Effect of Pre-Introduced Shear Bands Direction on Deformation Behavior in $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ Bulk Metallic Glass

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We investigated the effect of pre-introduced shear bands direction on compressive deformation behavior in $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ bulk metallic glass. The compressive deformation behavior varied with the difference of the direction of pre-introduced shear bands with respect to loading direction. The specimen in which shear bands were introduced at an angle of 45 degree to the loading direction showed largest plastic strain. This large plasticity was achieved due to the activity of pre-introduced shear bands and formation of multiple shear bands. The direction of pre-introduced shear bands is an important factor to improve the plasticity in bulk metallic glasses. [doi:10.2320/matertrans.MAW200920]

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1. Introduction

Bulk metallic glasses (BMGs) have attracted interest because of their unique properties such as their high strength, large elastic limit at room temperature, and considerable plasticity in the supercooled liquid region.^{1,2)} Because BMGs have immense potential for application in various fields, a variety of researches on BMGs have been undertaken.^{3–13)} Recently, there has been attention paid to investigating the deformation behavior of BMGs at room temperature. Since plastic deformation of BMGs at room temperature is highly localized into shear bands, which propagate easily and rapidly,¹⁴⁾ resulting in a limited plastic strain and catastrophic failure after yielding at an elastic deformation at room temperature. This lack of plastic deformability hampers the widespread adoption of BMGs in a range of potential applications. Therefore, plasticity enhancement of BMGs remains a challenge. One of effective approaches for enhancing plasticity is the fabrication of BMG composite. Enhanced plasticity is achieved by dispersion of embedded nanocrystals¹⁵⁾ or *in-situ* formed crystalline dendrite.¹⁶⁾ Recently, even monolithic BMGs exhibit large plasticity, which is attributed to nanoscale structural heterogeneity,¹⁷⁾ micrometer-sized porosity,¹⁸⁾ nanocrystallization induced deformation,¹⁹⁾ or high Poisson ratio.²⁰⁾ A common characteristic in these cases is the formation of a large number of uniformly distributed shear bands. However, monolithic BMGs showing plastic deformation are limited, and many BMGs do not show plastic deformation. As the approach for improving the plasticity at room temperature of brittle BMGs, it has been reported the pre-introduction of shear bands by cold rolling.^{21–24)} Pre-introduced shear bands can release applied strain and make up for uniform deformation. In the researches of cold-rolled BMGs, it has attracted the relationship between the density of pre-introduced shear bands and plastic deformability. However, there is no research about the effect of the direction of pre-introduced

shear bands on deformation behavior. In this study, we prepared compressive specimens with the different direction of pre-introduced shear bands with respect to the loading direction from the $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ BMG introduced shear bands by cold rolling, and investigated the relationship between the pre-introduced shear bands direction and compressive properties.

2. Experimental Procedures

A master ingot of $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ BMG was prepared by arc melting in an argon atmosphere. Plates of $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ BMG with 2.3 mm-thick were prepared by mold-clamp casting of the arc-melted ingot.²⁵⁾ The cast sample was cold-rolled with a small reduction of 0.2–0.5% per pass. The total reduction ratio of the cold-rolled $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ was about 3.8%. We prepared each compressive specimen at a different angle with respect to rolling direction (RD). Figure 1 shows the schematic illustration of (a) preparation of each compressive specimen from cold-rolled $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ and (b) prediction models of the direction of pre-introduced shear bands with respect to loading direction for each compressive specimen. In Fig. 1(a), the angle with respect to the RD is 0°, 22.5°, 45°, 67.5° and 90°. We defined each specimen prepared different angle with respect to RD as 0° specimen, 22.5° specimen, 45° specimen, 67.5° specimen and 90° specimen. The size of the compressive specimen was 1.8 mm × 1.8 mm × 3.6 mm (width, length and height). Compressive specimen surfaces were mechanically ground with silicon carbide papers up to #2400 and polished with 3 μm diamond slurry. Uniaxial compression tests were conducted at a constant strain rate of $5 \times 10^{-4} \text{ s}^{-1}$ at room temperature. The fracture surface was examined by scanning electron microscopy (SEM) with an acceleration voltage of 20 kV. The structures of the samples were examined by X-ray diffraction (XRD, $\text{CuK}\alpha$ radiation) and transmission electron microscopy (TEM).

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Fig. 1 Schematic illustration of (a) preparation of each compressive specimen from cold-rolled $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ and (b) prediction models of the direction of pre-introduced shear bands with respect to loading direction for each compressive specimen.

Fig. 2 (a) XRD pattern and (b) TEM bright-field image and selected-area diffraction (SAD) pattern of the as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$.

3. Results and Discussion

Figure 2 shows (a) XRD pattern and (b) a bright-field TEM image and the related selected-area diffraction (SAD) pattern of as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$. The XRD pattern shows only broad peaks with no detectable crystalline Bragg peaks, as is characteristic for glassy structures. The TEM image is featureless and the SAD pattern consists of a halo ring without any diffraction spots. These results indicate that as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ was basically a glassy structure.

Fig. 3 SEM image of the side surface of the cold-rolled $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$.

Fig. 4 Compressive stress-strain curves of the as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ and the specimens with the different direction of pre-introduced shear bands with respect to the loading direction.

Although we investigated the structure of the cold-rolled sample by XRD, there were no detectable crystalline Bragg peaks.

Figure 3 shows the SEM image of a side view of the cold-rolled $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ with a reduction ratio of 3.8%. Shear bands introduced uniformly by cold rolling are observed. The angle between the shear band and the RD is 45° – 48° . The surface flaws that can be seen at a low angle to the RD are due to polishing. The shear bands propagate in straight lines, passing through the entire thickness of the cold-rolled $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$, and shear bands introduced in different directions intersect each other.

