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Journal of Alloys and Compounds 434–435 (2007) 40–43

Journal of ALLOYS AND COMPOUNDS

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Strain rate dependence of deformation behavior in Zr-based bulk metallic glasses in the supercooled liquid region

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Available online 10 October 2006

Abstract

Zr-based bulk metallic glasses (BMG) have superior mechanical properties such as high strength, elastic strain limit and fracture toughness. However, the application fields of bulk metallic glasses have been limited because of their small size and lack of workability. In order to improve the workability using superplastic behavior, it is important to investigate the deformation behavior of BMGs in the supercooled liquid region. In this study, the strain rate dependence of the deformation behavior in a $Zr_{55}Al_{10}Ni_5Cu_{30}$ bulk metallic glass under tensile loading at temperatures between 680 K and 720 K were investigated. The flow behavior exhibited significant strain rate dependence, and the flow stress became lower with lowering strain rates. The crystallization of glass phase of the alloy occurred during testing at low strain rates and higher temperature in the supercooled liquid region, and eventually, shortened the elongation expected at lower strain rates.

Keywords: Amorphous metal; Strain rate; Flow stress; Supercooled liquid region; Superplasticity

1. Introduction

Bulk metallic glasses (BMG) have been developed for structural applications because of their high strength, large elastic deformation limit, and superior corrosion and wear resistance at room temperature [1–3]. When the bulk metallic glass is deformed at room temperature, however, it shows a unique deformation behavior by the formation of shear bands (inhomogeneous deformation) and catastrophic failure. With increasing temperature, the deformation mode changes from inhomogeneous to homogeneous deformation at a temperature of about $0.7T_g$ (T_g is the glass transition temperature) [4], above which metallic glasses exhibited significant plasticity. It has been reported that Zr-based BMG alloys with wide supercooled liquid region and high glass forming ability exhibit superplastic deformation in the supercooled liquid region depending on both the temperature and the strain rate [5].

Since the deformation behaviors of BMGs in the supercooled liquid region depended upon both thermal and mechanical conditions, the efforts for forming BMG alloys at low flow stress and high elongation, especially the understanding of the strain rate dependence on the superplastic deformation, are necessary for establishing the optimum forming condition.

In this study, therefore, the deformation behavior of $Zr_{55}Al_{10}Ni_5Cu_{30}$ bulk metallic glass in the supercooled liquid region has been investigated. The strain rate dependence of the plastic flow behavior including superplastic deformation of the alloy was discussed.

2. Experimental procedure

2.1. Specimen

The sample has a composition of $Zr_{55}Al_{10}Ni_5Cu_{30}$ prepared by copper mold casting in an argon atmosphere and a cylindrical rod shape of 4 mm in diameter and 50 mm in length. It was supplied as-cast state. The thermal properties of the $Zr_{55}Al_{10}Ni_5Cu_{30}$ alloy were measured using differential scanning calorimetry (DSC) with a heating rate of 0.33 K/s; the glass transition temperature (T_g), the crystallization temperature (T_x) and the peak temperature were 680 K, 762 K and 767 K, respectively. The heat of crystallization (ΔH_x) and supercooled liquid region ($\Delta T_x = T_x - T_g$) were 35.8 J/g and 81 K, respectively. The structure of $Zr_{55}Al_{10}Ni_5Cu_{30}$ alloy is cheked by using X-ray diffractometry (XRD). The X-ray diffraction pattern of as-cast $Zr_{55}Al_{10}Ni_5Cu_{30}$ alloy consists of a halo pattern showing a typical glassy phase without any distinct Bragg peaks.

In order to investigate the deformation behavior of $Zr_{55}Al_{10}Ni_5Cu_{30}$ alloy, the tensile specimen was fabricated from the as-cast rod. It has dimensions of 1.4 mm width, 1.2 mm thickness and 6 mm gage length, as shown in Fig. 1(a).

