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Effect of size and base-element on the jerky flow dynamics in metallic glass

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Abstract

The jerky flow behavior of metallic glasses (MGs) is systematically investigated in this work for various alloy compositions, ranging from the commonly conceived "ductile" MGs, such as those based on Zr and Cu, to the "brittle" ones, such as those based on Mg and Fe, on the microscopic scale. Through extensive microcompression studies, a clear sample size and base-element dependence of the jerky flow in MGs is revealed, which shows that the stress-drop amplitude, as normalized by the corresponding MG yield strength, reduces with decreasing sample size or increasing elastic modulus. Meanwhile, the temporal discontinuity of the jerky flow, as characterized by the duration of the stress-drop event and the delay between two consecutive events, also displays similar size and base-element dependence. Finally, a unified theory based on stick–slip dynamics is proposed to explain the coupled size and base-element effects.

Keywords: Metallic glass; Serrated flow; Shear band; Size effect; Ductility

1. Introduction

The plastic deformation behaviors of bulk metallic glass (BMGs) have been studied extensively owing to their unique mechanical/physical properties [1–10]. Despite substantial efforts, however, a self-consistent theory has yet to be established to describe the deformation phenomena of BMGs across different length scales. At temperatures far below the glass transition points of metallic glasses (MGs), these materials typically deform by flow localization and consequently nearly all plastic strains sustained by a MG sample are confined to one or a few narrow shear bands [3,11–14], which is completely different from the dislocation-mediated deformation of crystalline alloys. Hence, a better understanding of the macroscopic deformation behavior of BMGs, such as yielding and fracture, relies on a thorough investigation of the shear-banding process and the underlying physics that controls the initiation and development of shear banding from the atomic scale to above.

In the BMG literature, the most representative mean-field theories proposed for the atomic scale flow mechanism include the free volume [15] and shear transformation zone (STZ) theory [16]. Although these theories have successfully explained many important deformation features, such as shear localization or shear-band formation from the perspective of shear-induced softening/dilation [2,17], bridging the gap between the macroscopic deformation behavior and these microscopic deformation theories nevertheless still presents a major challenge. One typical example is the jerky flow that has been widely observed during the plastic deformation of BMGs [18–23].

In general, a jerky flow manifests itself as repeated cycles of a rapid load/stress drop followed by elastic reloading in the compressive stress–strain curve [20,21,23,24] or discrete pop-ins in the nanoindentation of BMGs [25,26]. Recent experiments by Chen et al. [18] showed that the jerky flow in BMGs is due to an intermittent or stick–slip-type shear banding process. In that regard, the jerky flow, as a direct

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reflection of the temporal behavior of shear banding, can be used to characterize the dynamic properties of shear bands, such as the shear-band velocity [27–29], the temperature rise [11,12,30] and the shear-band viscosity [31,32]. Despite extensive investigations, the connection between jerky flow and the distinctive plastic/fracture behavior in different MGs is still poorly understood.

Under uniaxial compression, the behavior of shear bands in MGs is rather complicated, which is related not only to various intrinsic factors, such as the Poisson's ratio [10,33], the glass transition temperature [34] and the elastic modulus of MGs [4], but is also affected by a number of extrinsic factors, such as the size/shape of the MG sample [33,35–39] and the machine stiffness [6,11,40]. Regardless of these complexities, some BMGs, such as those based on Pd and Zr, appear more ductile than others, such as those based on Mg and Fe, provided that all external conditions remain identical [41]. These facts indicate that, in addition to its well-recognized size dependence [6,37], shear banding in BMGs should also have a strong compositional dependence. To understand the coupled size and compositional effect, we have performed a systematic investigation of the jerky flow behavior of MGs with four different alloy compositions, i.e. based on Mg, Cu, Zr and Fe, respectively. To avoid brittle-like fracture, we used micropillars to deform these MGs, because extensive plastic flows develop in MG micropillars via stable shear banding; as a result, the compositional dependence of the jerky flow could be revealed.

2. Materials and methods

The nominal chemical compositions of the four MGs are $Mg_{58}Cu_{31}Nd_5Y_6$, $Cu_{46.25}Zr_{44.25}Al_{7.5}Er_2$, $(Fe_{44.3}Cr_5Co_5Mo_{12.8}Mn_{11.2}C_{15.8}B_{5.9})_{98.5}Y_{1.5}$ and $Zr_{55}Cu_{30}Ni_5Al_{10}$ (in at.%). For brevity, descriptions of the fabrication process are omitted here; interested readers may refer to Refs. [42–44] for details. To obtain flow-serration data within the stable shear-banding region, micropillars of different sizes, as listed in Table 1, with diameters ranging from 2 to 8 μm and height from 8 to 18 μm, were fabricated using the focused ion beam (FIB) technique on a FEI Quanta 200 3D FIB/SEM Dual-Beam™ System (FEI Company, Hillsboro, OR, USA). A sequential-milling approach was utilized for the shaping and final trimming of the micropillars in order to minimize FIB-induced damage [45], and this method resulted in a taper angle of 1°–3°. Details of the FIB milling were given in Refs. [39,44] and are also omitted here for brevity. Following sample preparation, the microcompression experiments were carried out under displacement control on a Triboscope™ Nanoindentation System (Hysitron, Minneapolis, MN, USA), which was equipped with a 10 μm flat-end conical diamond indenter. Note that the machine stiffness of the nanoindentation sys-

