RAPID PUBLICATION

Impact Fracture Energy of Bulk Amorphous $\text{Zr}_{55}\text{Al}_{10}\text{Cu}_{30}\text{Ni}_5$ Alloy

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The impact fracture energy and stress for the bulk amorphous $\text{Zr}_{55}\text{Al}_{10}\text{Cu}_{30}\text{Ni}_5$ alloy were measured by using the Charpy test specimen with U-shape notch. The maximum stress and displacement at the impact fracture are 1615 MPa and 0.44 mm, respectively, and the impact fracture energy is measured to be 63 kJ/m². The impact fracture stress is nearly the same as the static tensile fracture strength (≈ 1570 MPa) obtained in a wide strain rate range of 10^{-4} to 10^{-1} s⁻¹ for the Zr-based bulk amorphous alloy. The impact fracture energy is higher than those (12 to 36 kJ/m²) for newly developed Al-based high-strength alloys which have been used in some application fields. The fracture surface appearance changes from the vein pattern in the region near the U-shape notch to an equiaxed dimple-like pattern in the inner region. The first evidence of the high impact fracture energy is important for development of the Zr-based bulk amorphous alloy as a new engineering material.

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I. Introduction

It is known that the maximum thickness of amorphous alloys is usually limited to less than about 50 μm , though Pd- and Pt-based amorphous alloys are formed in the sample thickness range up to about 3 mm⁽¹⁾. With the aim of eliminating the limitation of the sample thickness for amorphous alloys, various kinds of consolidation techniques have been tried for the preparation of bulk amorphous alloys⁽²⁾. Although the consolidation technique causes the formation of bulk amorphous samples, the resulting amorphous alloys do not possess good ductile nature which is inherent to the corresponding melt-spun amorphous alloys. Consequently, there have been no data on the impact fracture energy which can be evaluated through the formation of bulk amorphous alloys, though a number of data on various mechanical properties except the impact fracture energy have been obtained for melt-spun amorphous alloy ribbons⁽³⁾. Since the success of synthesizing bulk amorphous alloys with high tensile strength and good ductility in Mg-Ln-TM⁽⁴⁾ and Ln-Al-TM⁽⁵⁾⁽⁶⁾ (Ln=lanthanide metal, TM=transition metal) systems in 1989, a number of bulk amorphous alloys have been produced in Zr-Al-TM⁽⁷⁾⁽⁸⁾, Zr-Ti-TM-Be⁽⁹⁾, Ti-Zr-Al-TM-Be⁽¹⁰⁾, Fe-(Al, Ga)-(P, C, B, Si, Ge)⁽¹¹⁾, Pd-Cu-Ni-P⁽¹²⁾, Nd-Al-Fe⁽¹³⁾ and Pr-Al-Fe⁽¹⁴⁾ systems by conventional casting processes. The sample thickness for glass formation reaches as large as about 30 mm⁽¹⁵⁾ for the Zr-Al-Cu-Ni alloy, 40 mm⁽¹²⁾ for the Pd-Cu-Ni-P alloy and 15 mm⁽¹⁶⁾ for the Nd-Al-Fe al-

loy. The formation of these bulk amorphous alloys has enabled the evaluation of an impact fracture energy for amorphous alloys with sample dimensions which satisfy the Japanese Industrial Standard (JIS) criterion. This paper is intended to present the first data on the impact fracture energy of a bulk amorphous $\text{Zr}_{55}\text{Al}_{10}\text{Cu}_{30}\text{Ni}_5$ alloy by the use of the Charpy specimen with U-shape notch which satisfies the JIS criterion and to investigate the level of the impact fracture energy for the amorphous alloy in comparison with those for other metallic crystalline alloys.

II. Experimental Procedure

A quaternary alloy with composition $\text{Zr}_{55}\text{Al}_{10}\text{Cu}_{30}\text{Ni}_5$ was used in the present study because it had a large glass-forming ability and a wide supercooled liquid region before crystallization in metallic amorphous alloys. A bulk amorphous alloy with a dimension of 10 mm $\times$ 5 mm $\times$ 70 mm was prepared by the suction casting method⁽¹⁷⁾ developed by the present authors. The amorphous nature was identified by X-ray diffractometry, differential scanning calorimetry (DSC) and optical microscopy (OM). The specimen for the impact fracture test was prepared by mechanical cutting the cast amorphous alloy. The shape and dimension of the Charpy test specimen with a U-shape notch agree with those for the JIS-No. 3 (2.5 mm in width) type and are illustrated in Fig. 1. The fracture stress and displacement at the impact fracture and the impact fracture energy were measured at room temperature with the Charpy testing machine. The

Fig. 1 Shape and dimension of the specimen (JIS No. 3, 2.5 mm in width) used for the Charpy test.

initial angle of the arm bar was 143.5 degrees and the moving velocity at the impact was 3.761 m/s. The load-displacement curve was stored in the computer and the impact fracture energy was simultaneously calculated from the load-displacement curve. The fracture surface appearance was examined by scanning electron microscopy (SEM).

III. Results and Discussion

Figure 2 shows the X-ray diffraction pattern taken from the region near the U-shape notch in the Zr-Al-Cu-Ni specimen used for the impact fracture test. The diffraction pattern consists of a main broad peak at a wave vector ($K_p = 2\pi \sin \theta / \lambda$) of about 25.6 nm^{-1} and no appreciable diffraction peak corresponding to a crystalline phase is seen. We have also confirmed that no distinct contrast revealing the precipitation of a crystalline phase is seen over the transverse cross section of the cast bulk amorphous sheet. These metallographic results indicate that the test specimen made from the cast amorphous sheet is composed of only an amorphous phase. The amorphous alloy exhibits the glass transition at about 670 K, followed by the appearance of the wide supercooled liquid region with the temperature interval of about 85 K and then the onset of crystallization at 755 K, as shown in Fig. 3. The T_g , T_x and $\Delta T_x (= T_x - T_g)$ values as well as the single-stage exothermic behavior are in agreement with the previous data⁽⁸⁾ of the melt-spun amorphous ribbon.

