Materials Science & Engineering A 651 (2016) 321–331

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

How hot is a shear band in a metallic glass?

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ARTICLE INFO

Article history:
Received 18 August 2015
Received in revised form
13 October 2015
Accepted 31 October 2015
Available online 2 November 2015

Keywords:
Metallic glass
Shear softening
Shear band
Temperature rise
Heat diffusion

ABSTRACT

Due to the localization in space and the transience in time, investigations on the shear bands in metallic glasses are extremely difficult. The liquid-like layer frozen on fracture surfaces suggests a decreased viscosity in the shear band. Whether it is resulted from locally heating remains controversial. In this paper, the temperature rise in shear bands is profiled as a function of the duration of shear banding event, the distance from the shear band center and the thickness of shear band. The elastic energies released from the specimen and the testing machine are estimated regarding the serrations with different load drops in the compressive load–displacement curve of a Zr-based metallic glass. The duration of shear event and the released energy by serration are the two main factors determining the temperature rise in shear bands. It is found that both "cold" and "hot" shear bands are attainable. Then the sliding speed, the viscosity and the crystallization probability of shear band are studied. These results can help to better understand and describe the operation of shear band in a quantified and analytical way.

1. Introduction

Although various parameters (e.g. Poisson's ratio [1–4], free volume [5–7], structure heterogeneity [8–10], local symmetry [11]) have been extensively proposed and argued in identifying the plasticity of metallic glasses (MGs), a broad consensus is that the plastic deformation in MGs is truly and wholly dominated by shear bands [12,13]. The proliferation of shear bands is considered as the necessary prerequisite for the plasticity in MGs [8]. The shear band itself, therefore, has been investigated from different aspects [12,13]. First and foremost, the temperature in an operating shear band is supposed to rise as a result of locally heating [13], with an estimated range from 0.05 K based on nanoindentation tests [14] to 900 K as suggested from tension tests [15]. Using a fusible coating, Lewandowski et al. [16] estimated that the temperature rise could approach a few thousand kelvin, which was usually thought to result in melting of the material in the shear band, thus leading to prominent vein patterns and liquid droplets on the fracture surface of fractured MGs. Wright et al. [17–19] believed that the final fracture process, rather than the shear event, results in melting on the fracture surface [19] because the temperature rise was no more than 209 K in the shear band [17], which was not high enough to melt the alloy.

A critical factor that has to be considered when trying to estimate the temperature rise is the thickness of the shear band, which is closely connected with the volume and therefore the heat capacity of the shear band. However, up to date, the exact value of the thickness is still under debate [20]. It was found that the shear band thickness was 10–20 nm in $Fe_{40}Ni_{40}B_{20}$ MG [21], and about 100 nm in $Ni_{50}Pd_{30}P_{20}$ MG [22], based on transmission electron microscopy (TEM) observations. In comparison, the liquid-like layer on the fracture surface of failed MGs is usually several micrometers thick according to scanning electron microscopy (SEM) observations [13]. Nevertheless, the thickness of a single shear band formed in a uniaxially compressed $Zr_{69.5}Cu_{12}Ni_{11}Al_{7.5}$ MG was measured to be 160 μm by nanoindentation [23]. Clearly, the discrepancy is considerable.

Furthermore, the duration of a shear banding event is another factor affecting temporarily temperature rise, and is also still under dispute [13]. It has been reported to be 560 μs as measured by high frequency imaging at 12.5 kHz [19]. An upper bound of the duration, 2–6 ms, was also observed by high frequency imaging, which was consistent with the displacement–time relation for a

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http://dx.doi.org/10.1016/j.msea.2015.10.125
0921-5093/

steady-state shear in compression [24,25]. Moreover, the low bound of the duration of the shear banding event was reckoned to be ~1 ns [16]. It is evident that the shear banding duration has a very large range that covers six orders of magnitude between the upper bound and low bound values.

As a consequence, we can pose a question: how hot are the shear bands in metallic glasses? To address this issue, the constitutive equations concerning the above two critical variables, i.e., the thickness of the shear band and the duration of shear-banding event, the intrinsic properties (e.g. thermal diffusivity) of MGs, and the extrinsic conditions (e.g. testing-machine stiffness) of the measurements are required to give a reasonable evaluation of the temperature rise. This is of importance not only for understanding the dynamics of shear banding but also for toughening metallic glasses.

In this paper, the energy transferred from the testing machine and the elastically strained matrix of the MG to the thin shear band is investigated. The energy absorbed by the shear band is partly consumed to increase the temperature of shear-band material, and partly diffuses outside the shear band as heat. The temperature profile around the shear band is determined. Then the comprehensive examination on the sliding speed, the viscosity of the operating shear band as well as the probability of crystallization in the shear band is made. The compression tests of a $Zr_{41.25}Ti_{13.75}Ni_{10}Cu_{12.5}Be_{22.5}$ (at%) MG (Vitreloy 1) are used to confirm the theoretical analysis.