Table 1
Summary of the size of the micropillar including the diameter D, the height H, the applied nominal strain rate $\dot{\varepsilon}_a$ and the true strain rate $\dot{\varepsilon}_t$, the characteristic parameters of the jerky flow including the mean value of the stress drop magnitude $\Delta\sigma_N$, the duration t_L and the delay t_W, and the basic mechanical properties including the Young's modulus E and the yield strength σ_y for the Mg-, Fe-, Cu- and Zr-based MGs.

Sample	D (μm)	H (μm)	$\dot{\varepsilon}_a$ (10^{-3} s^{-1})	$\dot{\varepsilon}_t$ (10^{-3} s^{-1})	$\Delta\sigma_N$ (MPa)	t_L (s)	t_W (s)	E (GPa)	σ_y (GPa)
Mg-based	2.32	12.54	6.5	5.3	108 ± 24	0.06 ± 0.01	0.18 ± 0.08	56	0.95
	2.32	10.06	6.5	5.2	208 ± 76	0.06 ± 0.01	0.25 ± 0.10	53	1.34
	4.02	8.53	6.5	4.6	329 ± 100	0.08 ± 0.02	0.67 ± 0.26	52	1.1
	6.3	14.47	6.5	4.6	241 ± 91	0.12 ± 0.02	0.58 ± 0.20	52	1.08
	6.67	12.36	6.5	4.5	334 ± 120	0.08 ± 0.02	0.68 ± 0.25	52	1.12
	8.5	15.71	6.5	4.5	460 ± 141	0.14 ± 0.02	1.18 ± 0.43	50	1.02
	7.5	18.5	6.5	4.5	304 ± 122	0.07 ± 0.01	0.61 ± 0.21	50	1.15
Fe-based	3.33	8.37	6.5	4.7	123 ± 22	0.10 ± 0.02	0.2 ± 0.03	233	3.13
	3.18	9.29	6.5	4.9	426 ± 68	0.10 ± 0.01	0.31 ± 0.05	231	4.27
	5.57	11.63	6.5	4.5	384 ± 97	0.17 ± 0.02	0.4 ± 0.07	234	4.00
	5.37	12.76	6.5	4.7	157 ± 13	0.15 ± 0.01	0.28 ± 0.02	225	3.46
	5.57	13.50	6.5	4.7	490 ± 137	0.17 ± 0.02	0.41 ± 0.08	233	3.47
	7.68	13.4	6.5	4.3	273 ± 132	0.19 ± 0.02	0.36 ± 0.08	229	3.08
Cu-based	2.07	7.42	6.5	5.1	356 ± 44	0.08 ± 0.02	0.24 ± 0.06	103	2.35
	4.12	8.64	6.5	4.6	231 ± 73	0.10 ± 0.02	0.40 ± 0.1	109	2.17
	5.32	15.48	6.5	4.9	207 ± 60	0.10 ± 0.01	0.45 ± 0.09	92.6	2.27
	5.12	15.4	6.5	4.9	169 ± 23	0.10 ± 0.01	0.27 ± 0.06	98.7	2.31
	7.7	16.4	6.5	4.6	99 ± 27	0.12 ± 0.02	0.30 ± 0.05	94.7	2.13
	7.26	17.91	6.5	4.7	207 ± 53	0.12 ± 0.02	0.39 ± 0.07	94	2.21
Zr-based	3.09	13.42	6.5	5.2	142 ± 35	0.06 ± 0.01	0.26 ± 0.05	98	1.87
	3.13	11.96	6.5	5.2	164 ± 58	0.07 ± 0.01	0.29 ± 0.07	95	1.83
	5.2	18.3	6.5	5.1	209 ± 60	0.08 ± 0.01	0.32 ± 0.1	94	1.82
	5.37	16.26	6.5	4.9	200 ± 36	0.09 ± 0.01	0.36 ± 0.07	90	1.68
	5.65	13.87	6.5	4.7	130 ± 48	0.09 ± 0.01	0.26 ± 0.06	90	1.91
	7.68	18.04	6.5	4.6	216 ± 32	0.12 ± 0.02	0.66 ± 0.11	87	1.82
	7.91	16.9	6.5	4.6	426 ± 100	0.13 ± 0.01	0.66 ± 0.18	84	1.91