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doi:10.1016/j.jallcom.2006.08.095

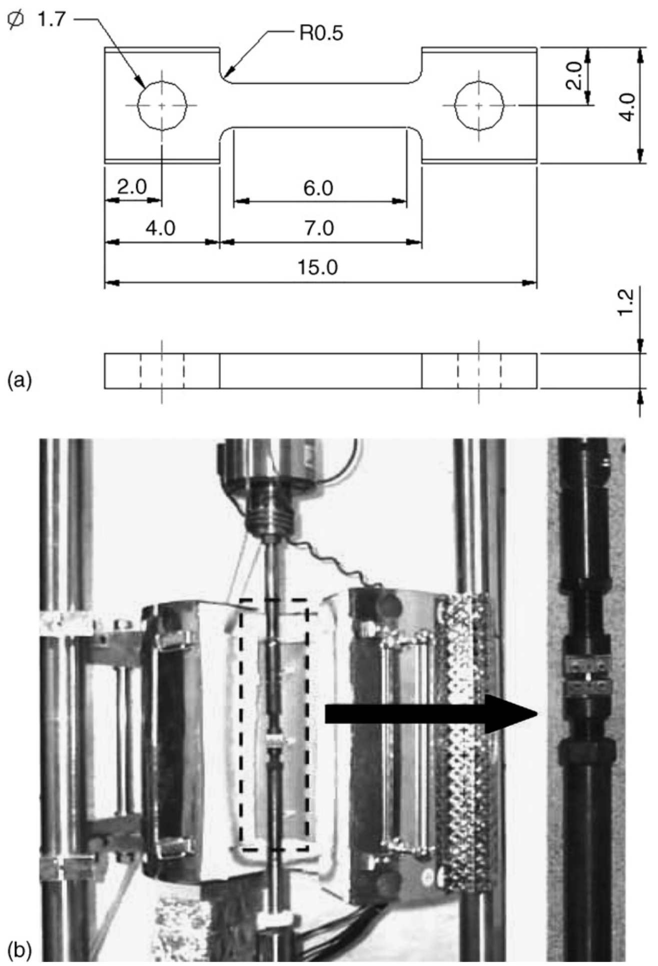

Fig. 1. (a) Shape and dimensions of the tensile specimen and (b) appearance of fixtures with specimen installed within the electric furnace.

2.2. Experimental

The tensile test was conducted in a supercooled liquid region using a hydraulic-servo material-testing machine (Instron type-8516, Loadcell: 5 kN) at an initial strain rate between 5×10^{-4}/s and 2×10^{-1}/s in air. A three-zone type electric furnace was used to heat the specimen. Fig. 1(b) shows the view of the furnace and specimen fixtures for tensile testing at elevated temperatures. A universal joint was introduced on the upper fixture to avoid the effects of misalignment of loading axis. The specimen temperature was measured using a K-type thermocouple attached on the specimen. The fluctuation of temperature during tests was controlled within ±1 K. The tensile test was started after 3 min when the temperature reached the set value at a heating rate of 20 K/min.

3. Experimental results and discussion

The tensile tests were carried out at three different temperatures of 700 K and 720 K in the supercooled liquid region, and at 680 K, T_g of the $Zr_{55}Al_{10}Ni_5Cu_{30}$ alloy. Fig. 2 shows the influence of initial strain rates on nominal stress–strain curves obtained at each temperature. At room temperature, the alloy failed catastrophically just after elastic deformation without any plastic deformation.

In the supercooled liquid region of the $Zr_{55}Al_{10}Ni_5Cu_{30}$ alloy, the specimens deformed significantly, and the initial strain rate influenced it. Generally, as the strain rate and the test temperature increased, there occurred lowering flow stress but increasing elongation. At the temperature of 740 K relatively close to T_x, however, it behaved differently, regardless of the initial strain rates adopted, all specimens showed brittle fracture as crystallization occurred at an early stage of testing in all the tested specimens [6].

