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Cryogenic-temperature-induced transition from shear to dilatational failure in metallic glasses

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Abstract

At temperatures well below the glass transition temperature, the failure of metallic glasses is generally induced by shear banding, which is a result of the self-organized shear transformation zones (STZs). Here, we demonstrate that, upon cooling down to liquid helium temperature (4.2 K), a Zr-based bulk metallic glass under quasi-static uniaxial tension can fracture via cavitation, rather than by shear banding, showing a transition from shear- to dilatation-dominated failure. This transition is supported by the breakdown of low-temperature strengthening of materials, as well as the changes in the macroscopic failure mode from shear to tension and in the microscopic fracture morphology from vein patterns to fine dimples or nanoscale periodic corrugations. According to the Mohr–Coulomb criterion, it is revealed that the capability of this glass to dilatation is enhanced with decreasing temperature, indicating the temperature-dependent normal stress sensitivity of failure. Our result implies that the shear-dominated STZs will convert into dilatation-dominated operations at very low temperatures.

Keywords: Metallic glass; Shear band; Shear transformation zone; Dilatation; Cryogenic temperature

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1. Introduction

Mechanical failure of metallic glasses continues to fascinate researchers [1–5], since dislocations, grain boundaries, crystallographic planes, etc., are not defined in this class of non-crystalline materials [6–9]. Instead, the shear transformation zone (STZ), i.e. the inelastic rearrangement of local atomic groups, is proposed as the fundamental unit of deformation of metallic glasses [10–13]. It is well known that STZs involve both shear and dilatation; in most cases, the former is dominant and the latter is minor. This results in the emergence of 10-nm-scaled shear bands, which macroscopically leads to shear-dominated failure [14,15]. However, recent experiments [14,16–18] and simulations [1,3] have revealed that the dilatation itself, whether induced by shear or hydrostatic tension, can dominate the brittle failure of metallic glasses. In this case, the crack tip propagates via cavitation events that involve a series of nanoscale void nucleation and coalescence processes with very limited plastic growth. The cavitation-mediated brittle failure is strongly suggested by the resulting fracture surface morphologies [14,16–17,19]: very fine dimples that are approximately equiaxed in shape and nanoscale periodic corrugations.

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It has been well documented that the inherent shear-and-dilatation coupling in STZs leads to the pressure (or normal stress) sensitivity of macroscopic failure (flow and fracture) of metallic glasses [20,21]. Two direct pieces of evidence of such pressure sensitivity are that fracture angles under either compression or tension always deviate from the maximum shear stress plane (45°) [22–24]; and shear stresses at yielding depend on the applied hydrostatic pressure or normal stress [24–26]. Because STZs are stress-driven, thermally activated events initiated around high free-volume regions, it can be seen that the pressure sensitivity depends on the loading mode [23,25] and is highly material/structure specific [25,27–29]. It is expected that temperature could also affect the pressure sensitivity of metallic glass failure, but this needs further experimental evidence.

In this work, we systematically investigated the failure behavior of a typical Zr-based (Vitreloy 1) bulk metallic glass by using environmental temperature as the only controlling parameter. A significant transition from shear to tensile failure was observed by the cryogenic cooling of Vitreloy 1 that was subjected to in situ quasi-static uniaxial tension from room temperature (300 K) to liquid helium temperature (4.2 K). This provides solid evidence that the dilatation of metallic glasses and the resulting normal stress sensitivity of failure are temperature dependent. The observed critical transition phenomenon coincides with the physical picture of the shear-to-dilatation transition in STZs at low temperatures, as originally proposed by Argon [10].

2. Experimental

We chose the Vitreloy 1 bulk metallic glass as the model material because it is a tough system, with room-temperature fracture toughness up to over 80 MPa $\sqrt{m}$ [30], and it has high thermal stability [31]. Vitreloy 1, with a nominal composition of $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10.0}Be_{22.5}$ (at.%), was cast into plates of dimensions $2 \times 30 \times 60\ mm^3$ in an arc-melter with an in situ suction facility. Dog-bone-shaped specimens with gauge dimensions of $13 \times 2 \times 2\ mm^3$ were

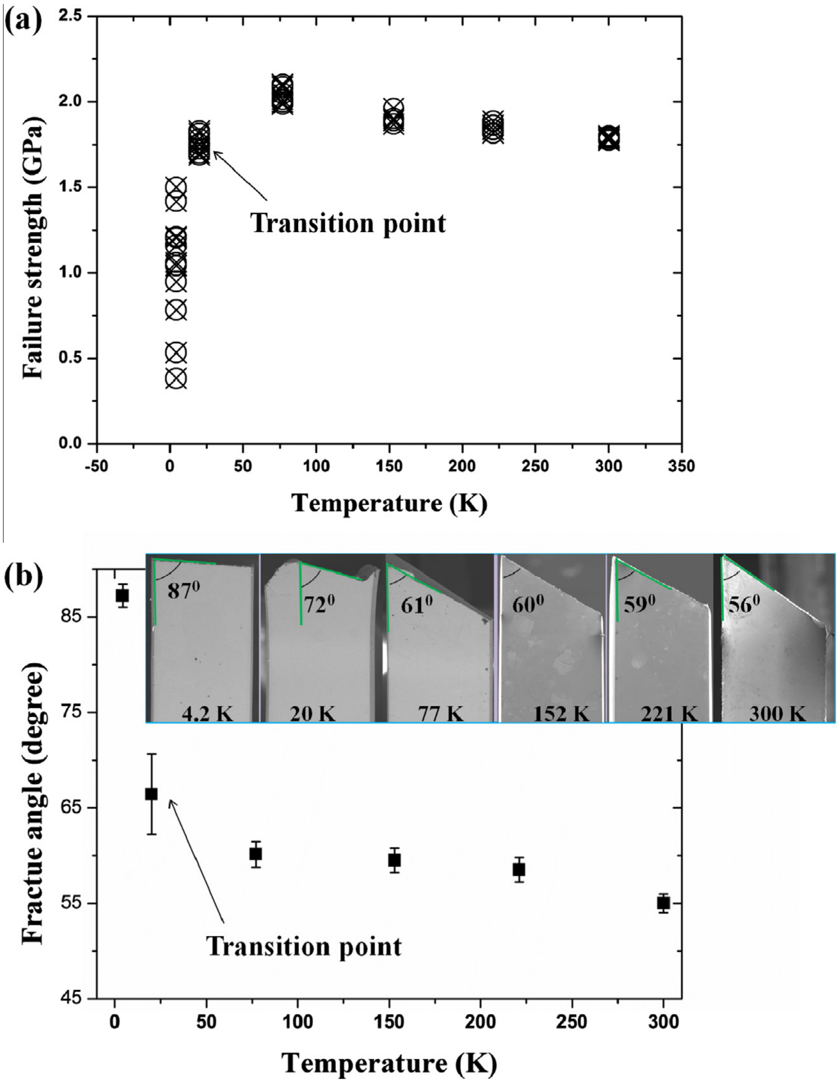

Fig. 1. (a) Tensile failure strength and (b) fracture angle as a function of temperature from room temperature (300 K) down to liquid helium temperature (4.2 K). The inset in (b) shows the representative failure modes at different temperatures.