Metallurgical Bonding of Bulk Metallic Glasses

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In order to establish metallurgical bonding technology of bulk metallic glasses, we have tried to weld $\text{Pd}_{40}\text{Ni}_{40}\text{P}_{20}$ and $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ bulk metallic glasses having a wide supercooled liquid region and high glass forming ability by two welding methods of friction and pulse-current. We have for the first time succeeded in joining bulk metallic glasses by both methods. No crystallization was observed in the interface and heat-affected zones. No visible defect was recognized at the interface, showing an achievement of metallurgical bonding of bulk metallic glasses. The tensile strength of the welded bulk metallic glasses was the same as that of the parent bulk metallic glasses.

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1. Introduction

Recently, a number of amorphous alloys having a wide supercooled liquid region before crystallization and high glass-forming ability have been discovered.^{1–3)} Such amorphous alloys 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. The new amorphous alloys are, therefore, called “bulk metallic glasses”. The bulk metallic glasses 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 and melt-spun ribbon.^{8,9)} These results demonstrate that the bulk metallic glasses can solve two main problems for amorphous alloys, namely, the limitation of product size and the lack of workability. The problem of welding is, however, still unsolved.

It has been reported that strong bonding of the powder particles is obtained by the breakdown and distribution of the surface oxide film on the powder particles, resulting from the superplastic deformation during the powder consolidation by extrusion.⁹⁾ A friction welding is expected to bond bulk metallic glasses using the superplastic deformation of the supercooled liquid.¹⁰⁾ On the other hand, the crystallization nose of Time-Temperature-Transformation (TTT) diagram of the bulk metallic glasses has been reported to be in the range of 1 to 100 s.²⁾ A pulse-current welding is expected to enable the welding of the bulk metallic glasses without a devitrification because its welding duration can be controlled within 1.0 s.¹⁰⁾ We have, therefore, tried the welding of the bulk metallic glasses by both the friction and pulse-current methods. In this paper, we will report successful results of the welding of the $\text{Pd}_{40}\text{Ni}_{40}\text{P}_{20}$ and $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ bulk metallic glasses by these methods.

2. Experimental Procedure

We have previously reported that the $\text{Pd}_{40}\text{Ni}_{40}\text{P}_{20}$ metallic glass exhibited high-strain-rate superplasticity in supercooled liquid state.⁶⁾ Friction method was investigated for the $\text{Pd}_{40}\text{Ni}_{40}\text{P}_{20}$ metallic glass. On the contrary,

the $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ metallic glass has been reported to have higher glass forming ability in Zr–Al–Ni–Cu metallic glasses.³⁾ Pulse-current method was, therefore, examined for the $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ metallic glass. The $\text{Pd}_{40}\text{Ni}_{40}\text{P}_{20}$ bulk metallic glasses, of which glass transition, crystallization and melting temperatures are 578, 651 and 973 K, respectively,⁶⁾ were prepared by water quenching method. The dimensions of the obtained bulk metallic glasses were 50 mm in length and 4.4 mm in diameter. The specimens to be welded, which were 4.4 mm in diameter and 10 mm in length, were prepared by machining the cast bulk metallic rods. The $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ bulk metallic glasses, of which glass transition, crystallization and melting temperatures are 684, 766 and 1100 K, respectively,³⁾ were prepared by Cu-mold casting. The dimensions of the obtained bulk metallic glasses were 2.5 mm in thickness, 7 mm in width and 50 mm in length. Specimens to be welded, which were 2 mm in thickness, 4 mm in width and 13.5 mm in length, were prepared by machining the cast bulk metallic plates. The formation of a single glassy phase in these specimens was confirmed by X-ray diffractometry.

The friction welding was performed using a conventional friction-welding machine. One specimen of a pair to be welded was rotated at the rate as fast as 6000 rpm. The pressure of the friction and upsetting was 100 and 150 MPa, respectively. The times of the friction and upsetting were 0.2 and 3.0 s, respectively. On the other hand, the pulse-current welding setup was developed in this study. The developed setup was equipped with a pair of holders of the specimens, an oil press, a transformer core and a power-supply unit of a low-voltage capacitor with $4 \times 10^4 \mu\text{F}$. Current passing through the specimens was controlled by the voltage charged in the capacitor. The charged voltage was 150 V. The current was discharged at the moment, when the pressure reached to 100 MPa. The current passing through the specimens was measured by a toroidal core.

The joining state was investigated by optical microscopy (OM) of the polished cross-sectional area of the interface in the welded specimens. The glassy structure was investigated by micro-area X-ray diffractometry using $\text{CrK}\alpha$ radiation. The diameter of the X-ray beam was 50 μm and 100 μm for the welded $\text{Pd}_{40}\text{Ni}_{40}\text{P}_{20}$ and $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ bulk metallic glasses, respectively. The bonding strength of the inter-

face 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 dimensions of the tensile test specimens that were prepared by machining the welded samples were a gauge length of 4.0 mm and a diameter of 1.7 mm for the $\text{Pd}_{40}\text{Ni}_{40}\text{P}_{20}$ metallic glass, and a gauge length of 6.0 mm, a thickness of 1.3 mm and a width of 2.0 mm for the $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ metallic glass. The tensile strength of the parent bulk metallic glass was measured for comparison.