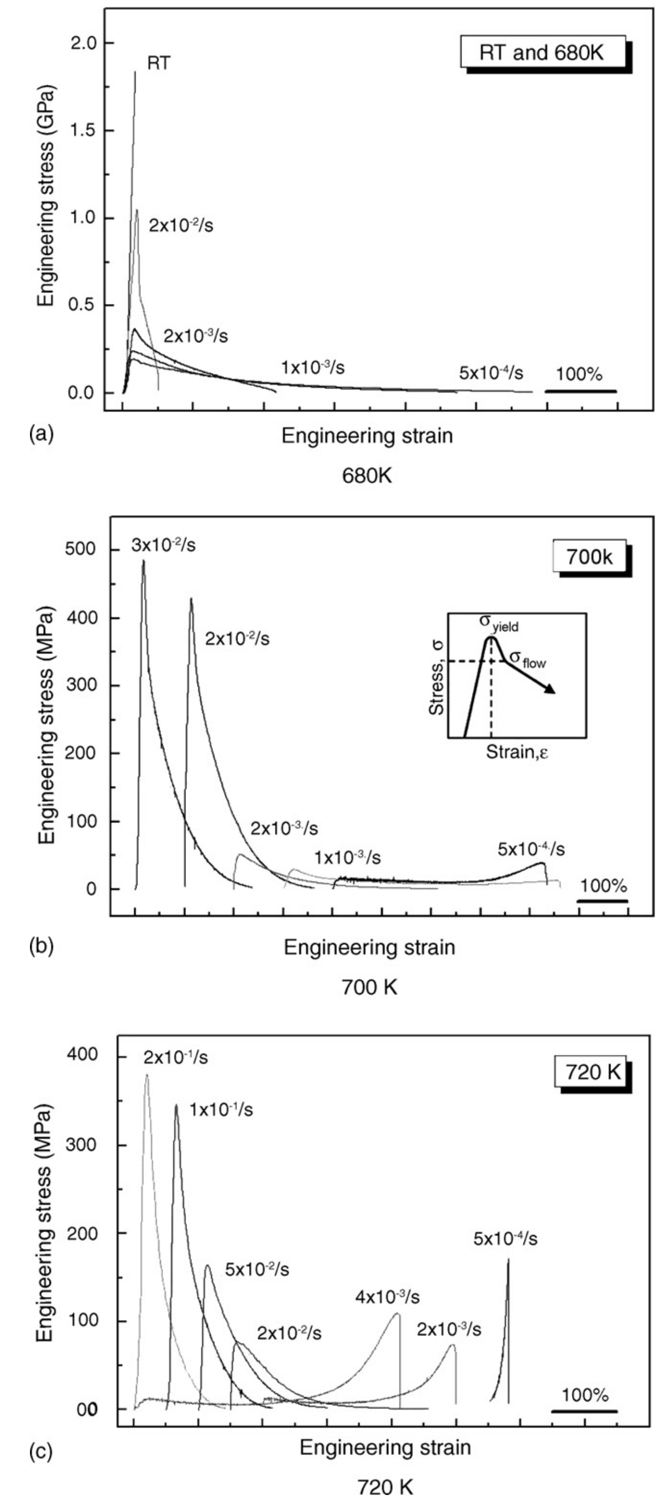

Fig. 2. Influences of initial strain rate on nominal stress–strain curves in the supercooled liquid region: (a) 680 K, (b) 700 K and (c) 720 K.

At 680 K of T_g, shown in Fig. 2(a), as the strain rate decreases, the flow stress decreased but the elongation increased significantly. At the strain rate of 5×10^{-4}/s, it showed a superior superplastic deformation behavior and the elongation approached about 560%. At this temperature, crystallization in the specimen and strain hardening did not occur even in a quite low strain rate region, with uniform deformation up to the failure of the specimen at lower strain rates than 1×10^{-3}/s, at a relatively high value of 200 MPa.

