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Gradual shear band cracking and apparent softening of metallic glass under low temperature compression

S.J. Wu[a,b], X.D. Wang[a], R.T. Qu[a,*], Z.W. Zhu[a], Z.Q. Liu[a], H.F. Zhang[a], Z.F. Zhang[a,**]

[a] Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang, 110016, PR China
[b] School of Materials Science and Engineering, University of Science and Technology of China, Hefei, 230026, PR China

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A B S T R A C T

Metallic glasses (MGs) usually exhibit synchronously enhanced plasticity and strength with decreasing the testing temperature. Although great efforts have been made, why MGs show better plasticity at low temperature remains unclear. In this work, the shear band cracking and fracture mechanism of a relatively brittle TiZr-based MG was investigated through methods of low temperature compression and 3D X-ray tomography. Pronounced apparent softening and profuse internal shear-band cracks were observed along with the improved plasticity, enhanced yield strength, decreased average softening rate, and reduced area of vein pattern as decreasing the testing temperature. Moreover, the fracture features can be correlated well with the compressive properties; and the true rupture stress that is carried by the still-bonded part of major shear band was found to be very close to the yield strength, demonstrating that the apparent softening should mainly originate from the cracking rather than dilation of shear band. The decreased softening rate can be fitted by a diffusion model, implying reduced atomic mobility and increased cracking resistance. Consequently, the improved plasticity of TiZr-MG at low temperature was attributed to the suppression of instant fracture and the enhanced resistance to shear band cracking, rather than the change of shear band density.

1. Introduction

As potential structural materials, metallic glasses (MGs) possess excellent mechanical properties such as high strength, high hardness and super elasticity [1,2]. Different from crystalline metals, MGs exhibit amorphous structure without periodic arrangement of atoms, thus the plastic deformation in MGs is not mediated by the well-studied dislocations, but usually localized into a narrow region, i.e., the so-called shear band [3]. This unique deformation mechanism renders MGs many interesting mechanical behaviors attracting attentions of researchers in both materials and mechanical fields. One of the most interesting mechanical behaviors of MGs is the synchronous enhancement of plasticity and strength at low temperature [4–10], which is quite abnormal as compared with crystalline metals (especially the body-centered cubic crystal metals). The reason for the strength increment can be attributed to the enhanced difficulty of shear transformation which is a thermo-activation process, and thus to the increased critical stress for plastic flow (or shear banding) [1,11–13]. However, why MGs usually show better plasticity at low temperature remains unclear.

Since the plastic strain in MGs is mediated by shear bands, the initiation, propagation, cracking and fracture of shear band essentially determine the plasticity of MGs [3,14,15]. If shear band is easy to initiate and difficult to propagate and cracking, profuse shear bands with small plastic strain but without cracking should be expected, leading to a better plasticity [15–17]. Because of the improved resistance to plastic flow induced by the low temperature, the critical stresses for both shear band initiation and propagation increase with decreasing temperature. However, the effect of temperature on the difference between the above two critical stresses, which are more directly related to the multiplication of shear band [15,18], remains unknown. And, the low temperature experiments concerning the shear band density also show controversial results [6,8,9,19,20]. On the other hand, the testing temperature has a strong effect on the dynamics of shear band sliding propagation, as manifested by the disappearance of serrations on the stress-strain curve at low temperature [8,19–23]. The temperature effect on shear band dynamics has been extensively studied and well explained [21–25], which is not the topic of the present work.

Another issue affecting the plasticity of MGs is how shear band

* Corresponding author.
** Corresponding author.
E-mail addresses: rtqu@imr.ac.cn (R.T. Qu), zhfzhang@imr.ac.cn (Z.F. Zhang).

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cracking and fracture occur. Usually, the fracture of ductile MGs occurs along shear band with the largest plastic strain or critical shear offset [26–32]. On the fracture surface, vein patterns formed due to the Taylor instability of liquid layer-air interaction are typical morphology features of shear fracture [33], implying a great heat release during fracture moment. It has been also found that cavitations or cracking of shear band are necessary for the final instant fracture of MGs under both tension and compression [34–37]. While great efforts have been made to study the cracking mechanism of shear band, little is known on how low temperature affects the shear band cracking and fracture mechanism of MGs.

In this work, we performed a systematic experimental investigation on the low temperature effect on shear band cracking and fracture under compression, by selecting a relatively brittle TiZr-based MG and using a 3D X-ray tomography (XRT) technique. Improved plasticity, enhanced yield strength, decreased apparent softening rate, and reduced area of vein pattern were observed as decreasing the testing temperature. By quantitatively comparing the fracture surface features with stress-strain behaviors, we concluded that the apparent softening originates from the cracking of shear band, and the suppression of cracking and fracture at low temperature contribute to the enhanced plasticity.

2. Experimental

$Ti_{32.8}Zr_{30.2}Ni_{5.3}Cu_9Be_{22.7}$ (at.%) (TiZr-MG) was used in this work; the synthesis details of the alloy are available in literature [38]. The as-cast MG samples were examined by using a Rigaku X-ray diffraction (XRD) and the lack of discrete peaks revealed the amorphous structure. The compressive samples were fabricated by cutting the as-cast MG plate into cuboid shape with dimensions of 2 mm × 2 mm × 4 mm. Prior to compression, all samples were ground and polished to a mirror finish.

