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Intrinsic versus extrinsic effects on serrated flow of bulk metallic glasses

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ABSTRACT

In this work, we systematically investigate the serrated flow behavior in the compression of bulk metallic glasses by varying the intrinsic composition and various extrinsic material and experimental factors including the sample size, the strain rate, and the testing machine stiffness. We find that the serrated flow, characterized by the amplitude of load serrations, can be suppressed for the higher Young's modulus, larger sample size, higher strain rate, and larger testing machine stiffness, respectively, and that it could completely disappear at certain critical strain rates. Meanwhile, the shape of serrated flow, which tends to become more "blunt", manifests as the increasing ratio of the duration time to the awaiting time of the serrated events. The dependence of the serrated flow on these various factors is interpreted from the stick-slip dynamics of a single dominant shear band in compression process and can be condensed into a unified theoretical parameter k/k_{cr}, where k is a parameter dependent on the Young's modulus, the sample size and the machine stiffness, and k_{cr} is expressed as a function of temperature and testing strain rate. The implication of the stick-slip shear band dynamics together with the tuning of these material factors and test parameters will lead to the design of ductile BMGs.

1. Introduction

As a new class of advance metallic material, bulk metallic glasses (BMGs) have absorbed considerable research interests, due to their attractive properties and wide potential applications [1–4]. Compared to their crystalline counterparts, however, many aspects of the disorder structure-property relationship for BMGs are poorly understood [5]. This is particularly applied to their plastic deformation process [6–8]. At room temperature, the plastic flow of BMGs is well known to be a spatially inhomogeneous process with the plastic strain localized into nanoscale shear bands [9–11], which is different from the dislocation-mediated plasticity in crystalline materials. Once initiated, one shear band will become strain softening, and could lead to the catastrophic failure of BMGs. Thus, the shear banding process is directly related with the macroscopic mechanical behaviors such as yielding and fracture [12–15] and elucidating the physical mechanism underlying the shear banding process, is not only of fundamental interests for disorder materials, but also of practical interests for the controlling and designing ductile BMGs.

Besides the spatial inhomogeneity, the plastic deformation of BMGs are also temporal inhomogeneous, which is manifested as the serrated flow behavior in load-constraint modes (such as compression and nanoindentation) [16–19]. In general, serrated flow reflects the intermittent shear-band activity, but the correlation between serrated flow and the number of shear bands participated in the serrated event, i.e. one serrated event corresponds to the operation of a single shear band or multiple shear bands, is still controversial. This ambiguity on the correlation between shear bands and serrations, however, now becomes much clearer in the case of compression. A series of recent studies [11,12] have found that serrated flow in the compression of BMGs is closely related with the intermittent or stick-slip shear banding process along the main dominant shear plane. This provides a basis to characterize the dynamic properties of a single shear band [9,20],

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e.g. shear band velocity, propagation time and viscosity, etc. Thus, characterizing the serrated flow is important to understand the shear-band dynamics in BMGs.

In addition, the shear stability of BMGs (often reflected from the ductility) has also been found to be a complex process, which depends on not only the intrinsic glassy structure [21,22] and the internal state [23,24], but also various extrinsic material properties and experimental factors (deformation rates, sample sizes and machine frame stiffness or second crystalline phases) [12,25–31]. As serrated flow is a reflection of the temporal behavior of shear bands, it is expected that these factors will have an effect on the serrated flow behavior. Indeed, it has been found that the temperature and the strain rate can affect the serrated flow, that is, serrations tend to be suppressed at lower temperatures [18,32,33] or higher strain rates [18]. However, a systematic investigation on these effects as well as a thorough interpretation of the underlying mechanism is still missing. In this letter, we experimentally studied the effects of various extrinsic and intrinsic factors (elastic modulus, machine stiffness, sample size, strain rate and the testing temperature) on the serrated flow behavior of BMGs, in an attempt to extract the underlying shear-band dynamics. We also interpreted these effects from the stick-slip shear band dynamics with a constitutive law derived from the atomic-scale deformation theory for BMGs.