3. Results and Discussion

Figure 1(a) shows the outer appearance of the $\text{Pd}_{40}\text{Ni}_{40}\text{P}_{20}$ bulk metallic glasses joined by the friction-welding method in which the friction time was 0.2 s. Protrusion with a thickness of about $450 \mu\text{m}$ and a length of about 6 mm was observed on the outside of the interface. Figure 1(b) shows the optical micrograph of the polished cross-section of the interface. No visible interface was observed, showing the achievement of metallurgical bonding of the bulk metallic glasses. It should be noticed that neither deformation nor swelling was observed beside the thin protrusion. Figure 2(a) shows the outer appearance of the $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ bulk metallic glasses joined by the pulse-current welding where the maximum value and half-maximum breadth of the welding current were 1.9 kA and 25 ms. A flash with a thickness of about 1 mm and a length of about 1 mm was observed on the outside of the interface. Figure 2(b) shows the optical micrograph of the polished cross-sectional area of the interface. There is no visible defect

or pore in the interface. This reveals that metallurgical bonding was achieved successfully by the pulse-current method. Figure 3 shows X-ray diffraction patterns of the interface of the $\text{Pd}_{40}\text{Ni}_{40}\text{P}_{20}$ and $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ metallic glasses welded by the friction and pulse-current methods. Each diffraction pattern consisted of a halo pattern showing the existence of only glassy phase. No detectable amounts of other phases were observed. These results demonstrate that the interface and heat-affected zones of the welded $\text{Pd}_{40}\text{Ni}_{40}\text{P}_{20}$ and $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ metallic glasses kept the amorphous nature without devitrification. Further investigations using a high-resolution electron microscopy, however, seem to be necessary in order to make absolutely certain the amorphous structure. The tensile strength of the welded metallic glasses was 1590 MPa for the $\text{Pd}_{40}\text{Ni}_{40}\text{P}_{20}$ metallic glass and 1540 MPa for the $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ metallic glass. These values of the tensile strength were the same as that of the parent bulk metallic glasses. Vein pattern, which is a typical fracture pattern for amorphous alloys with good bending ductility, was observed over the whole fracture surfaces. It was, therefore, confirmed that the bulk metallic glasses were successfully welded with metallurgical bonding, glassy phase, ductility and full strength.

Here we shall consider the welding mechanism of the bulk metallic glasses in the friction and pulse-current methods. The friction welding is a solid-state welding process in which the heat for welding is produced by the relative motion of the two interfaces.¹⁰⁾ In the friction welding of bulk metallic glasses, the temperature of the interface can be controlled in

Fig. 1 Outer appearance (a) and optical micrograph of the polished cross section of the interface (b) in the $\text{Pd}_{40}\text{Ni}_{40}\text{P}_{20}$ bulk metallic glasses joined by a friction welding.

Fig. 2 Outer appearance (a) and optical micrograph of the polished cross section of the interface (b) in the $\text{Zr}_{55}\text{Al}_{10}\text{Ni}_5\text{Cu}_{30}$ bulk metallic glasses joined by a pulse-current welding.

Fig. 3 Micro-focused X-ray diffraction patterns of the interface and heat-affected zones in Pd₄₀Ni₄₀P₂₀ bulk metallic glasses joined by the friction welding (a), and Zr₅₅Al₁₀Ni₅Cu₃₀ bulk metallic glasses joined by the pulse-current welding (b). The diffraction patterns were taken from the several points of the interface and heat-affected zone, as shown in the insets.

the range of the glass transition temperature to crystallization temperature because the viscosity of the supercooled liquid decreases drastically with increasing temperature.¹¹⁾ The projection seems to be formed by superplastic deformation of the supercooled liquid in the interface. The friction and formation of the protrusion seem to generate the discharge of the broken oxide films as well as the distribution and breakdown of the oxide films on the surface, resulting in metallurgical bonding through the freshened surfaces. Moreover, crystallization may have been avoided because of a short friction time of 0.2 s that is much shorter than crystallization nose time of Time-Temperature-Transformation (*TTT*) diagram of the Pd₄₀Ni₄₀P₂₀ metallic glass.²⁾ On the contrary, the pulse-current welding is a liquid-state welding process in which the

heat is generated from an arc produced by a rapid discharge of electrical energy.¹⁰⁾ The temperature of the interface reaches above the melting temperature. The metallurgical bonding can be obtained by the melting of the interface. The Zr–Al–Ni–Cu based bulk metallic glasses have been reported to have a crystallization nose time ranging from 1 to 10 s in *TTT* diagram and be fabricated from the melts in a bulk form with a thickness of about 10 mm.²⁾ The half-maximum breath of the current passing through the bulk metallic glasses was 25 ms and the thickness of the melted or heat-affected zone was less than 2 mm. The heat input of the welding was so concentrated and of such short duration that the melted interface and heat-affected zones seem to avoid the devitrification.

La–Al–Ni, Mg–Cu–Y, Pd–Ni–P, Zr–Ti–Cu–Ni–Be and Pd–Ni–Cu–P bulk metallic glasses have *TTT*-diagrams with a crystallization nose in the range of 1–100 s and a high glass forming ability.²⁾ Accordingly, these bulk metallic glasses can be welded successfully by the friction or spark welding method, as well as the Pd₄₀Ni₄₀P₂₀ and Zr₅₅Al₁₀Ni₅Cu₃₀ metallic glasses used in this study. Moreover, these welding methods are expected to permit the joining of bulk metallic glasses to bulk metallic glass with different compositions and to conventional crystalline materials.

4. Conclusions

We have succeeded in joining bulk metallic glasses of Pd₄₀Ni₄₀P₂₀ and Zr₅₅Al₁₀Ni₅Cu₃₀ alloys by both the friction and pulse-current welding methods, respectively. Metallurgical bonding was achieved. No crystallization was observed in the interface and heat-affected zones. No visible interface was, moreover, recognized. The tensile strength of the welded bulk metallic glasses was the same as that of the parent bulk metallic glasses. Given the possibility of welding bulk metallic glasses, one can expect that the bulk metallic glasses will make further progress in diverse applications.

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