Uniaxial compression tests were conducted at a strain rate of 10^{-4} s^{-1} by using an Instron 5982 testing machine. The compressive sample was located in an environment cabinet with which the testing temperature can be well controlled. Five testing temperatures ranging from room temperature to 173 K were selected. To ensure the repeatability, at least three samples were compressed for each temperature. After the mechanical testing, the deformation and fracture features were observed with a LEO Supra 35 scanning electron microscope (SEM). In order to study the shear band cracking behavior inside the samples, two compressive samples deformed at 198 K and 173 K were unloaded at different stages of compression and observed by a lab-based Versa XRM-500 XRT. The working accelerating voltage was 140 kV. A total of 1600 2D projections, each of which was exposed for 5–10 s, were recorded as the sample was rotated by 360° and computationally reconstructed via a filtered back projection algorithm to visualize the internal cracks inside the sample in 3D space.

3. Results

3.1. Compressive stress-strain behaviors

Fig. 1 presents the typical engineering stress-strain curves under compression at different testing temperatures. Clearly, the testing temperature has a great influence on the stress-strain behavior of TiZr-MG. At room temperature, the TiZr-MG exhibits brittle fracture with nearly zero plasticity. However, as decreasing the temperature, the plastic deformation is gradually improved; and pronounced apparent softening behavior was observed. In order to see more details about plastic deformation, the stress-strain curves are enlarged at the early stage of plastic deformation, as plotted it in Fig. 2(a), several interesting phenomena can be seen. Firstly, the apparent softening, which appears after the stress plateau, gradually becomes insignificant with decreasing the testing temperature, which has not been reported before and will be discussed in Section 4.3. Secondly, the serrations can be seen at higher temperature and then disappear at ∼198 K, consistent with the previous studies [8,19–22]. Thirdly, the yield strength (σ_s), which is defined as the stress corresponding to the point at which the stress-strain curve starts to deviate from the linear elasticity, slightly increases with decreasing the testing temperature (T) (Fig. 2(b)), which is also in accordance with the previous findings [4–6]. Lastly, the plastic deformation is enhanced quite evidently at low temperature. Because the apparent softening behavior may not be a normal reflection of the inherent plastic deformation of MGs, thus the nominal plasticity (ε_p) can be defined as the plastic strain corresponding to the stress that is 5% lower than the σ_s to characterize the shear plastic deformation, as shown in Fig. 2(a). The variation of ε_p with T is plotted in Fig. 2(c), which shows an obvious increase of ε_p with decreasing T. Therefore, the relatively brittle TiZr-MG shows the similar enhanced strength and plasticity as well as the gradually disappeared serrated flow with other ductile MGs; while pronounced apparent softening behavior with varying softening rate was observed in the present TiZr-MG under low temperature compression. To explore the inherent mechanism for these interesting phenomena, especially the softening behavior, the deformation and fracture features were further studied.

3.2. Deformation features and shear band cracking

Fig. 3 shows the typical external surface of failed samples at different testing temperatures. All samples failed in a shear mode along the major shear band. The shear fracture angle slightly decreases from ∼41° to ∼39° with decreasing the testing temperature, which is in contrast to the increased shear fracture angle under tension at low temperature [39,40]. Essentially, either the decreased shear fracture angle under compression or the increased shear angle under tension can be explained with the same physical reason [41–43], i.e., the increased resistance to shearing but the decreased resistance to cleavage at low temperature [39]. Furthermore, all the failed TiZr-MG samples exhibited nearly only one single shear band, which means that there is no significant change of shear band density with varying testing temperature. This result is different from the previous studies [5,6,19]. However, the critical shear offset of shear band prior to the final fracture dramatically increases with decreasing temperature. This can be seen especially in the samples tested at 198 K and 173 K, in which large shear-off steps of ∼0.7 mm can be observed (see Fig. 3(d) and (e)). The obviously increased critical shear offset at low temperatures is well consistent with the enhanced overall plasticity. Besides the shear band deformation, obvious shear band cracking can also be seen in the low-temperature tested samples, as shown in Fig. 3(d) and (e). However, it seems that with the similar shear-offset step the sample tested at 198 K exhibited longer and wider shear-band crack than the sample tested at 173 K, implying that the shear band cracking may be suppressed at lower temperature, which will be further discussed in Section 4.3.

To further examine the shear band cracking behavior inside the TiZr-MG sample, two samples (tested at 198 K and 173 K, respectively) were unloaded at different stages of compressive deformation and observed with the XRT. The XRT images of the deformed samples are exhibited in Fig. 4. For the 198 K tested sample shown in Fig. 4(a1), in which the major shear band deformed with a shear offset of 68 μm without obvious cracking from the external surface, many small and scattered internal cracks well located in the shear band plane can be clearly observed, as shown in Fig. 4(b1)-(d1). On the other hand, although the lower temperature may suppress the shear band cracking, as observed from Fig. 3, the 173 K tested sample in Fig. 4(a2)-(d2) with a shear offset of 701 μm (about ten times larger than that in the above sample tested at 198 K) showed much longer cracks. This implies that the evolution of crack growth, linkage and expansion is not only influenced by the testing temperature, but also greatly depends on the amount of shear plastic deformation. Additionally, in the 173 K