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Deformation-induced spatiotemporal fluctuation, evolution and localization of strain fields in a bulk metallic glass

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Deformation behavior and local strain evolutions upon loading and unloading of a bulk metallic glass (BMG) were systematically investigated by *in situ* digital image correlation (DIC). Distinct fluctuations and irreversible local strains were observed before the onset of macroscopic yielding. Statistical analysis shows that these fluctuations might be related to intrinsic structural heterogeneities, and that the evolution history and characteristics of local strain fields play an important role in the subsequent initiation of shear bands. Effects of sample size, pre-strain, and loading conditions were systematically analyzed in terms of the probability distributions of the resulting local strain fields. It is found that a higher degree of local shear strain heterogeneity corresponds to a more ductile stress–strain curve. Implications of these findings are discussed for the design of new materials.

1. Introduction

Bulk metallic glasses (BMGs) have been shown to have superior mechanical properties such as strength and ductility under geometrically constrained conditions, but are oftentimes brittle in unconstrained conditions such as uniaxial tension tests (Zhang et al., 2003; Schuh et al., 2007; Yang et al., 2010; Wang et al., 2012). The precursor of brittle failure is strain localization in thin bands or planes, which are referred to as shear bands. Despite many models and significant advances in recent decades (Spaepen, 1977; Argon, 1979; Johnson and Samwer, 2005), there is still a lack of understanding of the structure–property relationship that controls the initiation of shear bands and their evolution into fracture failure. From the atomistic point of view, the shear bands are believed to originate at local structural heterogeneities such as free volume regions, shear transformation zones, or some sorts of soft regions (Spaepen, 1977; Argon, 1979; Maloney and Lemaître, 2004; Wang et al., 2012; Zhao et al., 2013). These are intrinsic factors that govern the deformation behavior. Macroscopically, the applied strains are accommodated by the localized deformation in shear bands (Lewandowski et al., 2006; Jiang et al., 2007; Fornell et al., 2009), so the ductile-versus-brittle behavior has good correlation with the strain partitioning in shear bands. That is, the promotion of shear band multiplication or prevention of shear band propagation tend to reduce the strain in individual shear bands and thus prevent catastrophic failure (Chen et al., 2013); these are the extrinsic design principles

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utilized in composites and coating approaches (Zhou et al., 2013). A connection between the above atomistic and macroscopic processes will clearly broaden our design capabilities in order to achieve better ductility and toughness (Schuh et al., 2007; Barrat and de Pablo, 2007; Homer and Schuh, 2009). The critical information needed for this is the ability to visualize and quantify the full extent of shear banding, from initiation to propagation, to final fracture, across multiple length scales.

The shear banding process has been found to be jerky in time and inhomogeneous in space (Jiang et al., 2008; Wright et al., 2013; Wu et al., 2011), which makes it difficult to fully capture its initiation, propagation, interaction and especially the evolution of local strain fields. Among the many methods applied in BMG studies, transmission electron microscopy (TEM) can probe structural information of the local deformed region, but the reduction of the sampled volume to nanometer scale and the exposure to electron beam might lead to artifacts that complicate the understanding of shear banding behavior. Scanning electron microscopy (SEM) can observe the evolution of shear bands patterns, but cannot easily capture the initiation of shear bands (Li et al., 2003). Statistical analysis of the serrated flow, observed on stress–strain curves, can shed light on the collective shear banding dynamics, but the evolution of individual shear bands cannot be uniquely obtained (Song et al., 2008; Sun et al., 2010). Infrared thermography can measure the temperature field that reveals the shear bands where heating occurs due to the severe plastic deformation in the shear bands (Yang et al., 2004), but this method is limited by its poor spatial and temporal resolutions. The above limitations make it difficult to achieve an *in situ* measurement of the entire strain field and its evolution.

The digital image correlation (DIC) technique is a visualization method that tracks surface features on the test sample. Sequential digital images of sample surfaces are recorded during deformation and these images are post-processed to obtain strain fields based on a pattern-matching algorithm (Chu et al., 1985; Sutton et al., 2009). Because it provides a full-field strain map, the DIC method is ideal for *in situ* investigation of localized deformation behavior in BMGs (Zhang et al., 2009; Joo et al., 2013). For example, Joo et al. (2013) measured the shear band arrangements under different strain rates using DIC, and analyzed the dependence of deformation mode and fracture mechanism on strain rate. On the other hand, the local strain fields and their dynamic evolution during loading/unloading, which is the most significant advantage of the DIC method especially at the initial stage of shear band formation, have not been fully addressed in the literature. Therefore, in this work, from *in situ* DIC characterization of local strain field evolution and shear banding processes in a model BMG, we will compare the DIC strain measurements under different loading circumstances (such as tension versus compression, or tests on samples with different sizes), to explore the connections between the local deformation behavior and the macroscopic stress–strain curves in BMGs and to attempt to reveal the mechanisms that govern ductile versus brittle behavior in BMGs.

2. Experiments and methods

2.1. Sample preparation

The nominal composition of BMG samples used in this work is $Zr_{52.5}Ti_5Cu_{17.9}Ni_{14.6}Al_{10}$ (at%), denoted as BAM11 (Loffler et al., 2000). Master alloys were prepared by arc melting the pure elements (>99.99%) under a purified argon atmosphere. Each button was turned over and re-melted five times to maximize chemical homogeneity. Subsequently, cylindrical rods with diameters of 7 mm were obtained by casting the molten BMG into water-cooled copper molds under helium atmosphere. Compression specimens with an aspect ratio (height/diameter) of 2 and diameters of 2, 3, or 5 mm (denoted as D2mm, D3mm, and D5mm in these figures) were cut from the center of the as-cast rods. Stress relaxation of different-sized specimens was conducted by loading the specimens to a specific strain and then recording the stress variation while keeping the strain constant. Tensile specimens with gauge dimension of 10 mm × 1.5 mm × 1 mm were cut from the as-cast 10-mm rods. Pre-strained specimens were prepared by first compressing a disk-shaped sample with diameter of 7 mm and aspect ratio of 0.8 to a thickness reduction of 50%. Details of the pre-straining process can be found in Bei et al. (2006). Then samples with dimensions of 2 mm × 4 mm (diameter × height) were taken along the radial direction perpendicular to the compression direction. The amorphous structure was confirmed by x-ray diffraction.

2.2. In situ mechanical tests with DIC

The test specimens were ultrasonically cleaned in acetone, coated with a thin layer of white spray paint, and then a black toner powder was sprayed on to form a speckle pattern suitable for DIC measurements (e.g., Fig. 1a).

Compression/tension tests were conducted at an engineering strain rate of $5 \times 10^{-4}\ s^{-1}$ on an Instron 5881 machine. A high-resolution camera, model GRAS-50S5M-C, was used to record the speckle images during deformation at a speed of 5 images per second. The images were then analyzed by the Vic-2D 2009 software, which provided strain values. Since in-plane displacement fields are recorded, we have strains in longitudinal and transversal directions being ε_{yy} and ε_{xx}, respectively. Shear strain ε_{xy} in the DIC results is half of the engineering shear strain. The quality of the speckles, subset size and step size during calculation can influence the resolution of the strain map. A subset of 39 and step size of 2 pixels were used for our strain calculations, leading to a spatial resolution of 6 μm for the strain measurements.