2. Experimental procedures

BMG alloys with various compositions and elastic constants are chosen in this study. Alloy ingots with nominal compositions listed in Table 1 are prepared by the arc-melting of mixtures of pure elements in a Ti-gettered argon atmosphere and then were suck into the copper mold. Cylinders glassy rods of different diameters (1 mm, 1.5 mm, 2 mm, 2.5 mm and 3 mm) with a length of about 20–50 mm were obtained. The amorphous nature of as-cast specimens were examined by the X-ray diffraction (XRD, PANalytical X′ Pert PRO) with Co *Kα* radiation and differential scanning calorimetry (DSC, Perkin Elmer DSC7). Uniaxial compression tests were mainly performed the electromechnical testing machine Instron 5869 under various conditions (such as different compositions, different sample sizes and different strain rates) at the room temperature. To examine the influence of the testing machine stiffness on the serrated flow, we also performed some compression tests on other testing machines (Instron 3384 and MTS SANS 4304). All samples for the compression have an aspect ratio (the height to the diameter) of 2:1. At least three specimens are tested at the same experimental condition. During the compression test, the time, load, displacement were recorded and stored at a frequency of 50–200 Hz depending on the testing strain rate. The testing machines are also loaded without sample to obtain the load–displacement curves, from which the machine stiffness can be obtained. After deformation, the morphology of shear bands and fracture surfaces were examined with a high-resolution scanning electronic microscopy (SEM, Gemin 1530).

3. Results

3.1. Deformation behavior of BMGs under various conditions

We first performed compression tests on the BMGs with various compositions and modulus values (as listed in Table 1) while keeping other experimental factors fixed. Fig. 1(a) shows the stress–time curves of different BMGs for the 2 mm-diameter samples compressed at a strain rate of 2.5×10^{-4} s^{-1} with the Instron 5869. Obviously, these BMGs display different deformation behaviors such as different yield strengths, and plastic strains as manifested as different testing times. Despite these differences, all curves display obvious serrated flow behavior in the plastic deformation regime after yielding at an elastic strain about 2%. A typical enlarged view of serrated event (Vit105, $d = 1.5$ mm at $\dot{\varepsilon} = 2.5 \times 10^{-4}$ s^{-1}) is shown in Fig. 2. One can see that the serrations are characterized by the repeated cycles of the sudden stress drop part followed by the slow elastic reloading part. As has been studied by many recent studies [34,35], the serrated flow in most monolithic BMGs (except some ductile BMGs [36–38]) reflects the intermittent or stick-slip shear banding process along the primary shear plane where the sudden stress drop corresponds to the rapid shear band operation, whereas the elastic reloading corresponds to the arrest of the band.

Table 1
The composition, Young's modulus E, the sample diameter d, the deformation strain rate $\dot{\varepsilon}$, the calculated k, the experimentally mean stress drop magnitude $\boldsymbol{\sigma_N}$, the serration lasting time t_L and awaiting time t_W, for BMGs samples under various intrinsic and extrinsic conditions.

