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Influence of thermoplastic deformation on mechanical properties of Zr-based bulk metallic glasses at room temperature

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Abstract

The influence of thermoplastic deformation on the mechanical properties of $Zr_{55}Al_{10}Cu_{30}Ni_5$ and $Zr_{60}Al_{10}Cu_{25}Ni_5$ bulk metallic glasses (BMGs) at room temperature (RT) was studied. These BMGs lose their strength and become brittle at RT when heated under conditions that exceed their time–temperature–transformation (TTT) curves. For a general-purpose furnace, such conditions can be industrially represented by the upper limit temperature. In fact, these BMGs can be plastically deformed at a temperature considerably lower than the upper limit temperature. However, the strength at RT after thermoplastic deformation can be decreased with deformation under a hot condition, even if the temperature is lower than the upper limit temperature. It is assumed that the decrease in the strength and embrittlement is caused by the crystallization induced by thermoplastic deformation. The increase in the thermoplastic strain tends to decrease the fracture stress at RT. However, a high strain rate and low temperature are effective to avoid the decrease in the fracture stress at RT associated with an increase in the thermoplastic strain.

Keywords: Zirconium-based bulk metallic glass; Amorphous; Fracture stress; Room temperature; Thermoplastic deformation; Crystallization

1. Introduction

Bulk metallic glasses (BMGs) are alloys that have various features that are not observed in conventional metallic materials. BMGs consist of metallic elements with amorphous structures. Moreover, the BMG has the thickness enough to be applied to a structural material, i.e. bulk size, and exhibits the thermal stabilization different from so-called amorphous alloys. BMGs possess unique mechanical, chemical, and various other properties. Their fracture strength is several times greater than that of the steel used in many structural materials, and their Young's modulus is low as well as that of aluminum alloys [1,2]. BMGs have high corrosion resistance and exhibit a low magnetic coercive force. In particular, Zirconium-based BMGs have not only high mechanical properties but also high glass forming ability. Due to these remarkable properties, it is expected that Zr-based BMGs will be applied to new structural materials [3,4].

It is difficult to plastically deform BMGs at room temperature (RT), although they exhibit a very high fracture strength. In particular, under a tensile loading condition, their stress–strain curves are similar to those of brittle materials [5]. However, hot conditions can easily enable plastic deformation of BMGs. Therefore, BMGs must be worked and formed into the desired shape for mechanical applications at high temperatures [6–8].

However, it has been reported that certain hot-working processes such as long-time annealing and thermoplastic deformation, induce a decrease in the strength of BMGs at RT. This can be a disadvantage for the industrial application of BMGs because such a material cannot be used as a practical product due to the decrease in strength after hot working [8–10].

In this study, we investigate the influence of thermoplastic deformation on the properties of BMGs at RT. In particular, we focus on the effects of temperature, strain, and strain rate in thermoplastic deformation on the

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fracture stress of BMGs at RT. A comprehension of the dependence of these parameters under hot conditions on the material strength at RT will expedite the industrial use of BMGs.

2. Experimental method

We investigated $Zr_{55}Al_{10}Cu_{30}Ni_5$ and $Zr_{60}Al_{10}Cu_{25}Ni_5$ BMGs. These were cast and produced by the Institute for Materials Research of Tohoku University and YKK, Co., Ltd., respectively. The specimens were mechanically cut to suitable shapes for each experiment, as shown in Fig. 1.

The mechanical properties of these BMGs were investigated by a uni-axial tensile test and a uni-axial compressive test by using a mechanical loading machine (AG-10TC; Shimadzu Co., Ltd.) as shown in Fig. 2(a); the stress was calculated from the cross-sectional area of the specimen, the load was measured by using a load cell, and the strain was measured by using a strain gauge. A three-point bending test was also performed to study the strength property. The specimen for the three-point bending test

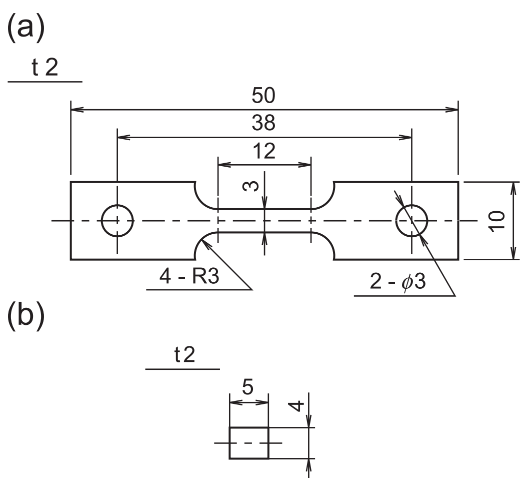

Fig. 1. Geometry of the specimen for mechanical test.

