Electron Beam Welding of Zr-Based Bulk Metallic Glass to Crystalline Zr Metal

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We have tried an electron-beam welding of a Zr-based bulk metallic glass plate to a polycrystalline Zr metal one for a $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ (at%) bulk metallic glass having an excellent glass forming ability. We have succeeded in butt-welding the bulk metallic glass and pure Zr metal plates with a thickness of 3 mm. Invisible defect or crack was detected around the bead and heat-affected zone. The bulk metallic glass around the interface kept the amorphous state. Formation of any crystalline phases except for hcp-Zr was not detected in the interface. The interface of the successfully welded sample exhibited enough toughness and joining strength to endure the bending through 90 degrees by hammering.

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1. Introduction

There have been three major subjects of limitation of product size, lack of workability and impossibility of welding in metallic glasses. The size limitation and poor workability have, however, been solved by developments of bulk metallic glasses with a thermally stable supercooled liquid. Bulk metallic glasses 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 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 bulk.^{8–10)} We have recently reported that the bulk metallic glasses were successfully welded by friction, pulse-current, explosion and electron-beam welding methods, resulting in solving the subject of welding.^{11–15)} The electron-beam welding has a very wide application as compared with the other methods. Welding of bulk metallic glasses to crystalline metals or alloys is expected to expand the application fields of the bulk metallic glasses. We have, therefore, tried an electron-beam welding of the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass plate to crystalline Ti or Zr metal plate. Consequently, the bulk metallic glass plate was successfully welded to the Zr metal plate with a tough and strong interface. 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 plate to crystalline Zr metal one.

2. Experimental Procedure

A $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ 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. Bulk metallic glass plate with 3.0 mm in thickness, 10 mm in width and 40 mm in length were prepared. The formation of a single glassy phase was confirmed by X-ray diffractometry. A polycrystalline pure Zr metal plate with 3.0 mm in thickness, 10 mm in width and 40 mm in length

were used for the welding. The butt-welding was carried out in a vacuum of 5×10^{-2} Pa using an electron beam welder with a maximum power of 9 kW. The electron-beam welding was carried out under the same conditions as the successful welding between the bulk metallic glass plates with a thickness of 3.5 mm.¹⁵⁾ The voltage for acceleration of electrons was 60 kV and the beam current was 20 mA. The work and the focus distances were 300 mm, respectively, resulting in the a_b value of 1.0. The scanning velocity of the electron beam was 33 mm/s. The welded samples were observed by optical microscopy (OM) of the polished cross-sectional area that was etched at ambient temperature with an aqueous solution containing 1% hydrogen fluoride. The polished cross-section was, moreover, investigated by electron probe micro analysis (EPMA). The glassy structure was investigated by micro-focused X-ray diffractometry using $\text{CuK}\alpha$ radiation. The diameter of the X-ray beam was 50 μm . A simple and easy bending test, in which the end of the bulk metallic glass was hammered under fixing the crystalline Zr metal, was carried out to evaluate the toughness and bonding strength of the interface. The bending test specimens having a thickness of 3.0 mm, a width of 3.0 mm and a length of 20 mm were prepared by machining the welded sample.

3. Results and Discussion

The electron beam of 20 mA bored through the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass and Zr metal plates. The surface in the front bead was very smooth and mirror-like. Figure 1 shows the optical micrograph of the etched cross-section around the interface between the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass and Zr metal plates welded with the electron beam of 20 mA. There was invisible defect, pore or crack around the interface. A bead was formed on the part of the bulk metallic glass. Although there was a distinguished contrast between the bulk metallic glass and crystalline Zr metal, visible contrast showing a formation of another phase besides amorphous and hcp-Zr ones was not observed around the interface. EPMA analysis of Zr element demonstrated that the thickness of the alloyed zone was 130 μm on the side of the bulk metallic glass and 140 μm on

Fig. 1 An optical micrograph of etched cross-section around the interface between $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass (BMG) and crystalline Zr metal plates that were welded by an electron beam of 20 mA.

Fig. 2 Micro-focused X-ray diffraction patterns of the cross-section around the interface between $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass (BMG) and crystalline Zr metal plates that were welded by an electron beam of 20 mA. The positions of the X-ray beam with a diameter of $50\text{ }\mu\text{m}$ were schematically shown in the inset.

the side of the Zr metal, resulting in the total alloyed thickness of $270\text{ }\mu\text{m}$. Figure 2 shows the micro-focused X-ray diffraction patterns of the cross-section around the interface between the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass and Zr metal plates welded with the electron beam of 20 mA. The X-ray diffraction patterns taken from the alloyed zone of the bulk metallic glass exhibited a halo pattern showing the keeping of the amorphous state. On the contrary, the X-ray diffraction pattern taken from the alloyed zone of the Zr metal exhibited diffraction peaks of α -Zr phase and non-detectable amounts of other phases were observed. This result reveals that the bulk metallic glass kept the amorphous structure and

Fig. 3 (a) A schematic illustration of the bending test by hammering, and (b) an outer appearance of the welded sample bent through about 90 degrees by hammering.

the melted zone was saved from the formation of brittle inter-metallic compounds. Figure 3(b) shows the outer appearance of the welded sample that was bent through about 90 degrees by hammering as shown in Fig. 3(a). The bending occurred at the crystalline Zr metal, and the bulk metallic glass containing the bead was not deformed. The Zr metal seemed to deform because the strength of the bulk metallic glass that is about $1900\text{ MPa}^{2)}$ is much higher than that of the crystalline Zr metal (less than 400 MPa). It should be noticed that the welded sample had enough toughness and joining strength to bear the bending by hammering.

The melting during the welding seems to occur in the metallic glass because the liquidus temperature of the bulk metallic glass is 1030 K that is one half of the melting temperature (2123 K) of the pure Zr metal.²⁾ The alloying of the bulk metallic glass with Zr was, therefore, restricted within a very thin region of $130\text{ }\mu\text{m}$. The Zr–Be–Ti–Ni–Cu alloy has a large glass-forming ability over a wide compositional region. For example, the maximum Zr content, where glass can be formed at a critical cooling rate of 500 K/s , is 57% in the Zr–Be–Ti–Ni–Cu alloys.²⁾ The alloyed region of the bulk metallic glass around the interface, therefore, seemed to be re-vitrified. On the other hand, the prevention of crystallization in the un-alloyed bead and heat-affected zone of the bulk metallic glass plate can be understood as a matter of course, because the $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass plates having a thickness of 3.5 mm could be successfully welded with keeping the original mechanical properties and amorphous structure by the electron-beam welding.¹⁵⁾ It is concluded that the considerable difference in melting point and the wide compositional region for high glass-forming

ability seem to prevent the crystallization of the bulk metallic glass and to suppress the formation of brittle intermetallic compounds, resulting in the tough and strong interface. 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 to the crystalline Zr metal are expected to push forward the application of bulk metallic glasses.

4. Conclusions

Electron-beam butt-welding of a $\text{Zr}_{41}\text{Ti}_{14}\text{Cu}_{12}\text{Ni}_{10}\text{Be}_{23}$ bulk metallic glass plate and crystalline Zr metal one has been tried. The bulk metallic glass plate with a thickness of 3 mm was successfully welded to the crystalline Zr plate under the conditions of an electron acceleration voltage of 60 kV, a beam current of 20 mA and a scanning velocity of 33 mm/s. The bulk metallic glass around the interface kept the amorphous state. Formation of any crystalline phases except for hcp-Zr was not observed around the interface. Invisible defect or crack was also detected around the interface. The interface of the welded sample exhibited enough toughness and joining strength to endure the bending by hammering.

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