Composition	E (GPa)	d (mm)	$\dot{\varepsilon}$ (s^{-1})	κ_M (10^7 N m^{-1})	k (10^{12} Pa m^{-1})	σ_N (MPa)	t_L (s)	t_W (s)
$Zr_{70}Ni_{16}Cu_6Al_8$	68	2	2.5×10^{-4}	9.4655	10.868	$15.504\pm^{5.640}_{4.848}$	$0.0971\pm^{.00942}_{.00942}$	$1.524\pm^{.0886}_{.2070}$
$Zr_{65}Ni_{10}Cu_{15}Al_{10}$	82	2	2.5×10^{-4}	9.4655	12.200	$14.199\pm^{4.063}_{2.292}$	$0.0977\pm^{.00968}_{.00968}$	$0.9264\pm^{.1848}_{.1556}$
$Zr_{52.5}Ti_5Cu_{17.9}Ni_{14.6}Al_{10}$ (Vit105)	88	2	2.5×10^{-4}	9.4655	12.715	$10.694\pm^{3.758}_{4.612}$	$0.104\pm^{.017}_{.017}$	$0.9179\pm^{.2403}_{.1893}$
$Zr_{56}Co_{28}Al_{16}$	92	2	2.5×10^{-4}	9.4655	13.043	$11.823\pm^{4.925}_{4.925}$	$0.129\pm^{.0380}_{.0380}$	$0.9589\pm^{.0538}_{.0538}$
$Ti_{45}Zr_5Cu_{45}Ni_5$	110	2	2.5×10^{-4}	9.4655	14.377	$5.442\pm^{1.600}_{1.600}$	$0.0787\pm^{.00398}_{.00398}$	$0.6575\pm^{.2686}_{.2686}$
$Cu_{60}Zr_{20}Hf_{10}Ti_{10}$	130	2	2.5×10^{-4}	9.4655	15.635	$5.596\pm^{2.947}_{2.600}$	$0.0793\pm^{.00109}_{.00109}$	$0.5544\pm^{.1822}_{.1871}$
$Zr_{65}Ni_{10}Cu_{15}Al_{10}$	82	2	2.5×10^{-4}	1.752	4.384	$23.710\pm^{2.476}_{2.476}$	$0.113\pm^{.00932}_{.00932}$	$2.248\pm^{.2530}_{.2530}$
$Zr_{65}Ni_{10}Cu_{15}Al_{10}$	82	2	2.5E-4	13.488	13.875	$12.764\pm^{2.235}_{2.235}$	$0.0822\pm^{.00122}_{.00122}$	$0.2982\pm^{.0230}_{.0230}$
Vit105	88	1	5×10^{-4}	9.4655	32.232	$14.507\pm^{1.381}_{1.381}$	$0.0748\pm^{.00709}_{.00709}$	$0.6590\pm^{.0259}_{.0259}$
Vit105	88	1.5	3.3×10^{-4}	9.4655	18.954	$9.086\pm^{1.082}_{1.082}$	$0.0754^{+.00983}_{-.00130}$	$0.4817\pm^{.0153}_{.0084}$
Vit105	88	2.5	2×10^{-4}	9.4655	9.202	$12.772^{1.177}_{1.177}$	$0.0750^{+.0069}_{-.0069}$	$0.6980\pm^{.02124}_{.02124}$
Vit105	88	3	1.67×10^{-4}	9.4655	6.999	$19.112\pm^{1.183}_{1.183}$	$0.103^{+.00431}_{-.00431}$	$1.246\pm^{.0623}_{.0623}$
Vit105	88	2	2.5×10^{-5}	9.4655	12.715	$20.875\pm^{1.087}_{1.087}$	$0.0928^{+.00380}_{-.00228}$	$1.931\pm^{.2490}_{.2490}$
Vit105	88	2	1.5×10^{-4}	9.4655	12.715	$9.619\pm^{0.840}_{0.840}$	$0.106^{+.00532}_{-.00532}$	$1.868\pm^{.1770}_{.1770}$
Vit105	88	2	2×10^{-4}	9.4655	12.715	$10.401\pm^{0.876}_{0.876}$	$0.0950^{+.00350}_{-.00268}$	$1.120\pm^{.2312}_{.2312}$
Vit105	88	2	5×10^{-4}	9.4655	12.715	$8.193\pm^{0.756}_{0.756}$	$0.0835^{+.00701}_{-.00701}$	$0.3624\pm^{.0331}_{.0331}$
Vit105	88	2	5×10^{-3}	9.4655	12.715	$3.729\pm^{0.756}_{0.756}$	$0.0387^{+.00292}_{-.00292}$	$0.05248\pm^{.00208}_{.00208}$
Vit105	88	2	1×10^{-2}	9.4655	12.715	$1.578\pm^{0.358}_{0.358}$	$0.0298^{+.00243}_{-.00243}$	$0.04277\pm^{.0041}_{.0041}$
Vit105	88	2	5×10^{-2}	9.4655	12.715	–	–	–