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Short Communication

Inhomogeneous creep deformation in metallic glasses

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ABSTRACT

Homogeneous creep is a commonly observed phenomenon in bulk metallic glasses. Here we reported inhomogeneous creep behavior that occurs under nanoindentation when the applied stress exceeds the yield stress. Extensive investigation showed that inhomogeneous creep is associated with the local microstructure and the operation of shear bands before creep. The mechanism responsible for inhomogeneous creep is discussed.

1. Introduction

Plastic deformation behavior of bulk metallic glasses (BMGs) has received significant attention since it is a key factor that limits the potential structural applications of BMGs [1–3]. The plastic deformation of BMGs is associated with multi-atom rearrangements in weak regions, which are referred to as shear transformation zones (STZs), with excessive free volumes or slightly low mass densities [4–5]. There are two types of plastic deformation in BMGs [4–6]. One is homogeneous flow, in which shear mediated strain is accommodated by independent STZs [4–6]. The other is inhomogeneous flow via localized shear banding events triggered by the avalanches of atomic rearrangements in coupled STZs [4–9].

Creep, as a time-dependent plastic deformation, is commonly observed in materials. Previous creep investigations were normally conducted using either uniaxial compression [10–13] or indentation [14–19]. Creep tests under uniaxial compression are always conducted below the yield stress to prevent catastrophic failure caused by localized shear banding events. Molecular dynamics simulations and elastostatic uniaxial compression tests of BMGs demonstrated that homogeneous deformation occurs as a result of irreversible structural disordering [10–13,20–21]. In a nanoindentation creep test using a sharp indenter, the applied stress can exceed the yield stress. This leads to dislocation avalanches and therefore inhomogeneous or step-like creep behavior in crystalline materials [22–24]. Analogy to crystalline materials, the avalanches of coupled STZs or shear banding at the loading stage might also result in inhomogeneous creep in BMGs. However, previous nanoindentation creep tests of BMGs did not report any inhomogeneous creep behavior [14–19]. In this paper, multiple nanoindentation creep tests with the applied stress higher than the yield stress were conducted to demonstrate the existence of inhomogeneous creep. Possible reasons that influence the occurrence of inhomogeneous creep were explored in details.

2. Experimental

A cylindrical $Cu_{36}Zr_{48}Al_8Ag_8$ (atomic percentage) BMG master ingot with a diameter of 10 mm and a length of 60 mm was fabricated by arc-melting high-purity copper (99.99 wt%), zirconium (99.7 wt%), aluminum (99.9 wt%) and silver (99.9 wt%) in a Ti-gettered high-purity argon atmosphere using the copper mold suction casting method [25]. To ensure the compositional homogeneity, the ingot was re-melted four times and stirred using a magnetic beater. The cylindrical rod was cut into disks with a thickness of ~2 mm using a low speed diamond saw under water-cooling. Structural characterization of the disks was conducted using a Dmax 2500VB X-ray diffractometer with Cu-Kα radiation and a JEOL-2100F transmission electron microscope (TEM). Both X-ray diffraction and TEM observations confirmed the amorphous nature of the disks, as shown in Fig. 1. The disks were mechanically polished to a mirror-like surface and tested using an Ultra nanoindentation tester with a Berkovich diamond tip under the loading control mode. All the nanoindentation tests were carried out under the same condition with a loading rate of 0.01 mN/s and the load limit of 25 mN (stress of about 0.4–0.6 GPa, calculated by

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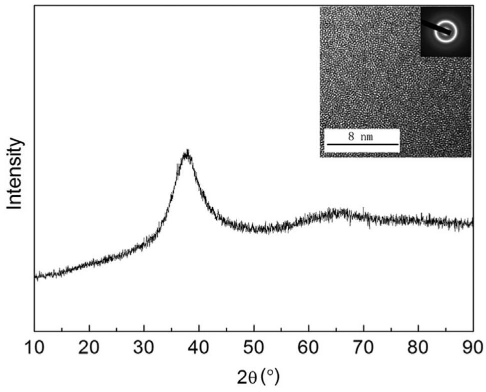

Fig. 1. An X-ray diffraction pattern, a high-resolution TEM image (inset) and the corresponding electron diffraction pattern of the BMG.

$\sigma \sim P/24.5h^2$, where P is the peak indentation load and h is the contact depth [26–27], being much higher than the yield stress of about 0.2 GPa [28]). At 25 mN, the load was held for 1000 s.

3. Results and discussion

Fig. 2a shows a typical complete nanoindentation displacement–time (*h*–*t*) curve that comprises the loading stage, the creep stage in which the load was kept constant, and the unloading stage. For the convenience of the discussion below, the loading stage is divided into L1–L5 parts. Enlarged L1 to L4 parts are shown in Fig. 2b, while enlarged L5 is inset in Fig. 2a. Different from smooth creep curves that have been reported before [14–19], creep curves with serrations were obtained in this study, as shown in the inset of Fig. 2a. As homogeneous creep deformation is always represented by continuous smooth creep curves, the many serrations, which are presented as sudden displacement jumps (or stress drops in stress–strain curves), shown at the creep stage in Fig. 2a indicates that the creep deformation occurred via inhomogeneous flow. Multiple tests under the same condition confirmed that inhomogeneous deformation is an intrinsic feature of creep for BMGs when the applied stress is higher than the yield stress. Our nanoindentation tests were carefully carried out to exclude any effect caused by external vibration.