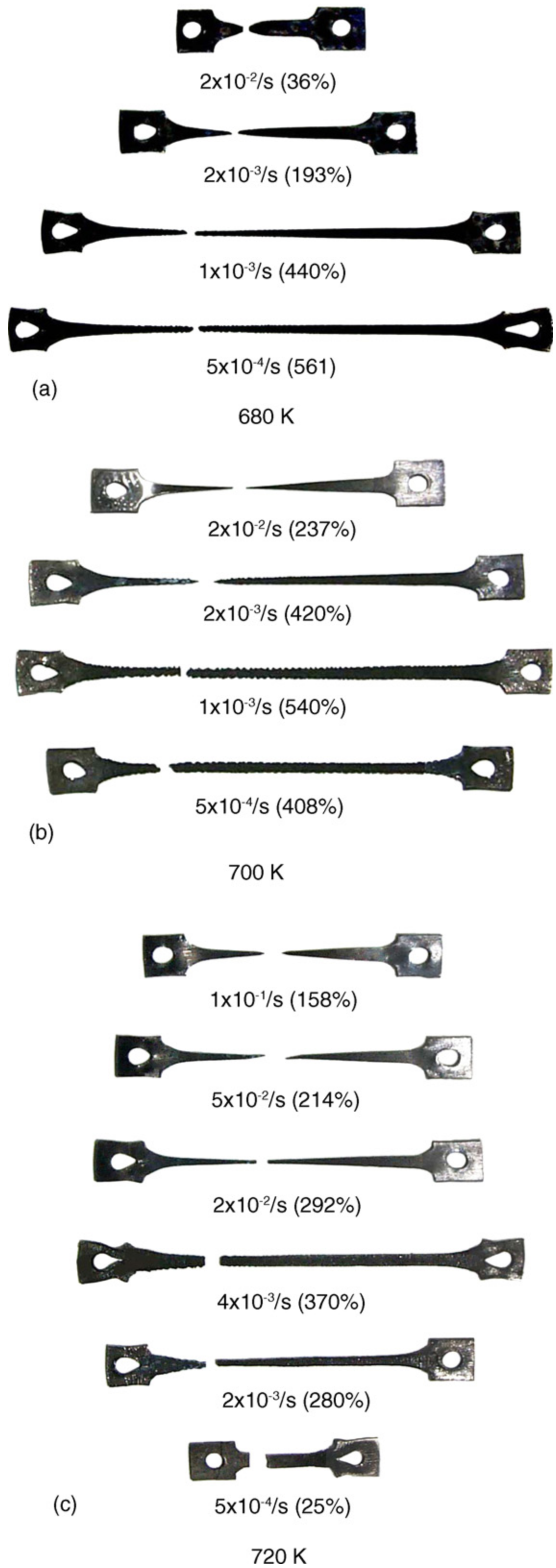

Fig. 3. Appearances of deformed specimens: (a) 680 K, (b) 700 K and (c) 720 K.

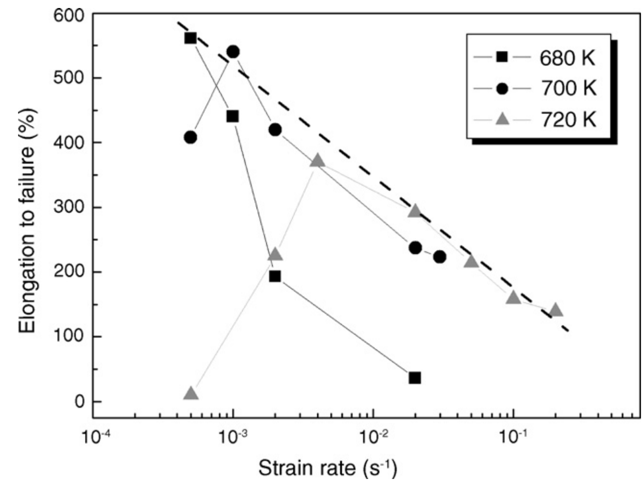

Fig. 4. Elongation to failure as a function of strain rate at each temperature.

At 700 K and 720 K in the supercooled liquid region, shown in Fig. 2(b) and (c), the deformation behavior can be distinguished roughly as two types depending on the initial strain rate applied. In the higher initial strain rate region, the stress increases linearly to the peak value, then decreased showing strain softening until failure. On the other hand, in the lower initial strain rate region, the behavior was the reverse. It deformed at a nearly constant flow stress after yielding at a low stress, and then strain hardening occurred with subsequent deformation and followed by a catastrophic failure. These behaviors are similar to the behavior of a Newtonian viscous flow [7,8]. The deformation behavior at 700 K showed larger at lower strain rates as compared with the case at 720 K. But, at 720 K, the extent of strain hardening became significant at the lower strain rates. It can be thought that the strain hardening resulted from the occurrence of crystallization in the specimen due to the longer time holding at that temperature. Especially, it became significant at the strain rate of 5×10^{-4}/s, producing only few percent elongations.

Thus, it was found that the $Zr_{55}Al_{10}Ni_5Cu_{30}$ alloy shows superior superplastic deformation behavior in the supercooled liquid region. However, there exists a large variation in the elongation to failure depending on the initial strain rate.

Appearances of deformed and fractured specimens are shown in Fig. 3. They explain well the deformation behaviors in Fig. 2 showing different morphologies depending on the strain rate at each temperature. The specimens deformed uniformly showing superplastic deformation with elongation exceeding about 200%. The mechanism has been explained by the change in the atomic mobility [9].

