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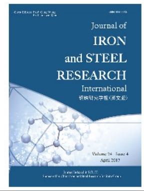

Statistical analysis on strain-rate effects during serrations in a Zr-based bulk metallic glass

Bo Yuan[1], Jiao-jiao Li[1], Jun-wei Qiao[1,2,*]

[1] College of Materials Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, Shanxi, China

[2] Key Laboratory of Interface Science and Engineering in Advanced Materials, Ministry of Education, Taiyuan University of Technology, Taiyuan 030024, Shanxi, China

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ABSTRACT

By means of statistical analysis, the deformation mechanisms taking place in elastic loading and plastic shearing stages during serrated flows on the stress-strain curves for bulk metallic glasses were studied comprehensively. Normalized serration number presented a linear increasing tendency with the decrease of applied strain rates due to the reduction of free volumes. An excellent plastic deformation was illustrated from the influences of structure arrangement with activation energy. By using mean-field theory (MFT), maximum elastic-energy density at different strain rates could be predicted by MFT besides maximum stress drops during serrations. These results were helpful for understanding the serrated flow behavior or designing decent schemes to improve the plasticity of bulk metallic glasses at room temperature.

1. Introduction

Bulk metallic glasses (BMGs) are viewed as a relatively new class of materials, which exhibit large elastic limit, high strength, and excellent wear and corrosion resistance[1,2]. These outstanding mechanical properties make BMGs to be potential as structural materials. Besides the confinement of crystal lattices and crystalline defects such as dislocations, the plastic deformation in BMGs is caused by rapid propagation of shear bands[3]. However, the poor plasticity at room temperature severely restricts the applications of BMGs as structural materials. Shear localization and strain or thermal softening may induce poor plasticity[2]. Significant attempts have been made to improve plasticity by changing internal and external conditions at room temperature: (1) changing internal stress state via pre-compression before yielding to increase free volumes and even produce nanocrystals in the glass matrix[4]; (2) depositing films on the surface of BMGs[5,6], which could provide high radial confinement stress, leading to more homogeneous formation of high-density shear bands; (3) introducing in-situ crystalline phases into the glass matrix to restrict shear-sliding along primary shear plane[7]; (4) lowering the aspect ratio of testing samples, revealing serrated flow dynamics from a chaotic state to a self-organized critical state[8]. As it is known, changing internal and external conditions are considered to be effective approaches to improve room-temperature plasticity. However, the deformation mechanisms in BMGs still remain elusive.

There are different plasticities at different strain rates in BMGs, corresponding to various serration shapes[9]. The serrated flow on stress-strain curves in BMGs is still a mystery, and the physical meaning has not been completely understood. Up to now, some theories about the plastic deformation mechanisms in BMGs have been successfully proposed, which may describe the serration dynamics in detail, including the classical free volumes[10], shear-transformation zones (STZs)[11], and tension-transformation zones (TTZs) modes[12,13]. Usually, serrations are associated with the nucleation or propagation of shear bands, in which STZs are considered as a basic shearing unit in BMGs[11]. Each serration is composed of two portions: the stress ascending and sharp stress drop on the stress-strain curves, which are taken as the elastic loading and the release of the strain energy, respectively. Thurnheer et al.[14] used a high-speed infrared camera equipped with an InSb detector to show five stages during

* Corresponding author. Prof., Ph.D.
E-mail address: *qiaojunwei@gmail.com* (*J.W. Qiao*).

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each serration: the end of elastic loading; the start of stress drop at a moderate rate; the increase of stress drop rate suddenly, which coincides with the onset of the temperature rise; the level of reaching the bottom stress; and the reduction of stress drop rates as well as the transition toward slow reloading. Despite these common senses have been reached, the ability to improve the plasticity of BMGs is often limited upon compression, and even the understanding of the serration and the shear banding still needs to be focused on in detail[15].

In this study, classical statistical analysis methods were used to explore several processes to illustrate corresponding relation with plasticity during plastic deformation at different strain rates. A linear relation between normalized serration numbers and applied strain rates was clearly presented. The slopes during stress ascending (L) demonstrated a regional distribution rather than a constant. The ratios of the stress dropped to elastic-energy density during serrations were mostly viewed as a steady value at different strain rates so that elastic-energy density might be predicted using mean-field theory (MFT).

