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Wallner lines, crack velocity and mechanisms of crack nucleation and growth in a brittle bulk metallic glass

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Abstract

Mode I fracture experiments were conducted on brittle bulk metallic glass (BMG) samples and the fracture surface features were analyzed in detail to understand the underlying physical processes. Wallner lines, which result from the interaction between the propagating crack front and shear waves emanating from a secondary source, were observed on the fracture surface and geometric analysis of them indicates that the maximum crack velocity is ~800 m s^{-1}, which corresponds to ~0.32 times the shear wave speed. Fractography reveals that the sharp crack nucleation at the notch tip occurs at the mid-section of the specimens with the observation of flat and half-penny-shaped cracks. On this basis, we conclude that the crack initiation in brittle BMGs is stress-controlled and occurs through hydrostatic stress-assisted cavity nucleation ahead of the notch tip. High magnification scanning electron and atomic force microscopies of the dynamic crack growth regions reveal highly organized, nanoscale periodic patterns with a spacing of ~79 nm. Juxtaposition of the crack velocity with this spacing suggests that the crack takes ~10^{-10} s for peak-to-peak propagation. This, and the estimated adiabatic temperature rise ahead of the propagating crack tip that suggests local softening, is utilized to critically discuss possible causes for the nano-corrugation formation. Taylor's fluid meniscus instability is unequivocally ruled out. Then, two other possible mechanisms, viz. (a) crack tip blunting and resharpening through nanovoid nucleation and growth ahead of the crack tip and eventual coalescence, and (b) dynamic oscillation of the crack in a thin slab of softened zone ahead of the crack-tip, are critically discussed.

Keywords: Metallic glass; Brittle fracture; Crack propagation; Fracture mechanisms; Cavitation

1. Introduction

The mechanical behavior, and in particular the fracture response, of bulk metallic glasses (BMGs) has been a topic of active research [1,2]. Those BMGs which exhibit plastic deformation by way of multiple shear band formation and propagation are typically termed "ductile". Tandaiya et al. [3] have recently shown that in these "ductile" BMGs, crack growth occurs within a dominant shear band with a finite fracture process zone, whose size is on the order of several tens of microns. This size is controlled by the extent of positive hydrostatic stress gradient ahead of the notch tip, which leads to the operation of Taylor's fluid meniscus instability (FMI) mechanism inside the shear band (wherein the material is fluid-like) [4–7]. The fracture surface morphology in these glasses contains a notch blunting zone, a region dominated by "finger-like" features (caused by the FMI mechanism), followed by vein morphology characterized by deep valleys and ridges in the unstable crack growth regime.

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A necessary condition for a BMG to be ductile is that plastic deformation through multiple shear bands must take place. In many BMGs, however, such a deformation does not occur at all. These BMGs are termed "brittle" and have low fracture toughness, K_{Ic}, values [2]. Note that some BMGs such as Fe-based ones are brittle in the as-processed state itself whereas some other BMGs become brittle when subjected to an annealing treatment at temperatures below their glass transition temperature, T_g (referred to as structural relaxation) [8–12]. Yet, some other glasses are also brittle, but only under specific combinations of experimental conditions (typically low temperatures and high strain rates) [9,13]. Irrespective of these variations, all brittle BMGs exhibit some unique fracture surface features [13–16].

Fractography of brittle materials such as silicate glasses or glassy polymers indicates that there are three distinct zones on the fracture surface, namely: mist, mirror and hackle [17]. In general, the most dominant one amongst these is the mirror zone, which appears featureless in low magnification imaging. It indicates fast fracture wherein the crack velocity is independent of the imposed loading rate [18]. In turn, observation of these zones on fracture surfaces indicates that the propagating crack does not experience energy dissipative processes such as plasticity (profuse shear banding ahead of the crack tip in the case of BMGs) or crack bridging, which can retard crack growth in a substantial manner. Higher resolution fractography of brittle BMGs shows nanoscale striped patterns with a high degree of periodicity [13,14,16,19,20]. Although widely reported, our understanding of the physics behind the mechanisms of brittle fracture in BMGs is relatively poor as postmortem examination of the fracture surface features has been the only available tool for inferring the fracture processes in these materials. In addition, almost all the tests that are reported hitherto – and on whose basis the brittle fracture mechanisms are inferred – are performed in either un-notched tensile or compression geometries, i.e., the specimens utilized do not conform to "proper" fracture geometries. As a result, the mechanistic inferences are always clouded by issues such as the crack growth direction, the inability to accurately delineate crack nucleation vs. propagation regimes, accelerating vs. decelerating crack regimes, etc. In many instances, brittle and ductile fracture mechanisms are also not clearly differentiated, leading to considerable confusion.

