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Joining of Zr-based bulk metallic glasses using the friction welding method

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Abstract

Friction welding of Zr-based bulk metallic glass ($Zr_{55}Al_{10}Ni_5Cu_{30}$ alloy) has been tried. Friction time and friction pressure were chosen as the control parameters for the friction welding process. Their influences on the shape and volume of the protrusion formed from the welded interface were investigated. Temperature distribution around the interface during friction welding was measured using an infrared thermal imager. Successful joining of $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG was accomplished through the precise control of friction time and friction pressure. Whether crystallization occurred or not during friction welding correlated to the volume of the protrusion formed at the welded interface.

Keywords: Amorphous materials; X-ray diffraction; Friction welding; High pressure

1. Introduction

Recently, a number of multi-component alloy systems capable of formation of glass phase at relatively low cooling rates (1–100 K/s) were discovered and show higher thermal stability against crystallization [1–3]. Bulk metallic glasses (BMG) have been developed for structural applications utilizing their high strength, large elastic deformation limit, and superior corrosion and wear resistance at room temperature. Although bulk BMG of cm-order dimension can be produced, the size to be used for some engineering and structural applications may be superior. Therefore, efforts to overcome the size limit through the improvement of the workability of BMGs are needed [1,2].

In this study, to solve this size limit problem, the friction welding of $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG has been tried, utilizing the superplastic-like deformation behavior in the supercooled liquid region. An apparatus which allows to control precisely both the friction time and the friction pressure applied to the BMG specimens during friction welding was devised.

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2. Experimental procedure

The BMG has a composition of $Zr_{55}Al_{10}Ni_5Cu_{30}$ and a cylindrical rod shape of 4 mm in diameter and 40 mm in length. It was prepared by copper mold casting in an argon atmosphere. The thermal properties were measured using differential scanning calorimetry (DSC) with a heating rate of 0.33 K/s; the glass transition temperature (T_g), the crystallization onset temperature (T_x) and peak temperature were 680, 762 and 767 K, respectively. The heat of crystallization (ΔH_x) and supercooled liquid region ($\Delta T_x = T_x - T_g$) were 35.8 J/g and 81 K, respectively.

A pair of specimens for friction welding was fabricated from the as-cast rod. They have dimensions of 4 mm in diameter, 12 mm in length and 0.5 mm chamfer at the contacting part. An apparatus for the friction welding of BMGs which adopted a pneumatic actuator and gripper based on a conventional lathe was devised. During the welding process, the friction time and the motion of pneumatic actuator which applies the friction pressure to specimens were controlled using a DAQ board and a PC based program. The friction welding process is shown in Fig. 1. The friction pressure and friction time adopted in this study were in the range of 100–200 MPa and 0.4–1.0 s, respectively. The rotational speed was fixed at 1800 rpm. Firstly, the rotating specimen was chucked in and rotated at a constant speed of 1800 rpm, the stationary specimen was simply fixed by the pneumatic gripper. Secondly, a friction pressure was applied to the stationary side specimen by the pneumatic actuator which was controlled by pneumatic pressure. Then the stationary side specimen moved toward the rotating side specimen generating a protrusion at the weld interface. When a specified length was moved due to the movement of the pneumatic actuator, the pneumatic gripper released the welded specimen finishing the welding process, and the rotation was stopped by braking.

During friction welding, the temperature distribution around the weld interface of specimens was simultaneously measured using an infrared thermal

