Tensile Plastic Deformation Behavior of $\text{Zr}_{70}\text{Ni}_{16}\text{Cu}_6\text{Al}_8$ Bulk Metallic Glass at Cryogenic Temperature

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A hypoeutectic Zr–Ni–Cu–Al bulk metallic glass (BMG) shows a clear tensile plastic deformation under a high strain rate condition at room temperature. In this study, the effect of cryogenic temperature and strain rate on the tensile plastic deformation behavior of the hypoeutectic Zr–Ni–Cu–Al BMG was investigated. Tensile tests were performed for the hypoeutectic Zr–Ni–Cu–Al BMG specimen with gauge part dimensions of 2.3 mm in length and 0.8 mm in diameter at cryogenic temperature (133 K) under different strain rate conditions (10^{-4} and 10^{-1} s^{-1}). As the results, the tensile plastic deformation occurs under both strain rate conditions. Especially, in low strain rate condition (10^{-4} s^{-1}), the amount of plastic deformation is clearly larger than that under the high strain rate condition (10^{-1} s^{-1}). Furthermore, it was found that there is no positive correlation between the amount of tensile plastic deformation and the number of shear band. In addition, it was inferred that the tensile plastic deformation of the hypoeutectic Zr–Ni–Cu–Al BMG at cryogenic temperature was induced by specimen sliding along only one major shear band. [doi:10.2320/matertrans.M2012102]

(Received March 19, 2012; Accepted May 8, 2012; Published June 27, 2012)

Keywords: tensile plastic deformation, bulk metallic glass, supercooled liquid, cryogenic temperature, strain rate dependence

1. Introduction

The plastic deformation of bulk metallic glass (BMG) is induced by the initiation and propagation of a shear band instead of the dislocation motion of a crystallized alloy. In addition, once the shear band initiates, the local temperature within the shear band increases rapidly via the release of elastic strain energy, and the BMG within the shear band exists at least in a supercooled liquid state.¹⁾ Therefore, under a tensile loading condition, most BMGs exhibit only slight plasticity and a catastrophic fracture occurs just after yielding via single shear band propagation. Therefore, the improvement of the plasticity of BMGs is an important problem from an industrial viewpoint.

There are a few reports about the tensile plastic deformation of BMGs at room temperature.^{2–6)} For example, Sergueeva *et al.* have reported a tensile plastic elongation of more than 3% by using a Zr–Ti–Cu–Ni–Be BMG owing to multiple shear band formation. The report also mentions that the presence of a large number of shear bands is associated with an increase in plasticity.²⁾ On the other hand, the authors' group has reported that the tensile plastic deformation of a hypoeutectic Zr–Ni–Cu–Al BMG under a high strain rate condition occurs because of sliding deformation of the specimen along only one shear band.^{4–6)} So far, however, little information has emerged on the relationship between the number of shear bands and the tensile plasticity of BMGs.

In contrast, some recent results have indicated that the tensile plastic deformation of BMGs occurs at cryogenic temperature on the basis of experiments performed using Zr–Cu–Al BMG,⁷⁾ Zr–Cu based BMG⁸⁾ and Zr–Ni–Cu–Al BMG.⁹⁾ These results suggest that the tensile plastic deformation behavior of BMGs depends on the strain rate and temperature. In any case, a more detailed investigation is necessary to improve the plasticity of BMGs.

The present study focuses on the effect of the cryogenic temperature and strain rate on the tensile deformation behavior of the hypoeutectic Zr–Ni–Cu–Al BMG. Specifically, tensile tests are performed at cryogenic temperature under different strain rate conditions using the hypoeutectic Zr–Ni–Cu–Al BMG. First, the effect of the strain rate on the tensile plastic deformation behavior of the hypoeutectic Zr–Ni–Cu–Al BMG is studied at cryogenic temperature. Then, the relationships between the number of shear bands and the plasticity of the hypoeutectic Zr–Ni–Cu–Al BMG are presented and discussed. Finally, the tensile plastic deformation mechanism of the hypoeutectic Zr–Ni–Cu–Al BMG at cryogenic temperature is discussed.

2. Experimental Procedure

The alloy composition of the specimen was $\text{Zr}_{70}\text{Ni}_{16}\text{Cu}_6\text{Al}_8$ (at%). The detailed preparing procedures of the BMG have been described elsewhere.⁴⁾ The gauge part of the specimen was machined to be 2.3 mm in length and 0.8 mm in diameter. Then, by using abrasive papers (#800, #1200 and #2000), the gauge part was polished in the direction of the tensile load axis.

Tensile tests were performed at a constant stroke rate using a Shimadzu servo-hydraulic fatigue machine with a 4830-type control device at cryogenic temperature (133 K). The strain rate conditions were 10^{-4} s^{-1} (low strain rate) and 10^{-1} s^{-1} (high strain rate). The elongation of the gauge part was measured by using a linear variable differential transformer, which was attached to the testing machine. After the tensile tests, the specimen surface and fracture surface were observed by using a scanning electron microscope (SEM).

