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# Mode II fracture behavior of a Zr-based bulk metallic glass

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**Abstract**

Shear band formation and fracture are characterized during mode II loading of a Zr-based bulk metallic glass. The measured mode II fracture toughness, $K_{IIc} = 75 \pm 4\,MPa\sqrt{m}$, exceeds the reported mode I fracture toughness by ~4 times, suggesting that normal or mean stresses play a significant role in the deformation process at the crack tip. This effect is explained in light of a mean stress modified free volume model for shear localization in metallic glasses. Thermal imaging of deformation at the mode II crack tip further reveals that shear bands initiate, arrest, and reactivate along the same path, indicating that flow in the shear band leads to permanent changes in the glass structure that retain a memory of the shear band path. The measured temperature increase within the shear band is a fraction of a degree. However, heat dissipation models indicate that the temperature could have exceeded the glass transition temperature for less than 1 ms immediately after the shear band formed. It is shown that this time scale is sufficient for mechanical relaxation slightly above the glass transition temperature.
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## 1. Introduction

The deformation and fracture behavior of metallic glasses in thin ribbon and, more recently, bulk form has been studied extensively (Masumoto and Maddin, 1971; Alpas

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et al., 1987; Donovan, 1989; Bruck et al., 1994; Gilbert et al., 1997; Lowhaphandu and Lewandowski, 1998; Flores and Dauskardt, 1999a, b, 2001b; Hess et al., 2005; Sergueeva et al., 2005). It is well known that plasticity is highly localized in shear bands, where the glass viscosity is lower than in the surrounding material, as evidenced by molten droplets and characteristic vein patterns on the failure surface. Several explanations for this localized viscosity decrease have been proposed, including adiabatic heating to above the glass transition temperature and a mean stress induced dilatation of the free volume (Spaepen, 1977; Argon et al., 1985; Liu et al., 1998; Flores and Dauskardt, 2001b). While the formation and propagation of shear bands in tensile loading typically leads to unstable failure, the highly localized stress field ahead of a crack tip may be used to constrain the shear bands in a stable damage zone, allowing detailed study as previously reported for mode I loading (Flores and Dauskardt, 1999a, b). The objective of the present study was to examine such crack tip shear banding and fracture mechanisms associated with pure mode II loading.

In the case of brittle materials, the mode II fracture toughness is typically equal to or greater than the mode I toughness (Suresh et al., 1990; Awaji, 1998; Awaji and Kato, 1998). For ductile metals, however, several authors have reported lower mode II toughnesses for a variety of alloys (Aoki et al., 1990; Prasad et al., 1994; Laukkanen et al., 1999). This has been attributed to the different micromechanisms of fracture in brittle and ductile materials (Laukkanen et al., 1999). Fracture in brittle materials is typically stress-controlled, with the maximum principal or normal crack tip stress controlling the fracture process. For ductile materials, the crack tip fracture process is generally strain-controlled. Increased shear loading contributes to the crack tip plastic strain, lowering the resistance to fracture under mode II loading. While the fracture surfaces of metallic glasses may appear ductile in that they exhibit local softening, it is has not been established that a strain-controlled fracture criterion is valid for these materials. Rather, studies suggest that normal or hydrostatic stresses play a significant role for incipient flow and shear banding processes (Liu et al., 1998; Lowhaphandu et al., 1999; Flores and Dauskardt, 2001b; Wright et al., 2001; Zhang et al., 2003). An examination of the mode II fracture, in which a state of pure in-plane shear exists ahead of the crack tip, is therefore of interest.

Questions surrounding the contribution of flow-induced dilatation or adiabatic heating to the viscosity decrease within shear bands have led to numerous examinations of the temperature change associated with flow. In situ high resolution infrared images have been obtained at a crack tip loaded in mode I (Flores and Dauskardt, 1999b) as well as during tensile and fatigue loading of round bars (Yang et al., 2004, 2005). These prior studies revealed very small temperature increases ($<1$ K) associated with the formation of shear bands. More recent observations using a low melting temperature metal coating suggest a minimum temperature increase of $\sim$200 K (Lewandowski and Greer, 2006). Significantly larger temperature increases, on the order of several hundred degrees, have been observed under high strain rate or impact conditions, wherein the energy dissipated and therefore temperature rise are expected to be much larger than under quasi-static conditions (Bruck et al., 1996; Gilbert et al., 1999).

In the present study, the first observations of the mode II fracture behavior of a Zr–Ti–Ni–Cu–Be bulk metallic glass are presented. Prior to failure, the temperature increase associated with crack tip shear bands formed under mode II loading was examined in situ using a high resolution infrared imaging system. Plastic flow, again revealed by a small ($<1$ K) increase in temperature along a shear band in front of the

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