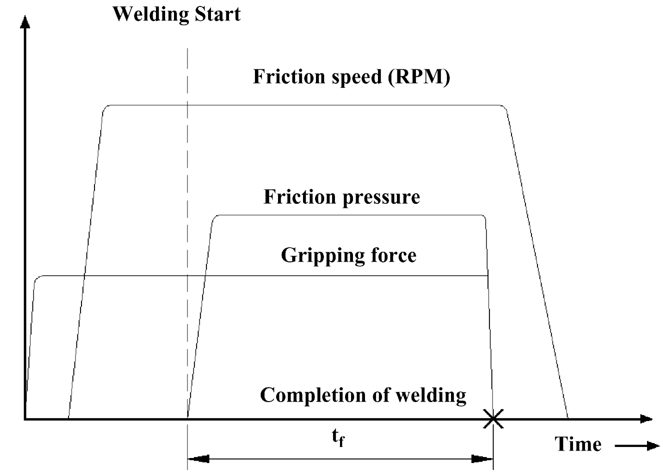

Fig. 1. Friction welding process of BMGs using a newly devised apparatus.

imager. After the welding test, the development of the protrusion was investigated. X-ray diffraction (XRD) and micrographic observations on the cross-sections of the welded BMGs were carried out.

3. Results and discussion

Fig. 2 shows appearance of $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG specimens joined by friction welding. Protrusions were formed at the interface of welded specimens. Their shape and volume were different depending on the adopted friction pressure–friction time combination. As the friction pressure and friction time increased, generally, a significant protrusion was formed around the whole welded interface. Material at the interface was moved outward forming a protrusion caused by superplastic deformation when a friction pressure was applied [4–6] and the contact surfaces heated up above the glass transition temperature (T_g). Eventually, expulsion of the oxide film at the interface in the form of protrusion resulted in the metallurgical bonding between the freshened surfaces [7]. Fig. 3 shows optical micrographs of cross-sections after polishing friction welded specimens at various friction times under a pressure of 200 MPa. The protrusion was formed in all welded specimens successfully welded without any defect, crack or discontinuous part. Fig. 4 shows the change of the volume of protrusion as a function of friction time at each friction pressure applied. The volume of protrusion increased linearly with friction time. It was found that the friction time had a larger influence on protrusion formation as compared with the friction pressure.

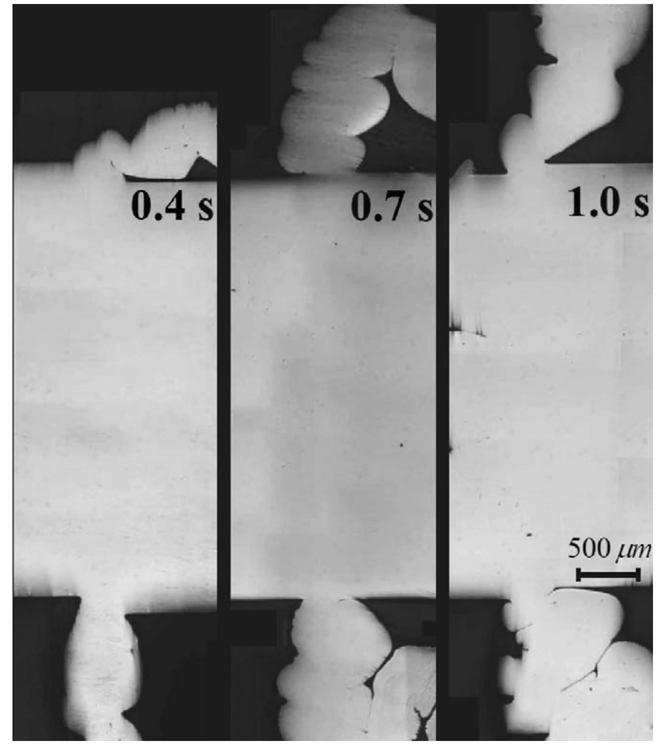

Fig. 3. Optical micrographs of polished cross-sections after friction welding at friction pressure of 200 MPa.

