growth during thermal actuation of shape memory alloys

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ARTICLE INFO

Article history:
Received 8 December 2014
Received in revised form
18 November 2015
Accepted 19 December 2015
Available online 28 December 2015

Keywords:
Shape Memory Alloys
Actuation
Phase transformation
Fracture toughness
Finite elements

ABSTRACT

The effect of thermomechanically 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 a thermal actuation cycle under mechanical load in plain strain. 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. A substantial increase of the energy release rate – an order of magnitude for some material systems – is observed during the thermal cycle due to the stress redistribution induced by large scale phase transformation. Thus, phase transformation occurring due to thermal variations under mechanical load may result in crack growth if the crack-tip energy release rate reaches a material specific critical value.

1. Introduction

Shape Memory Alloys (SMAs) are metallic materials that can recover large, apparently permanent, strains when subjected to the appropriate thermal procedure. Generally, 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 from austenite to martensite and vice versa. SMA actuators take advantage of this property to provide a significant amount of actuation with an extremely small envelope volume. SMA actuators are therefore used as an alternative to electromagnetic actuators when a small volume and/or large force and stroke are required and thermodynamic efficiency is not essential (Hartl and Lagoudas, 2007; Sreekumar et al., 2007; Nespoli et al., 2010).

The effective implementation of SMAs as actuators requires the assessment of their fracture properties under actuation loading paths, i.e., under combined thermal and mechanical loading. Such studies will enable the practice of fracture mechanics concepts in SMA actuators, and can potentially result in criteria that will connect fracture properties to measurable and hopefully controllable thermomechanical characteristics and microstructural features to provide a knowledge base that can be used in the design of SMA material systems. However, to the best of the authors' knowledge, such studies are lacking in the literature. As recently observed, notched, precipitation-hardened $Ni_{60}Ti_{40}$ (wt%) SMA specimens may fail during

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http://dx.doi.org/10.1016/j.jmps.2015.12.011
0022-5096/

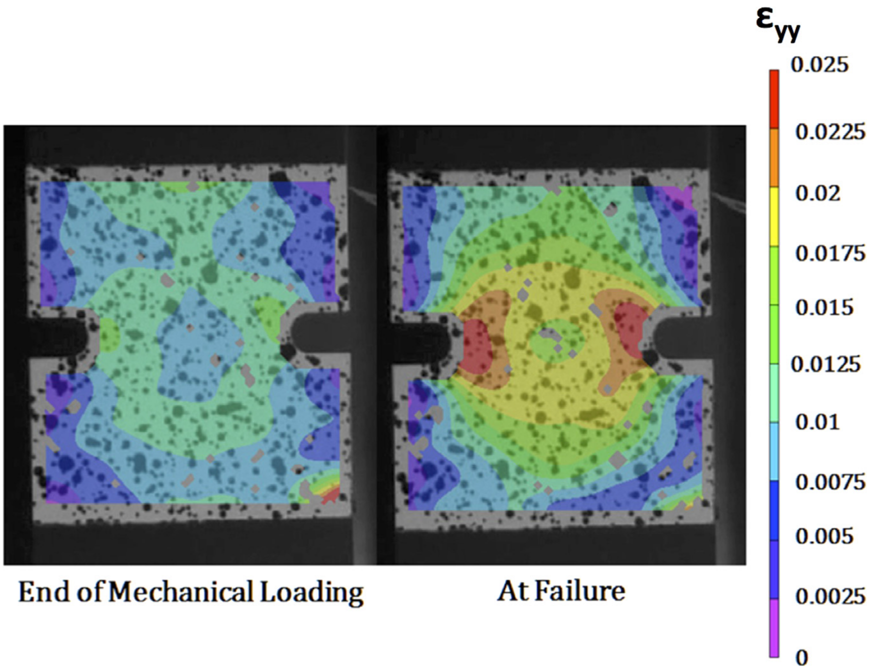

Fig. 1. Strain in the direction of the tensile applied loading (vertical to the axis of the notches) at the end of the isothermal loading (60% of the isothermal strength at that temperature) and just before the formation of an unstable crack under the same bias load at a lower temperature, higher than the martensitic-finish temperature. Taken from (Baxevanis and Lagoudas, 2015).

cooling under a constant applied tensile load that is lower than the isothermal strength at the beginning of cooling. For the U-shape notched specimens tested,[2] failure by the formation of an unstable crack during cooling was observed for bias load levels as low as 60% of the isothermal load needed for failure at the beginning of cooling (Fig. 1). This is an intriguing response, characteristic of SMAs, that from an energetic point of view may seem in disagreement with the general view of dissipative processes resulting in an enhancement of fracture toughness. In most conventional elastic–plastic metals, cooling under a constant load does not considerably affect the existing plastic zone close to the crack tip and thermal contraction results in crack shielding rather than anti-shielding.

Currently, only the fracture response of SMAs during mechanical loading at constant ambient temperatures has received attention in the literature (McKelvey and Ritchie, 2001; Robertson et al., 2007; Daymond et al., 2007; Gollerthan et al., 2009; Creuziger et al., 2008; Baxevanis and Lagoudas, 2012; Baxevanis et al., 2012, 2013, 2014a, 2014b; Baxevanis and Lagoudas, 2015). These studies have been driven by the desire to understand the effect of stress-induced phase transformation or detwinning on the fracture properties of SMAs, stemming mainly from their suitability for medical applications. In their finite element analysis of SMAs obeying power-law hardening flow theory for the evolution equations of the plastic strains, Baxevanis et al. (2012) arrived at the conclusion that stress redistribution due to stress-induced martensitic transformation results in plastic zone sizes at the vicinity of the crack tip an order of magnitude smaller that the size expected in conventional elastic–plastic materials. Experimental evidence on binary martensitic $Ni_{50.3}Ti_{49.7}$ (at%) and pseudoelastic $Ni_{50.7}Ti_{49.3}$ (at%) material systems shows appreciable plastic deformation in uniaxial loading (Gall et al., 2001; Gollerthan et al., 2009), indicating that phase transformation reduces the extent of plastic deformation close to the crack tip and support the numerical results. In Gall et al. (2001), cleavage fracture and river markings consistent with markings from traditional brittle intermetallic alloys were reported in $Ni_{50.7}Ti_{49.3}$ systems containing semi-coherent precipitates. Gollerthan et al. (2009) observed that the crack tips stay sharp during crack growth in both the aforementioned martensitic and pseudoelastic SMAs alloys and all martensitic features in front of the crack tip in the pseudoelastic ones disappear after unloading. The latter observation excludes the formation of stabilized martensite, which cannot reverse transform, because it is hindered by the presence of dislocations. Crack tip blunting is associated with dislocation processes, and the absence of blunting in NiTi may well reflect the fact that dislocation activity at the crack tip plays a much smaller role. Therefore it seems reasonable to assume that in SMAs, even beyond those that show appreciable strength against dislocation plasticity such as, for example, nano-precipitation hardened SMAs, the length scale of the plastic deformation zone surrounding the crack tip is small enough to ensure the validity of (i) an analysis of the fracture response of SMAs on the basis of a constitutive law that does not account for plastic deformation and (ii) a single parameter for characterizing the *fracture toughness of martensite* forming at the crack tip. Thus, crack growth can be presumed to proceed at a critical level of the

[2] The experiments were performed at Texas A&M University and at Naval Research Laboratory and will be presented elsewhere.