2. Experimental Procedure

Alloy ingots with a nominal composition of $Zr_{52.5}$-$Ti_5Cu_{17.9}Ni_{14.6}Al_{10}$ (Vit105) were prepared by arc melting a mixture of pure metal elements (with weight purity of no less than 99.9%) in a Ti-gettered argon atmosphere. In order to avoid chemical inhomogeneity, each ingot was remelted at least five times. Subsequently, the cylindrical rods were prepared by suction casting into a water-cooled copper mold with a diameter of 2 mm and a length of about 70 mm. The two compression planes of testing specimens were polished so as to guarantee parallelism with an aspect ratio (height to diameter) of 2 : 1. Uniaxial compression tests were conducted using cylindrical samples with diameter of 2 mm. The uniaxial-compression tests were conducted on the cylindrical specimens using Instron 5969 materials-testing machine at the strain rates of 2×10^{-2}, 2×10^{-3}, 2×10^{-4}, and 2×10^{-5} s^{-1} at 298 K (room temperature). Besides, a method of data collection setting the stress change 1 MPa was used to collect a data point so that the stress fluctuation caused by machine vibration can be effectively avoided on the engineering stress-strain curves. After fracture, the fracture morphology was observed to identify the deformation mechanisms by scanning-electron microscope (SEM).

3. Results and Discussion

Fig. 1(a) exhibits the engineering stress-strain curves at different strain rates of 2×10^{-2}, 2×10^{-3}, 2×10^{-4}, and 2×10^{-5} s^{-1} until final failure at 298 K, with the joggle of mechanical machine shown in the inset. It can be seen that the stress fluctuation nearly disappears at the strain rate of 2×10^{-2} s^{-1}, and the stress-strain curves at other strain rates of 2×10^{-3}, 2×10^{-4}, and 2×10^{-5} s^{-1} clearly present serrations during plastic flows after yielding. The serration process is characterized by repeating cycles of a sudden stress drops, followed by reloading elastically, as shown in Fig. 1(b). The disappearance of serrations with increasing the strain rates has been found in the nanoindentation tests[1,16] and the displacement-controlled compression experiments[17,18]. The plastic strains vary from about 8.4% (2×10^{-5} s^{-1}) to about 17.3% (2×10^{-4} s^{-1}), and the maximum stress is about 2200 MPa. The inset in Fig. 1(a) shows the stress fluctuation on stress-strain curves at elastic stage due to the vibration of testing machine, and the fluctuation amplitude is measured to be about 0.6 MPa. The magnification of the serration events at the strain rate of 2×10^{-4} s^{-1} is shown in Fig. 1(b). Interestingly, there are several small stress declines before a large stress-drop event at the strain rate of 2×10^{-4} s^{-1}. Moreover, it has been demonstrated that, once yielding, the strain energy dissipates within thin shear layers, which leads to atomic rearrangement instantly due to adiabatic heating[19]. Thus, it seems that the generation of free volumes due to structure rearrangement causes multi-step shearing.

Although the feature of serrations can be identified on the engineering stress-strain curves, as shown in Fig. 1(b), it is still difficult to formulate the stochastic magnitude with the strain and analyze serration dynamics. Here, the normalized serration numbers (N/ε_n) at different strain rates are plotted in Fig. 1(c). N and ε_n refer to total serration numbers and total plastic strain for a single stress-strain curve, respectively. N/ε_n can be understood briefly as serration formation ability. Apparently, a good linear relation between N/ε_n and four different strain rates is obtained. It is well known that the shear deformation in BMGs is closely related with the creation and annihilation of free volumes[20]. During the steady-state deformation, the creation and annihilation rates of free volumes are the same, and the relationship between the strain rate and average free volumes per atom can be established as follows[15,20]:

$$\dot{\varepsilon}=kV_f\exp\frac{\alpha V^*}{V_f} \qquad (1)$$

where, $\dot{\varepsilon}$ is the applied strain rate; k is a constant; V_f is the average free volumes of an atom; α is a constant between 0.5 and 1.0; and V^* is the effective hard-sphere volume of atoms. From Eq. (1), it can be concluded that the higher the strain rate is, the more free volumes are created. More free volumes facilitate the generation of serrations with a