The thickness of the protrusion was measured at its root. The change of the thickness of protrusion with friction time is shown

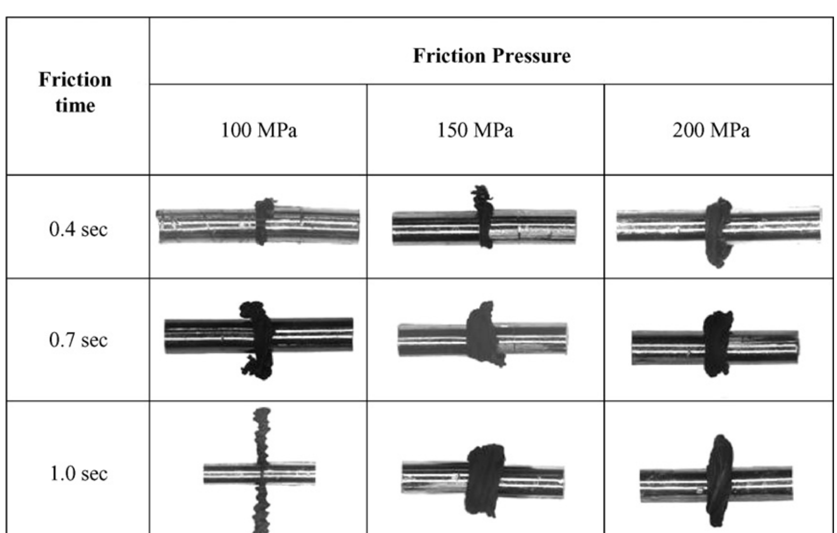

Fig. 2. Appearance of friction welded $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG specimens.

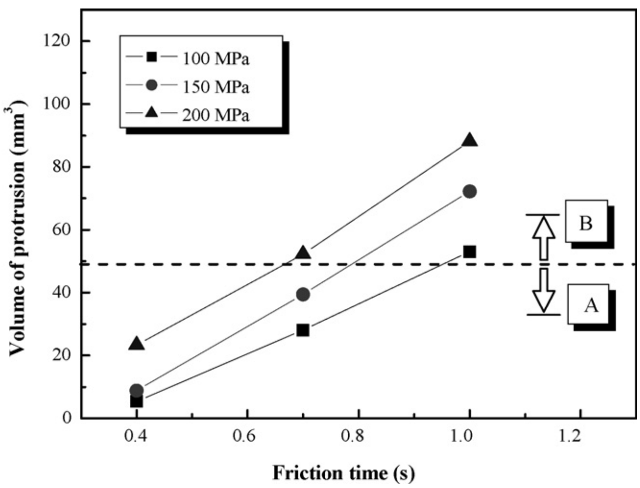

Fig. 4. Changes in the volume of protrusion with friction time.

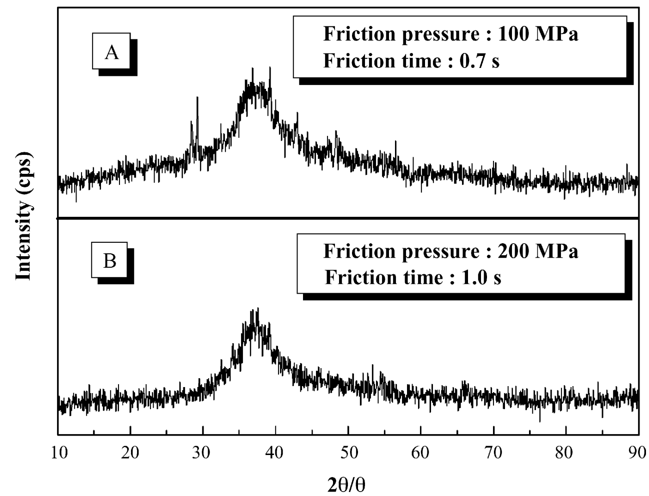

Fig. 6. X-ray diffraction traces on cross-section including welded interface.

in Fig. 5. At a low friction pressure of 100 MPa, the protrusion thickness became wider with the increase of friction time, but at higher friction pressures, the protrusion thickness was nearly constant regardless of friction time; about 420 μm, shown as a slash line in Fig. 5. The heating up of the interface due to friction resulted in the low viscosity of the bulk metallic glass near the interface. Then a continuous protrusion at critical thickness was formed by superplastic deformation during friction welding when the applied pressure was high [8].

