Successful Electron-Beam Welding of Bulk Metallic Glass

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We have tried an electron beam welding of a $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ (at%) bulk metallic glass plate that has an excellent glass forming ability and a thermally stable supercooled liquid. We have for the first time succeeded in the electron-beam welding of the bulk metallic glass plate with a thickness of 3.5 mm. No crystallization was observed in the bead and heat-affected zone. No visible defect or crack was recognized around the bead and heat-affected zone. The tensile strength of the welded bulk metallic glass was the same as that of the parent bulk metallic glass. The successful condition of the electron-beam welding was an electron acceleration voltage of 60 kV, beam currents of 15 to 20 mA and a scanning velocity of 33 mm/s.

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1. Introduction

Bulk metallic glasses having a high glass-forming ability can be fabricated directly from the melt in a bulk form with a thickness of ~ 10 mm at slow cooling rates of the order of 1–100 K/s.^{1–3)} The bulk metallic glasses also have a wide supercooled liquid region before crystallization, and exhibit high-strain-rate superplasticity^{4–6)} and excellent workability⁷⁾ in the supercooled liquid state. Powder metallurgy processing using the superplasticity, moreover, enables the production of large-scaled bulk metallic glasses with the same tensile strength as the cast bulks.^{8–10)} These results demonstrate that the bulk metallic glasses solved two major problems in amorphous alloys, namely, limitation of product size and lack of workability. In 2001, we have solved another major subject that is lack of weldability. The bulk metallic glasses have been successfully welded by three methods of friction, pulse-current and explosion.^{10–14)} Electron-beam welding, where the high welding energy can be concentrated within a narrow zone, has a very wide application as compared with the friction, pulse-current and explosive methods. Recently, we have tried an electron-beam welding of a $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass, resulting in successful welding with keeping original mechanical properties and amorphous structure. In this paper, we will report the successful results of the electron-beam welding of the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass.

2. Experimental Procedure

A $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ (at%) ingot was re-melted in an evacuated quartz tube using an induction-heating coil and then injected through a nozzle into a copper mold using high purity argon gas. Specimens with 3.5 mm in thickness, 20 mm in width and 40 mm in length were prepared. The formation of a single glassy phase was confirmed by X-ray diffractometry. Figure 1(a) shows the schematic illustration of the bead-on-plate method used in this study. The electron-beam welding was carried out in a vacuum of 4×10^{-4} Torr using an electron beam welder with a maximum power of 9 kW. The

Fig. 1 Schematic illustration of welding method (a) and location of tensile test specimen (b).

voltage for acceleration of electrons was 60 kV and the beam current was 4, 8, 11, 15 and 20 mA. The work distance and the focus distance were 300 mm, respectively, resulting in the α_b value of 1.0. The scanning velocity of the electron beam was 33 mm/s. The welded samples were evaluated by optical microscopy of the polished cross-sectional area. The polished cross-section was etched at ambient temperature with an aqueous solution containing 1% hydrogen fluoride. The glassy structure was investigated by X-ray diffractometry using $\text{CuK}\alpha$ radiation. The strength of the welded samples was estimated by tensile tests. The tensile tests were carried out using an Instron tensile test machine at a strain rate of $5 \times 10^{-4} \text{ s}^{-1}$. The tensile test specimens having a gauge length of 10 mm, a thickness of 2 mm and a width of 2 mm were prepared by machining the welded bulk metallic glass, as shown in Fig. 1(b).

3. Results and Discussion

The surface of the front beads that were formed by scanning electron beams of 4 to 20 mA was very smooth and

mirror-like. The depth of the bead increased with increasing the electron-beam current. The electron beams of 15 and 20 mA formed beads on the backside of the bulk metallic glass plate with a thickness of 3.5 mm. It was, especially, observed during the welding that the electron beam of 20 mA bored through the bulk metallic glass plate. Figure 2 shows the optical micrograph of the polished cross-section of the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass scanned with the electron beam of 15 mA. There was no visible defect, pore or crack in both the bead and heat-affected zone (HAZ) for all the beam currents. After etching, no contrast was observed on the polished cross-section. Figure 3 shows the X-ray diffraction pattern of the cross-section of the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass welded by scanning the electron beam of 15 mA. The sample containing the bead and HAZ was used for the X-ray diffractometry, as shown in the inset of Fig. 3. The diffraction pattern consisted of a halo pattern, showing the existence of only glassy phase. No detectable amounts of other phases formed by crystallization were ob-

Fig. 2 Optical micrograph of the polished cross-section around the bead and HAZ of the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass plate scanned with an electron beam of 15 mA.

