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Short communication

Effect of temperature on the yield strength of a binary CuZr metallic glass: Stress-induced glass transition

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ABSTRACT

Compression tests were conducted on the binary $Cu_{50}Zr_{50}$ metallic glass in a temperature range below glass transition temperature where deformation mode was inhomogeneous. The yield strength of the glass was found to decrease monotonically with the increase of testing temperature in a non-linear fashion. The strength–temperature relation for the binary glass, as well as several other metallic glass systems, could be well correlated through the concept of stress-induced glass transition. The viscosity in the propagating shear band of the binary glass was also measured and found to be insensitive to the sample size and test temperature.

1. Introduction

Localized shear banding, which confines large plastic strain in an extremely thin ribbon-like region (~10–20 nm [1–3]), is the dominant deformation mode of metallic glasses in the inhomogeneous deformation region [4,5]. It controls the plasticity and determines the strength of metallic glasses [6]. The evolution of shear bands in amorphous alloys still remains unclear, however, the process must be radically different from that known for crystalline alloys (e.g. dislocations). It is generally recognized that shear banding is associated with a local viscosity drop [4,7]. Many have argued that the viscosity drop was associated with a significant temperature rise in shear bands [8–11]. For instance, Yang et al. [12] employed thermography to estimate the temperature increase in a shear band is close to the glass transition temperature T_g. However, it is now agreed that temperature rise within shear bands is a consequence rather than a cause of shear banding [8]. Meanwhile, the strain rate and viscosity inside a propagating shear band have also been measured by several groups using various techniques [13–15]. The shear rate ($\sim 10^4$–10^5 s^{-1}) is typically quite fast and the viscosity value ($\sim 10^4$–10^6 pa s) is in a similar range as that usually obtained in BMGs homogeneously deformed at low strain rates near the glass transition temperature or in the supercooled liquid region [16,17]. From the viscosity point of view, there must be a correlation between temperature and strain rate (or stress).

Recently, using molecular dynamic simulations, Guan et al. [18] pointed out that applied stress and temperature are equivalent and shear banding is a stress-induced glass transition process. They developed a stress–temperature relationship for the steady-state flow in metallic glasses based on the constant viscosity. Although many experimental strength–temperature data have been measured from conventional tension/compression tests and nanoindentation [19,20], Guan et al. [18] offers a new view on the origin of shear banding in glassy materials.

In the current study, we carry out micro-compression tests on a binary CuZr bulk metallic glass at different temperatures within the inhomogeneous deformation region, i.e. temperatures well below the glass transition temperature T_g. As a model material, the glass forming ability, crystallization, and room-temperature plasticity of the binary CuZr system have been well studied [21–26]. The correlation between the yield strength and the test temperature is established and discussed in light of the concept of stress-

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induced glass transition. Taking the advantage of high spatial and temporal resolutions of nanoindentation, we measure the viscosity in the propagating shear band at different test temperatures.

2. Materials and methods

The metallic glass used in the current study has a chemical composition of $Cu_{50}Zr_{50}$ (denoted as CuZr) with a glass transition temperature T_g of ~700 K [27]. Thin disks were sliced from a 1.5-mm rod, and the surface was grinded and polished to mirror finish before further fabrication. Micro-scaled pillar samples for compression tests were fabricated using a Seiko SMI3050 dual FIB system [28]. The diameter of the pillar was chosen to be 2 μm and the height was at least 4 μm to maintain a minimum 2:1 aspect ratio. The micro-compression testing technique and sample fabrication by FIB have been extensively discussed in the literature [29–32].

Micro-compression tests were performed using a TriboIndenter (Hysitron, Inc., Minneapolis, MN) with a heating stage, equipped with a conical flat tip with extended Macor holder for the sake of thermal shielding when used at elevated temperatures. The diameter of the tip was 10 μm. A thermal shield was installed to prevent overheating of the transducer. Detailed experimental design can be found elsewhere [33]. The test temperatures were selected at 5, 50, 120 and 180 °C, which correspond to 0.40, 0.46, 0.56 and 0.65 T_g, respectively. Tests were conducted under open-loop load-control mode to maximize the data acquisition rate and, specifically, a fixed loading rate of 0.4 mN/s was applied and the maximum load was limited at 8 mN. Test pillars were examined before and after deformation for the deformation mode using scanning electron microscopy.