3. Results and Discussions

Figure 1 shows the strain rate dependence of the nominal stress–strain curves of the hypoeutectic Zr–Ni–Cu–Al BMG

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obtained by performing the tensile test at a temperature of 133 K. As shown in this figure, tensile plastic deformation occurs under both strain rate conditions (10^{-1} and 10^{-4} s^{-1}). At room temperature, the hypoeutectic Zr–Ni–Cu–Al BMG shows tensile plastic deformation only under the high strain rate condition.^{4,5)} Therefore, it is inferred that cryogenic temperature induces tensile plasticity in the hypoeutectic Zr–Ni–Cu–Al BMG. In addition, it is found that the tensile plastic deformation behavior of the hypoeutectic Zr–Ni–Cu–Al BMG depends on the strain rate. The amount of plastic deformation under the low strain rate condition is clearly larger than that under the high strain rate condition. The effect of cryogenic temperature on the tensile plastic deformation behavior and the mechanism of tensile plasticity

Fig. 1 Nominal stress–strain curves of $\text{Zr}_{70}\text{Ni}_{16}\text{Cu}_6\text{Al}_8$ BMG obtained by tensile test at 133 K. (a) Strain rate of 10^{-1} s^{-1} . (b) Strain rate of 10^{-4} s^{-1} .

enhancement under the low strain rate condition are discussed later.

Figure 2 shows the SEM images of specimen surfaces obtained by performing the tensile test at a temperature of 133 K and strain rates of 10^{-1} and 10^{-4} s^{-1} . First, as shown in Figs. 2(a) and 2(b), at a strain rate of 10^{-1} s^{-1} , many shear bands can be observed over a wide area of the gauge part of the specimen surface. In addition, curving and branching of shear bands frequently occur. On the other hand, at a strain rate of 10^{-4} s^{-1} , few shear bands can be observed in the vicinity of the fracture surface, as shown in Figs. 2(c) and 2(d). Therefore, it is inferred that the high strain rate induces the initiation of many shear bands. In addition, it is found that there is no positive correlation between the amount of tensile plastic deformation and the number of shear bands.

Figure 3 shows the SEM images of fracture surfaces obtained by performing the tensile test at a temperature of 133 K and strain rate of 10^{-1} s^{-1} . First, it should be noted that a line exists on the fracture surface, as indicated by the arrows in Figs. 3(a) and 3(b). In addition, the line is connected to the shear band, which exists on the specimen surface, as shown in Fig. 3(b). Therefore, the existence of the line on the fracture surface confirms that two major shear bands, which fully penetrate the specimen, intersect each other during tensile deformation. Second, it is found that most areas of the fracture surface show well-developed vein patterns, as shown in Figs. 3(a) and 3(c). This result indicates that the material within the major shear band exists in a supercooled liquid state even at cryogenic temperature.

Fig. 2 Specimen surface morphologies obtained by SEM observation. (a) Strain rate of 10^{-1} s^{-1} . (b) Enlarged view of (b) in (a). (c) Strain rate of 10^{-4} s^{-1} . (d) Enlarged view of (d) in (c).

Fig. 3 Fracture surface morphologies obtained by SEM observation after tensile test at 133 K and strain rate of 10^{-1} s^{-1} . (a) Overall view of fracture surface. (b) Enlarged view of fracture surface and specimen surface. (c) Overall view of fracture surface. Definition of first and second area. (d) Enlarged view of (d) in (c). (e) Enlarged view of (e) in (c).

Furthermore, a careful observation of the fracture surface indicates that the vein pattern region can be separated into two regions, and the boundary line separating the two regions lies on the fracture surface, as shown in Fig. 3(c). Hereinafter, we refer to the regions below and above the boundary line as the first and second areas, respectively. The vein patterns in the first area are denser and smaller than those in the second area, as shown in Figs. 3(c), 3(d) and 3(e). In addition, the lines in each vein pattern in the first area are wavier than those in the second area, as shown in Figs. 3(d) and 3(e). These features indicate the lower fluidity and higher viscosity of the supercooled liquid within the major shear band in the first area.⁸⁾ From these experimental results, the tensile plastic deformation process of the BMG at a temperature of 133 K and strain rate of 10^{-1} s^{-1} is speculated to be as follows. (1) Two major shear bands, which penetrate

the specimen, are generated in the specimen, as shown in Fig. 4(a). (2) These bands intersect with each other as shown in Fig. 4(b). (3) The intersection of the major shear bands act as a deterrent against sliding deformation along major shear band ①. Consequently, sliding deformation occurs along major shear band ②, and the specimen begins to separate because of the interaction of the shear and normal forces, as shown in Fig. 4(c). At this stage, denser and wavier vein patterns are generated in the first area of the fracture surface because the viscosity of the supercooled liquid in the major shear band ① is still high. (4) Because of the decrease in the net cross-sectional area and increase in the thickness of shear band, the viscosity of the supercooled liquid in major shear band ① decreases rapidly. Then, the specimen fully separates, as shown in Fig. 4(d). Consequently, the second area of the fracture surface is formed. In the present study,

Fig. 4 Illustration of the fracture processes at a temperature of 133 K and strain rate of 10^{-1} s^{-1} .