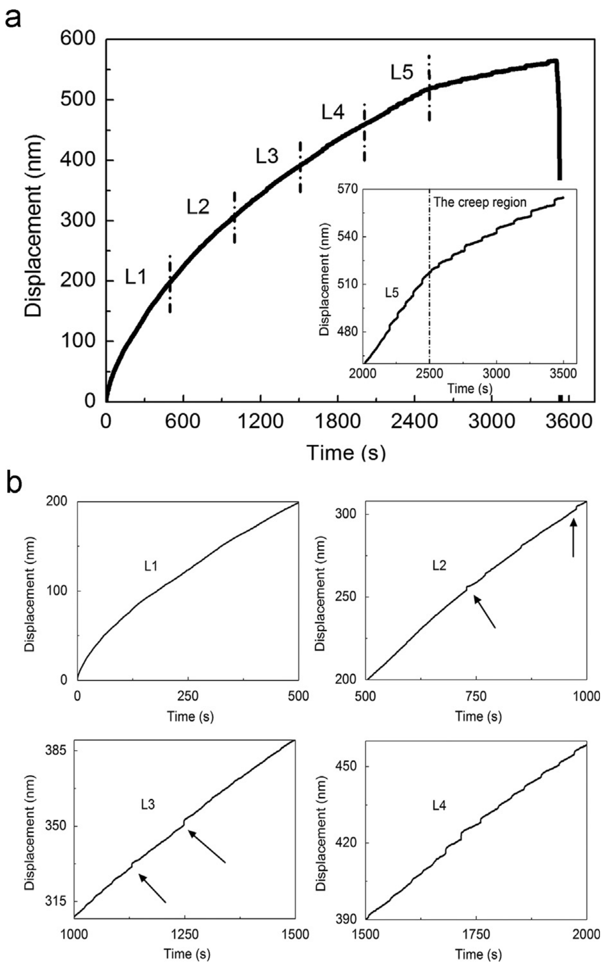

Fig. 2. (a) A typical complete nanoindentation *h*–*t* curve. The loading region of the *h*–*t* curve is divided into L1–L5 parts. The inset shows an enlarged L5 part and the creep region of the *h*–*t* curve. (b) Enlarged curves of L1, L2, L3, and L4. Arrows indicate the positions of large serrations in L2 and L3.

Different numbers of the serrations occurred at different parts of the loading stage with the indenter permeating into the sample gradually. It has been demonstrated that serrations were related to slip avalanches of STZs or shear banding [8–9,29–30]. Shear banding events lead to softening and increase substantially the free volume of plastically deformed regions [3–6]. The latter is likely to aid the subsequent operation of STZs during the creep process [17]. Meanwhile, it has been reported that nanocrystallization occurred as a consequence of shear banding events during nanoindentation [31]. The nanocrystallization processes led to slight local volume reduction because of the slightly higher density of nanocrystals than the surrounding amorphous matrix. This would increase the magnitude of the shear banding induced serrations via strong interaction between shear bands and nanocrystals [32]. In addition, as demonstrated in our previous investigation that structural diversity in different positions leads to different numbers and characteristics of serrations [33], the distribution of serrations also reflects the structural characteristic of plastic deformation under indenter. Soft regions being able to trigger numerous shear bands at the loading stage are also likely to result in inhomogeneous creep, compared to hard regions. Thus, the distribution of serrations at the loading stage is of significant importance for understanding the behavior of inhomogeneous creep.

The operation of shear bands could also be of great importance. At the loading stage, there are two types of serrations. One is discrete and random large serrations (more than 1 nm, arrowed) distributed in L2 and L3, respectively. The other is concentrated and relative regularly, as shown in L4 and L5. The random and irregular serrations at the initial stages of the loading curve are suppose to be related to the formation of discrete and highly localized shear bands [34–36]. The concentrated and regularly serrations at the later stage could be associated with either more frequent initiation of the new shear bands and/or repeated post-initiation growth (reactivation) of preexisting shear bands [37]. As shown in the inset in Fig. 2a, the high frequent operation of shear bands (initiation and/or post-initiation) occurs immediately before creep and will continue to operate at the creep stage.

To understand the influence of the local microstructures of deformation regions and the operation of shear bands before creep on inhomogeneous creep, nanoindentation creep experiments were conducted at different positions on the same sample. Fig. 3a shows four typical creep *h*–*t* curves. To compare these curves clearly, the starting point of the creep curves was shifted to the same height. Both homogeneous creep and inhomogeneous creep are observed. Curves (1, 2 and 3) present inhomogeneous creep deformation because of the appearance of different numbers of serrations in the *h*–*t* curves. No serration is seen in curve 4, indicating homogeneous creep deformation. Homogeneous nanoindentation creep deformation of BMGs has been reported by