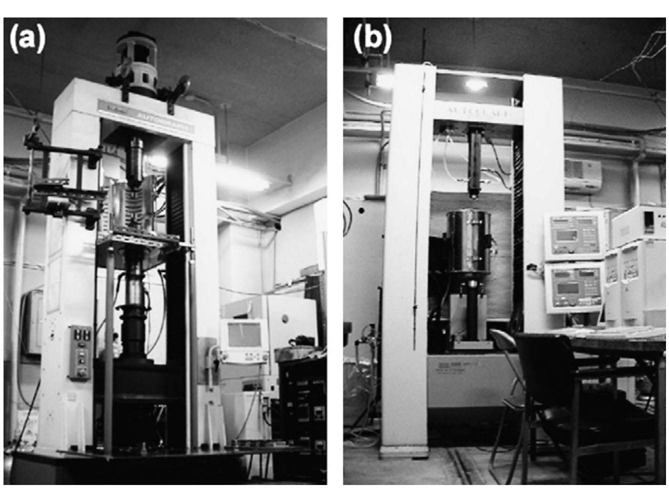

Fig. 2. Mechanical loading machine.

had the gauge length of 40 mm, and its shape was a sheet with the dimensions of $5 \times 2 \times 50\,mm^3$. The hardnesses of these BMGs were measured by using a Vickers hardness tester (MVK-E; Akashi Co., Ltd.). All the above-mentioned experiments were conducted at RT (293 K).

The plastic deformation behavior of these BMGs at high temperature was studied by using a hot loading machine (AG-G 20 kN; Shimadzu Co., Ltd.), as shown in Fig. 2(b). Loading tests under various hot conditions can be performed by using this machine to which an electrical furnace is attached. The tensile tests were performed at various temperature conditions and strain rates. The strain rate and strain were calculated from the crosshead displacement, its constantly controlled speed, and the initial gauge length of each specimen before plastic deformation because a strain gauge cannot be used at the high temperatures in the furnace. The deforming stress was calculated from the initial cross-sectional area of the specimen, and the load was measured by using a load cell. And then true strain and true stress were calculated.

All the thermoplastic deformation experiments were stopped before the fracture of the specimens in order to study the mechanical properties at RT. The amount of strain at which the deformation was stopped was diversely varied in the range from 20% to 90% for each condition of the strain rate. The range of strain rate was from 5.7×10^{-5} to $3.9 \times 10^{-3}\,s^{-1}$. After the required value of strain was obtained by the elongation of a specimen, the motion of the crosshead was stopped, and the specimen was gradually cooled to RT in the furnace. After thermoplastic deformation, the dimensions of the specimens were measured again, and then the strength properties were measured following the above-mentioned methods.

Moreover, to investigate the influence of heating alone on the mechanical and atomic structural properties of these BMGs at RT, specimens were prepared into shapes suitable for the mechanical tests and were heated at temperatures ranging from 450 to 760 K in a muffle furnace (ETR-11K; Isuzu Seisakusho Co., Ltd.) for 60 min and then cooled with water. Subsequently, mechanical loading tests were performed at RT. To study the change in their atomic structure due to heating, an X-ray diffractometer (XRD) was used for samples ($5 \times 5 \times 2\,mm^3$) of the $Zr_{55}Al_{10}$ $Cu_{30}Ni_5$ BMG heated by this method.

For all the procedures under hot conditions, the surface temperatures of the specimens were measured with a thermo-couple. The thermo-couple was the type K (chromel-alumel). The thermo-couple was fixed on the jig and always contacted on the surface of a specimen by the elastic property of itself.

To investigate the thermal properties of the $Zr_{55}Al_{10}Cu_{30}Ni_5$ and $Zr_{60}Al_{10}Cu_{25}Ni_5$ BMGs, a differential scanning calorimeter (DSC) was used.

After mechanical loading tests, the surface and shape of the fractural location were observed by using a scanning electrical microscope (SEM) and an optical microscope, respectively.