Figure 4 shows the Charpy impact load-displacement curve for the $\text{Zr}_{55}\text{Al}_{10}\text{Cu}_{30}\text{Ni}_5$ amorphous alloy. The maximum load is measured to be 4.3 kN and hence the maximum impact fracture stress is evaluated to be 1615 MPa. It is to be noticed that the impact fracture stress is nearly the same as the static tensile fracture strength (about 1570 MPa)⁽¹⁸⁾ obtained in the wide strain rate range of 10^{-4} to 10^{-1} s^{-1} for the cast bulk Zr-Al-Cu-Ni amorphous alloy and the maximum displacement is as large as 0.44 mm. Furthermore, the impact fracture energy was measured to be 63 kJ/m². In comparison with the Charpy impact fracture energies for other metallic crystalline alloys, one can notice that the present impact fracture energy exceeds largely those (12 to 36 kJ/m²)⁽¹⁹⁾ for newly developed Al-based high-strength alloys which have al-

Fig. 2 X-ray diffraction pattern of the transverse cross section of the cast amorphous $\text{Zr}_{55}\text{Al}_{10}\text{Cu}_{30}\text{Ni}_5$ specimen used for the impact fracture test.

Fig. 3 DSC curve of the cast amorphous $\text{Zr}_{55}\text{Al}_{10}\text{Cu}_{30}\text{Ni}_5$ alloy.

Fig. 4 Charpy impact fracture load-displacement curve of the cast amorphous $\text{Zr}_{55}\text{Al}_{10}\text{Cu}_{30}\text{Ni}_5$ specimen.

ready been used in some application fields⁽¹⁹⁾. The comparison allows us to conclude that the present bulk amorphous alloy possesses the impact fracture energy which is high enough to enable the application as a structural material. The distinction to the three peaks in the impact load-displacement curve has frequently been observed in the Charpy test and is presumed to result from the

Fig. 5 Scanning electron micrograph of the Charpy impact fracture surface of the cast amorphous $\text{Zr}_{35}\text{Al}_{10}\text{Cu}_{30}\text{Ni}_5$ specimen.

sympathetic vibrations of the specimen at the impact fracture.

It is of importance to clarify the impact fracture mode of the Zr-based amorphous alloy with the high impact fracture energy. Figure 5 shows the whole fracture surface appearance of the cast amorphous Zr-Al-Cu-Ni specimen with the U-shape notch. In addition, the enlarged SEM images revealing the typical fracture surface appearance in the regions marked with A, B and C in Fig. 5 are shown in Fig. 6. The fracture surface consists of the typical vein pattern in the region just near the U-shape notch and changes to an equiaxed dimple-like pattern which occupies most of the region in the fracture surface. Neither shell-like pattern nor featureless cleavage-like pattern typical for embrittled amorphous alloys is seen over the whole fracture surface. The feature of the fracture surface appearance indicates clearly that the cast bulk amorphous alloy has the good ductility leading to the severe deformation even in the impact fracture mode. Besides, one can see secondary failures and the change in the fracture surface appearance from equiaxed dimple-like pattern to vein pattern is recognized near the failures. In Figs. 5 and 6, the secondary failures appear to occur in a close relation to casting defects. That is, the casting defect marked with an arrow seems to correspond to the interface between the formerly solidified amorphous region and the latterly solidified amorphous region. The amorphous phase region near the interface is subjected to subsequent heating. The subsequent heating seems to cause the decrease in ductility as compared with the as-cast amorphous phase without subsequent heating, leading to the generation of the secondary failures. Although the complete disappearance of the interface between the formerly and latterly solidified amorphous alloys is very difficult in the casting process, the decrease in the number of the interface is expected to cause a further increase in impact fracture energy.

IV. Summary

The impact fracture test of the bulk amorphous $\text{Zr}_{35}\text{Al}_{10}\text{Cu}_{30}\text{Ni}_5$ alloy was carried out at room temperature by using the JIS Charpy test specimen with U-shape

U-shape notch

Fig. 6 Enlarged scanning electron micrographs of the Charpy impact fracture surface of the cast amorphous $\text{Zr}_{35}\text{Al}_{10}\text{Cu}_{30}\text{Ni}_5$ specimen. The micrographs (a), (b) and (c) were taken from the regions A, B and C, respectively, in Fig. 5.

notch. The maximum stress and displacement at the impact fracture are 1615 MPa and 0.44 mm and the impact fracture energy is measured to be 63 kJ/m². The impact fracture energy is higher than those (12 to 36 kJ/m²) for the newly developed high-strength Al-based alloys in practical uses and the maximum fracture stress is also comparable to the static tensile strength (about 1570 MPa) for the Zr-based amorphous alloy. The fracture surface appearance changes from the vein pattern in the region just near the U-shape notch to the equiaxed dimple-like pattern with increasing distance from the notch site. Besides, secondary failures are observed and the failures appear to occur along the interface between the formerly and latterly solidified amorphous alloys. The good impact characteristics of high fracture energy, high fracture stress and large displacement indicate the possibility of future development of the bulk amorphous Zr-based alloy as a new engineering material.

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