3. Results

The nominal stress–strain curves at different temperatures were plotted in Fig. 1a. As samples are slightly tapered, the stress distribution is, in fact, inhomogeneous along the axial direction. As a result, yielding usually initiates at the top part of a pillar where the sample experiences the highest stress, while the part underneath experiences only elastic deformation [32,34]. In the current study, we only focus on the yield strength, which is the stress causing the formation of the first notable shear band at the top of the pillar. Therefore, for the convenience of analysis, the nominal stress is defined as the ratio of load over the area of the pillar top, which is essentially the engineering stress prior to yielding. The curves exhibit some serrations before the macroscopic yielding, especially at high temperatures. These serrations are mainly caused by the random shear band formation and quickly dissipated in the sample. The first serration usually occurs at a stress level that is dependent upon the resolution limit of the displacement measurement [14,35]. In the current study, we choose the stress at the first sizable displacement burst as our yield strength since it marks the onset of macroscopic plastic flow. In this manner, the yield strength (2.1–2.3 GPa) appears to decrease with the test temperature, at least within the current temperature range (0.4–0.65 T_g) where inhomogeneous deformation dominates. Similar result has been observed previously in another $Cu_{57}Zr_{43}$ metallic glass [36]. SEM images of the CuZr pillar before and after deformation at 278 K are presented in Fig. 1b and c, respectively. It is readily observed that the pillar is deformed by one large shear band extending across the entire sample plus some smaller ones. Since the micro-compression was performed under a load-control mode, multiple contacts occurred between the punch and the sample immediately after the major shear event. Thus, data obtained after the multiple contacts have limited significance.

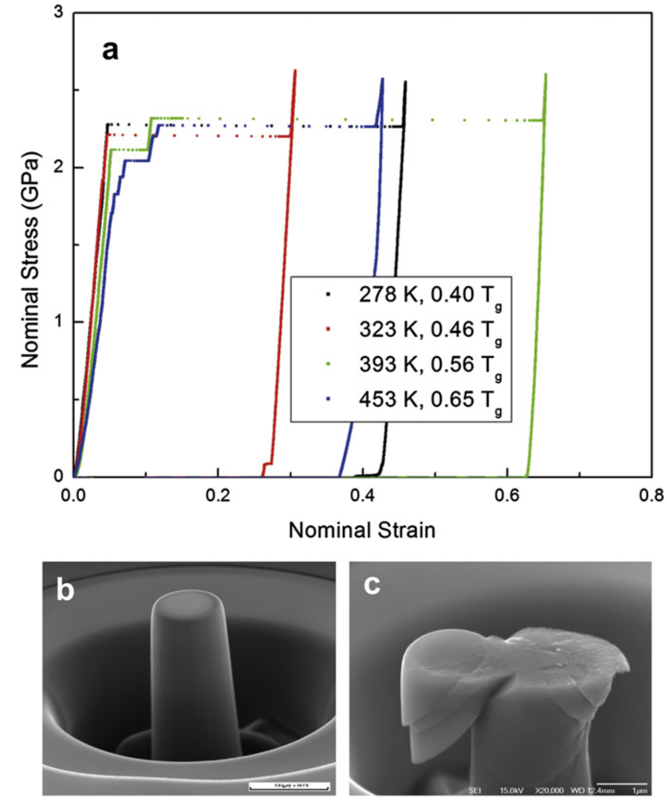

Fig. 1. Nominal stress–strain curves (a) of CuZr under micro-compression at different temperatures under a constant loading rate of 0.4 mN/s (equivalent to a strain rate of ~0.003 s^{-1}) and SEM images of CuZr pillar deformed at 278 K (b) Before deformation and (c) after deformation.

Several years ago, Yang et al. [37] argued that, different from crystal solids in which yielding involves bond switch in an orderly manner, yielding in metallic glasses should be determined by bond breakage. By computing separately the mechanical and thermal energies that are required for bond breakage and, then, equating them, they derived a simple equation as [37]

$$\sigma_y = 50\frac{\rho}{M}(T_g - T), \tag{1}$$

where σ_y is the yield strength, T is the ambient temperature, ρ is the density, M is the molar mass, and T_g is the glass transition temperature. This linear relationship between yield strength and temperature was additionally confirmed by Liu et al. [38]. Yield strength of the current CuZr as a function of temperature is plotted in Fig. 2. The yield strength is noted to decrease with increasing temperature, but apparently does not scale linearly with the temperature. A nonlinear relationship between σ_y and T_g has been reported before. For example, Schuh et al. [6] showed that the yield strength is nonlinear (it in fact gives the power-law exponent as 1/2, similar to that proposed by Guan et al. [18]). Johnson and Samwer [19] also proposed a power-law exponent of 2/3 instead of 1/2, based on the potential energy landscape perspective [39]. However, fitting of the data with the 3/2 power law is better than the linear but worse than the 1/2 power.

4. Discussion

According to the stress-assisted glass transition model [18], the applied stress biases the local energy landscape, and causes some atoms unstable, or liquid-like. When the density of the liquid-like