Fig. 5 Fracture surface morphologies obtained by SEM observation after tensile test at a temperature of 133 K and strain rate of 10^{-4} s^{-1} .

tensile test was carried out four times under same conditions (high strain rate and cryogenic temperature). As the result, one out of four results show the above feature, namely, two major shear bands intersection and the generation of tensile plastic deformation. On the other hand, the catastrophic fracture occurs just after yielding via single major shear band propagation in the other tensile test.

Figure 5 shows the SEM images of the fracture surface obtained by performing the tensile test at a temperature of 133 K and strain rate of 10^{-4} s^{-1} . No vein pattern is found on the fracture surface. Vein patterns are formed during the rapid separation of the specimen because of the interaction of the normal and shear forces, as illustrated in Figs. 4(c) and 4(d). Therefore, the features of the fracture surface reveal that the rapid separation of the specimen does not occur in this tensile test. Then, to investigate the tensile plastic deformation process at a temperature of 133 K and strain rate of 10^{-4} s^{-1} , the tensile load is unloaded during plastic deformation. Figure 6 shows the specimen morphologies after unloading. As shown in Fig. 6, sliding deformation occurs along one major shear band. In addition, it is confirmed that the specimen does not separate after unloading. These results suggest that tensile plastic deformation is induced by specimen sliding deformation along only one major shear

Fig. 6 Specimen surface morphologies obtained by SEM observation after unloading of tensile test at a temperature of 133 K and strain rate of 10^{-4} s^{-1} .

band. In addition, the hypoeutectic Zr–Ni–Cu–Al BMG within the major shear band exists in a supercooled liquid state during tensile plastic deformation even at cryogenic temperature.

As mentioned above, it is found that the viscosity of the supercooled liquid of the hypoeutectic Zr–Ni–Cu–Al BMG is important for tensile plastic deformation. In general, the viscosity of Zr-based BMGs in the supercooled liquid region increases by approximately one order of magnitude for every temperature decrease of 30 K.¹⁰⁾ Therefore, it can be speculated that the supercooled liquid within the major shear band in the tensile test at cryogenic temperature possesses higher viscosity than that in the tensile test at room temperature. Therefore, the supercooled liquid within the major shear band acts as the separation resistance of the specimen, and some sliding deformation occurs under each strain rate condition, as shown in Fig. 1.

In addition, the strain rate dependence of the tensile plastic deformation of the hypoeutectic Zr–Ni–Cu–Al BMG (Fig. 1) can be explained in terms of the viscosity of the supercooled liquid of BMGs. That is, it is well known that the viscosity of the supercooled liquid of BMGs depends on the strain rate.^{11,12)} For example, Kawamura *et al.* investigated the strain rate dependence of the viscosity of $\text{La}_{55}\text{Al}_{25}\text{Ni}_{20}$ metallic glass at various temperatures.¹²⁾ The report mentioned that the viscosity of the supercooled liquid of $\text{La}_{55}\text{Al}_{25}\text{Ni}_{20}$ metallic glass is essentially independent of the strain rate at low strain rates (Newtonian flow), while the viscosity decreases as the strain rate increases further (non-Newtonian flow). In addition, under Newtonian flow, namely, when the material is in a supercooled liquid state and the strain rate is low, $\text{La}_{55}\text{Al}_{25}\text{Ni}_{20}$ metallic glass exhibits large tensile plastic deformation. On the other hand, the amount of tensile plastic deformation decreases with increasing strain rate. Therefore, it can be considered that the supercooled liquid within the major shear band of the hypoeutectic Zr–Ni–Cu–Al BMG in the tensile test at cryogenic temperature and a low strain rate represents a Newtonian flow and possesses high viscosity during sliding deformation along the major shear band.

4. Conclusion

Tensile tests were performed for the hypoeutectic Zr–Ni–Cu–Al BMG at cryogenic temperature and strain rates of 10^{-4} and 10^{-1} s^{-1} . The obtained results are as follows.

- (1) The tensile plastic deformation occurs under both strain rate conditions. Especially, large tensile plastic deformation occurs under a strain rate of 10^{-4} s^{-1} . Therefore it was inferred that the cryogenic temperature and low strain rate condition enhance the tensile plasticity of the hypoeutectic Zr–Ni–Cu–Al BMG.
- (2) While many shear bands were occurred at strain rate of 10^{-1} s^{-1} , few shear bands were occurred at strain rate of 10^{-4} s^{-1} . Therefore, it was found that there is no positive correlation between the amount of tensile plastic deformation and the number of shear band.
- (3) In high strain rate condition tensile test, it was found that most areas of the fracture surface show well-developed vein patterns. This result indicates that the material within the major shear band exists in a supercooled liquid state even at cryogenic temperature.

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