Fig. 3 X-ray diffraction pattern of the cross-section around the bead and HAZ of the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass plate scanned with an electron beam of 15 mA. The welded sample used for X-ray diffractometry is schematically illustrated in the inset.

served. This result reveals that the bead and HAZ were saved from devitrification and kept the amorphous structure. The tensile strength of the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ metallic glass scanned with the electron beam of 15 mA was 1840 ± 40 MPa. This tensile strength was the same as that of the parent $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass.²⁾ Vain patterns, which are typical of the fracture surface in amorphous alloys with good bending ductility, were observed over the whole fracture surface. It is concluded from the above-mentioned results that the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass plate with a thickness of 3.5 mm was perfectly welded with amorphous structure, full strength and ductility.

It has been reported that the nose time of the solid-heating *TTT*-diagram of the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ metallic glass is 5 s that is much smaller than 70 s of the melt-cooling *TTT* nose time.^{15,16)} This result suggests that the HAZ is liable to crystallize more easily than the bead zone. The duration, in which the bead and HAZ were heated from ambient temperature to the nose temperature or more and then cooled to the nose temperature, is estimated to be similar to or smaller than the nose times of the melt-cooling and solid-heating *TTT*-diagrams. The bead and HAZ, therefore, seem to avoid the devitrification during the welding process. Bulk metallic glasses having a melt-cooling *TTT* curve with a nose time above several tens seconds, such as Pd–Ni–P and Pd–Ni–Cu–P alloys, are expected to be successfully welded by the electron-beam welding. The electron-beam welding has a very wide application as compared with the pulse-current, friction and explosive methods. The successful results of the electron-beam welding are, therefore, expected to push forward the application of bulk metallic glasses.

4. Conclusions

We have tried an electron-beam welding of a $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ (at%) bulk metallic glass with an excellent glass forming ability. The bulk metallic glass plate with a thickness of 3.5 mm was successfully welded under the conditions of an electron acceleration voltage of 60 kV, beam currents of 15 to 20 mA and a scanning velocity of 33 mm/s. No crystallization was observed and no visible defect or crack was recognized in the bead and heat-affected zone. The tensile strength of the welded $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass was 1840 MPa that was almost the same as that of the parent bulk metallic glass. The heat input of the electron beam with high energy was so concentrated that the duration of the heating and cooling of the bead and heat-affected zone could be controlled within the melt-cooling and solid-heating *TTT* nose times for the crystallization of the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass.

REFERENCES

- 1) T. Masumoto: *Mater. Sci. Eng.* **A181/A182** (1994) 8–16.
- 2) W. L. Johnson: *MRS Symp. Proc.* **554** (1999) 311–339.
- 3) A. Inoue: *Bulk Amorphous Alloys, Preparation and Fundamental Characteristics*, (Trans Tech Publications, NH, 1998) pp. 1–37.
- 4) Y. Kawamura, T. Nakamura, A. Inoue and T. Masumoto: *Mater. Trans., JIM* **40** (1999) 794–803.
- 5) Y. Kawamura, T. Shibata, A. Inoue and T. Masumoto: *Scr. Metall. Mater.* **37** (1997) 431–436.

- 6) Y. Kawamura, T. Nakamura and A. Inoue: *Scr. Metall. Mater.* **39** (1998) 301–306.
- 7) Y. Kawamura, T. Shibata, A. Inoue and T. Masumoto: *Acta Mater.* **37** (1998) 253–263.
- 8) Y. Kawamura, H. Kato, A. Inoue and T. Masumoto: *Appl. Phys. Lett.* **67** (1995) 2008–2010.
- 9) Y. Kawamura, H. Kato, A. Inoue and T. Masumoto: *Mater. Sci. Eng.* **A219** (1996) 39–43.
- 10) Y. Kawamura, H. Kato, A. Inoue and T. Masumoto: *Int. J. Powder Metall.* **33** (1997) 50–61.
- 11) Y. Kawamura and Y. Ohno: *Mater. Trans.* **42** (2001) 717–719.
- 12) Y. Kawamura and Y. Ohno: *Scripta Mater.* **45** (2001) 279–285.
- 13) Y. Kawamura and Y. Ohno: *Scripta Mater.* **45** (2001) 127–132.
- 14) Y. Kawamura, Y. Ohno and A. Chiba: *Mater. Sci. Forum*, (2001), in press.
- 15) J. Schroers, A. Masuhr, R. Busch and W. L. Johnson: *MRS Symp. Proc.* **554** (1999) 263–268.
- 16) Y. J. Kim, R. Busch, W. L. Johnson, A. J. Rulison and W. K. Rhim: *Appl. Phys. Lett.* **68** (1996) 1057–1059.