Fig. 4 shows the strain rate dependence of the elongation obtained at each temperature. At each temperature, the elongation varied having a peak with the increase of the strain rate. At 680 K, the peak was obtained at the strain rate of 5×10^{-4}/s, and the elongation decreased with the increase of the strain rate. At 700 K and 720 K, the peak elongation was obtained at the strain rate of 1×10^{-3}/s and 4×10^{-3}/s, respectively. They were 540% and 370%, respectively. As the temperature increased, the peak elongation became lower and moved to a higher strain rate. This behavior resulted from crystallization as longer holding times at low strain rates disturbed the uniform deformation or Newtonian viscous flow of the alloy leading to strain hardening at the later stage of deformation, eventually shortening the elongation.

Since the deformation behavior of $Zr_{55}Al_{10}Ni_5Cu_{30}$ alloy in the supercooled liquid region corresponds to viscous flow, there exists a relation of $\sigma = k\dot{\varepsilon}^m$ between the flow stress and the strain rate applied [8], where σ is the flow stress, $\dot{\varepsilon}$ the applied strain rate and m is the strain rate sensitivity exponent. The flow stress decreased with decreasing strain rate. The flow stress was defined as the stress required for causing continuous plastic flow when the plastic deformation was initiated, as shown in the inset of Fig. 3(b). Using the data from Fig. 3, a logarithm flow stress versus logarithm strain rate plot was produced, as shown in Fig. 5. The slope of the curve, n, represents the stress exponent, and it was found to vary with strain rate. Specifically, the value of n was about 1 in the strain rate range up to $2 \times 10^{-2}\,s^{-1}$ at 700 K and $1 \times 10^{-1}\,s^{-1}$ at 720 K. It shows that the Newtonian viscous flow governed the deformation at the initial stage of deformation around the peak stress. However, when the stain rate increased over the above-mentioned values at each temperature, the n value increased to about 2, as deformation changed to the non-Newtonian viscous flow. Thus, flow stress at the supercooled liquid region was influenced significantly by both the strain rate and the temperature. On the other hand, at the temperature of 680 K

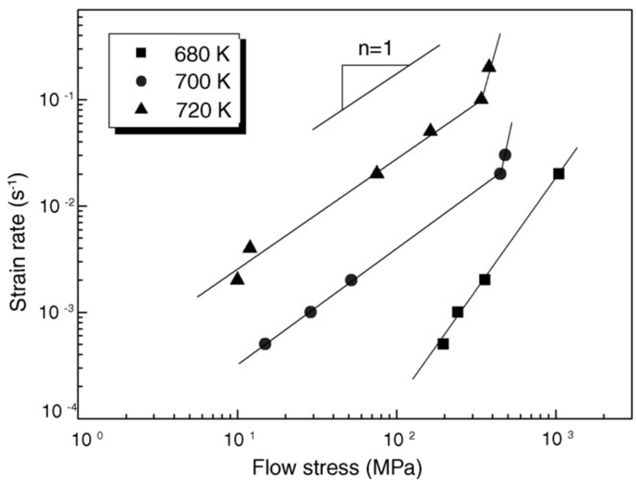

Fig. 5. Strain rate dependence of the flow stress for $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG at various temperatures.

corresponding to the glass transition temperature (T_g), n was larger than 1 and the deformation governed by the non-Newtonian viscous flow.

4. Conclusions

The $Zr_{55}Al_{10}Ni_5Cu_{30}$ bulk metallic glass showed superior superplastic deformation behavior in the supercooled liquid region. The deformation behavior could be characterized into two types depending on the temperature–strain rate combination. The flow behavior exhibited significant strain rate dependence, and the flow stress became lower with the lowering of strain rates. At higher temperature in the supercooled liquid region and lower strain rate, the $Zr_{55}Al_{10}Ni_5Cu_{30}$ alloy hardened at the later stage of deformation as crystallization at longer holding times disturbed uniform deformation and shortened the elongation.

Acknowledgements

This study was supported by grant no. R05-2003-000-11614-0 from the Basic Research Program of the KRF/KOSEF and the 2004 Special Research Program of Andong National University, Korea. The authors appreciate Dr. H. Kato and Prof. A. Inoue of Tohoku University for supplying the sample.

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