In the friction welding process, the conditions should be selected to avoid crystallization during friction welding. If the temperature at the interface is known, we can estimate the friction time to avoid crystallization based on the T–T–T diagram [5,9]. In order to measure the temperature distribution at the interface during friction welding using the infrared thermal imager, it is necessary to tune the emissivity. In the case of $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG, it was set at 0.33 at the initial stage, but it increased to 0.9 after protrusion occurred. As a result, the maximum temperature measured at the weld interface of $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG was in the range of 720–770 K according to test conditions. Considering the measured temperature and the friction time adopted, it could be confirmed that crystallization did not occur at a longer friction time on the T–T–T diagram of $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG [4,5]. Therefore, it is possible to maintain a longer friction time forming sufficient protrusion and creating freshened surfaces, and preventing crystallization.

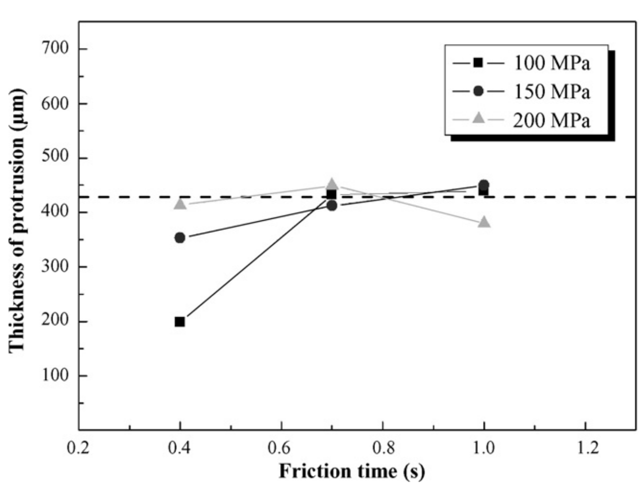

Fig. 5. Changes in the thickness of protrusion with friction time at each friction pressure.

The XRD measurements were carried out to confirm the occurrence of crystallization during friction welding. XRD traces are shown in Fig. 6. They could be classified into two types; Type A: exhibited a diffraction peak of crystalline phase. Type B: exhibited a halo pattern, showing the existence of only glassy phase. The types exhibited at each welding condition were summarized in Fig. 7. Type A was obtained at the lower friction pressure–shorter friction time conditions, but Type B occurred in the region of higher friction pressure–longer friction time. The minimum protrusion volume could be assessed from the conditions which exhibited Type B, it corresponded to about 50 mm^3, and the value was plotted as a slash line in Fig. 4 dividing the results shown in Fig. 4 into Type A and B regions. When sufficient protrusion formed, the oxide film did not exist at the interface any more and only glassy phase (Type B) was observed. On the other hand, when the protrusion formed was not sufficient, some oxide films still existed at the interface and some crystalline phase (Type A) was detected [10,11]. Therefore it is important to know that a minimum volume of protrusion has to be formed in order to achieve a successful welding of BMG without crystallization.

Time \ Pressure	100 MPa	150 MPa	200 MPa
0.4 s	A	A	A
0.7 s	A	A	B
1.0 s	B	B	B

Fig. 7. XRD types obtained after friction welding at each test condition.

4. Conclusions

Using a newly devised friction welding apparatus which incorporates a pneumatic actuator and gripper to give precise control of the friction time and pressure, the friction welding of Zr-based BMG was successfully accomplished without visible defects, pores or cracks on the interface. Through the measurements of temperature at the welded interface during friction welding and XRD after welding, it was confirmed that crystallization did not occur at the condition of longer friction time-higher friction pressure. Friction time has a significant effect on the formation of protrusion as compared with the friction pressure. It is necessary to have a minimum volume of protrusion formed from the welded interface to achieve successful friction welding of BMG without crystallization.

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