2. Experimental methods

Vitreloy 1 alloy ingot was fabricated by arc-melting pure metals under a Ti-gettered purified argon atmosphere, followed by suction casting into a copper mold to form a rod of 2 mm in diameter and 65 mm in length. Its glassy structure was ascertained by X-ray diffraction (XRD). Compression test specimens were cut from the as-cast MG sample by a diamond saw with cooling water, having a height of 4 mm and a diameter of 2 mm. Compression tests were conducted using an Instron 8562 machine at a strain rate of $2.5\times10^{-4}\,s^{-1}$. APHENOM™ G2, FEI, a scanning electron microscope (SEM), was used to observe the fractography.

3. Results and discussion

3.1. Energy conservation in a shear banding event

At room temperature, the shear banding events in malleable MGs (e.g., Pt- [1] and Zr- [8] based MGs) are characterized as a series of serrations in the plastic regime of the compression load–displacement curves at a quasi-static strain rate [12,26]. Usually, these serrations are conceptually ascribed to the successive formations of multiple shear bands [1,8], or intermittently sliding of a single primary shear band [27,28]. Recently, both ex-situ [27,28] and in-situ [19] observations have corroborated that the plastic deformation of MG proceeds mainly by iterative sliding of one part of the specimen over another along a primary shear band. Few secondary shear bands are able to form unless the primary shear band is arrested artificially [8,29]. Therefore, in the present study, one shear banding event is phenomenally simplified to correspond to one serration in the load–displacement curve. Theoretically, the shear band can propagate in two possible ways, i.e., in simultaneous manner or in progressive manner [13]. Recent in-situ video filmed by high frequency camera, however, demonstrates the simultaneous way is more preferable [19], at least within the revolution limit of the employed camera. So, the shear is treated in the simultaneous manner in the present study.

A representative load–displacement curve for the compression test of a malleable MG is illustrated in Fig. 1a. According to the amplitude size of the serrations, we classify the serrations into three types, i.e., medium serration (i.e., nos. 1 and 2), large serration (i.e., no. 3), and small serration (i.e., no. 4), as marked by red arrows in Fig. 1a. The elastic energy, ΔE, released from the testing system during a shear banding event, is sketched in Fig. 1a, and can be expressed as,

$$\Delta E = \frac{1}{2k}\left(F_p^2 - F_v^2\right), \tag{1}$$

where $k=k_sk_m/(k_s+k_m)$ ($k_s=EA/l$, E is Young's modulus, A is the cross-section area of the specimen, and l is the length of the specimen; k_m is the stiffness of the machine) [28,30], and F_p and F_v are the peak and valley load values of the serration, respectively. Thus, $\Delta F=F_p-F_v$ in Fig. 1a. In Fig. 1b, the testing machine can be simplified as a spring because it is actually not ideally rigid [31,32].

If the temperature of the shear band increases by ΔT above the ambient temperature (~300 K), the required energy, ΔE_H, must be

$$\Delta E_H = 2A'h\rho c\Delta T, \tag{2}$$

where h is the half thickness of the shear band (see details in Fig. 1c), ρ is the density, c is the specific heat of the material. Because the shear band slides along the shear plane in a simultaneous way through the sample, $A'=A/\sin\theta$ (θ is the angle between the shear plane and the loading direction, as shown in Fig. 1b). If the shear-banding event is fast enough, the heat conduction will be negligible, which is so-called adiabatic shear [33]. However, the shearing process cannot be fully adiabatic because the heat diffusion is, more or less, inevitable [13,16,34,35,41,42]. Regarding the heat diffused outside the shear band, Q, during the shear banding event, we can easy to obtain

$$\Delta E_H = \alpha\Delta E - Q, \tag{3}$$

where α is a dimensionless factor considering the fraction of ΔE transferred into the shear band [28–33].

3.2. Model of a shear band with zero thickness

Eqs. (1)–(3) provide a necessary but rough description of the shear-banding event based on energy balance. Lewandowski and Greer idealized the shear band with a zero thickness, and treated it as a planar heat source [16]. They then gave the temperature rise, ΔT, as a function of time, t, and distance, x, expressed as

$$\Delta T = \frac{H}{2\rho c\sqrt{\pi\kappa t}}\exp\left(-\frac{x^2}{4\kappa t}\right), \tag{4}$$

where H is the heat content per unit area, and κ is the thermal diffusivity. Clearly, at the position of $x=0$ and the initial time of $t=0$, the temperature rise, ΔT, is a singularity, i.e., $\Delta T\to\infty$. This indicates two points. One is that the idealization, i.e., the zero thickness of shear band, is not a true physical fact, and the other one is that the energy transfer from the sample–machine system into the band is neither adiabatic nor instantaneous. Keeping the thickness of the shear band as zero, and the elapsed time of the energy transfer to be δt, one can profile the temperature rise as a function of t as [19,35,42]

$$\Delta T = \frac{f}{K}\left[\sqrt{\frac{\kappa t}{\pi}}\exp\left(-\frac{x^2}{4\kappa t}\right) - \frac{x}{2}\mathrm{erfc}\left(\frac{x}{2\sqrt{\kappa t}}\right)\right] \qquad (t<\delta t), \tag{5}$$

where f is the heat flux per unit area and per unit time, K is the thermal conductivity and erfc is the complementary error function. Wright et al. [19] suggested,