Figure 4 shows the typical compressive stress-strain curves of as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ and the specimens with pre-introduced shear bands. The yield stress and plastic strain of as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ are 1705 MPa and 0.2%. On the other hand, the compressive deformation behavior varies with the direction of pre-introduced shear bands to loading direction. The yield stress of 90° specimen showed highest value of 1890 MPa compared with any other specimen. In contrast, the yield stress of 0° specimen shows lowest value of 1640 MPa, which is lower than that of as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$. The yield stress of 22.5° specimen and 67.5° specimen are almost the same value as as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$. As the plastic strain, the 45° specimen

shows significant plastic strain in compressive deformation in contrast to the as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ and any other specimens with pre-introduced shear bands. The largest plastic strain in several compression tests of 45° specimens is 37.6% (45° -#2 in Fig. 4). Plastic strain of the specimens with pre-introduced shear bands other than the 45° specimen is slightly improved.

Figure 5 shows the SEM images of (a) and (b) the as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$, (c) and (d) the 0° specimen, (e) and (f) the 45° -#1 specimen, and (g) and (h) the 45° -#2 specimen after fracture. In Fig. 5(a) and (b), the angle of fracture plane of as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ is about 45° with respect to loading direction. The fracture surface shows a shear vein pattern. These results indicate typical shear fracture mode in BMG. Only a few shear bands are observed on the surface except a major shear bands caused fracture. On the other hand, a large number of shear bands are formed in 0° specimen and 45° -#1 specimen [Fig. 5(d) and (e)]. Here, we focus on the orientation of the fracture plane and shear bands in 45° -#1 specimen. Orientation of fracture plane and direction of shear bands is not 45° with respect to loading direction as seen in as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ and is almost in agreement with the prediction model of 45° specimen in Fig. 1(b). So, we believe that the shear bands in 45° -#1 specimen after deformation [Fig. 5(e) and (f)] will be the pre-introduced shear bands by cold rolling. Similarly, shear bands in 0° specimen after deformation [Fig. 5(d)] will be also the pre-introduced shear bands by cold rolling because the number of shear bands in 0° specimen is obviously large compared with that in as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ and orientation of shear bands is almost in agreement with the prediction model.

Magnified image of the corner-side surface in 45° -#1 specimen is shown in Fig. 5(f). The active operation of pre-introduced shear bands can be seen. In our previous study, we clarified that pre-introduced shear bands operate before yielding.²⁴⁾ The plastic deformation of the 45° -#1 specimen was mainly due to the activation of pre-introduced shear bands. In Fig. 5(g) and (h), the 45° -#2 specimen heavily deforms. A large number of shear bands with different scales is observed. Linear or wavy shear bands are formed and they branch and intersect each other. Formation of multiple shear bands in addition to the activation of pre-introduced shear bands results in the significant plastic deformation demonstrated in Fig. 4. However, the constraining of shear band propagation by compression platform in compression test of BMGs has been reported recently.²⁶⁾ Stress will be likely to increase when the constraining of shear band propagation by compression platform occurs. Additionally, deformation will continue without showing clear fracture because the compressive specimen cannot freely run off. So, the deformation after stress begins to increase again (allows in Fig. 4) in 45° -#1 specimen and 45° -#2 specimen is due to the constraining of shear band propagation by compression platform. However, the fact remains that 45° specimens show large plastic strain (e.g., about 10% in 45° -#1 specimen) even if the plastic strain due to the constraining of shear band propagation by compression platform is cut out.

The morphology including the direction of the fracture plane and shear bands of 22.5° specimen, 67.5° specimen and

Fig. 5 SEM images of (a) and (b) the as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$, (c) and (d) the 0° specimen, (e) and (f) the 45° -#1 specimen, and (g) and (h) the 45° -#2 specimen after fracture.

90° specimen were different from the prediction model as shown in Fig. 1. The detail analysis of these specimens will investigate in our future work.

As seen in Fig. 4, the deformation behavior of the $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ with the pre-introduced shear bands varied with the difference of the direction of pre-introduced shear bands with respect to loading direction. Although the density of pre-introduced shear bands has effect on the plasticity,²¹⁻²³⁾ that of each specimen in this study is almost the same. So, it seems that the direction of pre-introduced shear bands affect the deformation behavior and an optimum direction of pre-introduced shear bands for improvement of plastic strain and strength in BMGs exists. On the other hands, pre-introduced shear bands do not always improve

compressive properties. The yield strength of 0° specimen reduced, although plastic strain was improved a little, compared to as-cast $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$. We consider this reason is that the direction of pre-introduced shear bands in 0° specimen is same direction as maximum shear stress direction. As is well known, shear band forms and propagates easily along the maximum shear stress direction. We consider that the activation of pre-introduced shear bands caused the fracture in the 0° specimen. In this case, stress localization would occur in one of the pre-introduced shear bands. In fact, some pre-introduced shear bands were observed in the 0° specimen, but they did not operate actively [Fig. 5(d)]. By contrast, a large number of pre-introduced shear bands were observed and most of the pre-introduced shear bands operated actively in the 45°-#1 specimen [Fig. 5(f)]. So, the optimum direction of pre-introduced shear bands for improvement of compressive properties means that the strain is distributed to each pre-introduced shear bands and the pre-introduced shear bands operate collectively and actively.

4. Conclusion

We investigated the effect of pre-introduced shear bands direction on compressive deformation behavior in $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ BMG. The direction of pre-introduced shear bands affected the compressive deformation behavior. The compressive strength and plastic strain was drastically improved due to introduction of shear bands in the direction that pre-introduced shear bands prefer to operate collectively and actively. The direction of pre-introduced shear bands is an important factor to improve the mechanical properties in BMGs.

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