With the objective of understanding the fracture mechanisms in brittle BMGs and in turn bringing some clarity to the physics that governs fracture in them, we conducted mode I fracture experiments on notched BMG bars that were intentionally made brittle through structural relaxation treatments. We report the observation of a distinct fracture surface feature, namely Wallner lines, whose geometrical features were utilized to estimate the dynamic crack velocity in BMGs. The crack initiation and growth regions were examined in detail through scanning electron microscopy (SEM) and atomic force microscopy (AFM). Although the mirror and mist zones of the fracture surfaces are smooth and featureless at the microscale, high resolution fractography indicates a distinct – and yet highly consistent and repeated – corrugation pattern at the nanoscale. The characteristic length scale of this pattern was utilized, in conjunction with the crack velocity inferred from the analysis of Wallner lines, for estimating the time taken by the crack to propagate from peak-to-peak of the corrugations as on the order of 0.1 ns. This insight into the physics of fracture of brittle BMGs is utilized to discuss various hypotheses proposed in the literature in order to identify potential mechanisms of fracture.

2. Material and experiments

Cylindrical rods of fully amorphous BMG, $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (also known as Vitreloy 1, $T_g = 625$ K [9]), with a diameter of 9.5 mm and a length of 90 mm, are used in this study. Symmetric four-point bend fracture specimens – 46 mm long, 5 mm wide and 3 mm thick – are machined from these rods using wire-cut electrical discharge machining (EDM) process. They are then pre-notched to a depth of 2.5 mm by means of EDM, employing a smaller diameter wire such that the resulting width of the notch is ~60 μm. Subsequently, these specimens are vacuum-sealed in quartz tubes and annealed either at 500 ± 5 K for 24 h or at 563 K for 12 h. (Note that these temperatures correspond to ~0.8 and 0.9 T_g, respectively.) Hereafter, the samples annealed at 500 K will be referred to as SR-I and those annealed at 563 K as SR-II. It is well known that such an annealing treatment leads to structural relaxation of the glass and reduces the free volume considerably [8]. This, in turn, makes the BMG brittle, which is otherwise "ductile", with high fracture toughness caused by considerable plastic dissipation through the occurrence of multiple shear bands [21].

A schematic of the four-point bend fracture specimen is shown in Fig. 1. Also, shown in the figure are the loading pins which are 3 mm in diameter and made of high speed steel (AISI M2). These loading pins are fastened to a fixture attached to the testing machine. Grooves are machined in the specimens at the load application points to avoid large contact stresses and to prevent crushing of the specimen under the pins. Furthermore, the grooves cut in the specimens ensure accurate positioning of the

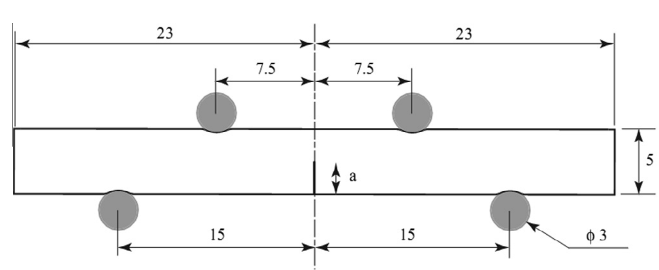

Fig. 1. A schematic of the notched four-point bend specimen along with dimensions (in mm) and the positions of the loading pins (shaded).