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# FRICTION WELDING OF $Cu_{45}Zr_{45}Ag_5Al_5$ BULK METALLIC GLASS

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**Abstract.** The friction welding of a Cu-based bulk metallic glass (BMG) to similar and dissimilar BMGs was tried. An apparatus which can precisely control friction time and pressure was devised. The influences of welding condition on the shape and volume of the protrusion formed from the welded interface were investigated. Through the precise control of friction time and friction pressure, a successful joining at the welded interface could be accomplished in both the similar $Cu_{45}Zr_{45}Ag_5Al_5/Cu_{45}Zr_{45}Ag_5Al_5$ BMG alloy and the dissimilar $Cu_{45}Zr_{45}Ag_5Al_5/Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG combinations without crystallization. The friction welding of $Cu_{45}Zr_{45}Ag_5Al_5$ BMG to the crystalline materials of Ti-4V-6Al alloy was also tried.

## 1. INTRODUCTION

Bulk metallic glasses (BMGs) have been developed for structural applications utilizing their superior mechanical properties. But the size to be used for engineering and structural application fields is still not enough. Therefore, efforts to solve the size limit through the improvement of the workability of BMGs are needed [1-3]. In this study, in order to solve this size limit problem, the friction welding of a $Cu_{45}Zr_{45}Ag_5Al_5$ BMG[4] to similar and dissimilar BMGs was tried, utilizing the superplastic-like deformation behavior in the supercooled liquid region.

## 2. EXPERIMENTAL

The sample supplied had a composition of $Cu_{45}Zr_{45}Ag_5Al_5$ and $Zr_{55}Al_{10}Ni_5Cu_{30}$ with a cylindrical rod shape of 4 mm in diameter and 50 mm in length. It was prepared by copper mold casting in an argon atmosphere. Their thermal properties were measured using differential scanning calorimetry (DSC) with a heating rate of 0.33 K/s.

A pair of specimens for friction welding was fabricated from the as-cast rod. They had dimensions of 4 mm in diameter, 12 ~ 14 mm in length and a 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. The details of the apparatus and welding procedure adopted were described in previously reported Ref. [5]. The friction pressure and friction time adopted were in the range of 100~200 MPa and 0.4~1.0 sec, respectively. 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

The measured thermal properties of $Cu_{45}Zr_{45}Ag_5Al_5$ and $Zr_{55}Al_{10}Ni_5Cu_{30}$ BMGs are summarized in Table 1. Both BMG alloys exhibit similar characteristics in $T_g$, $T_x$, and $\Delta T_x$.

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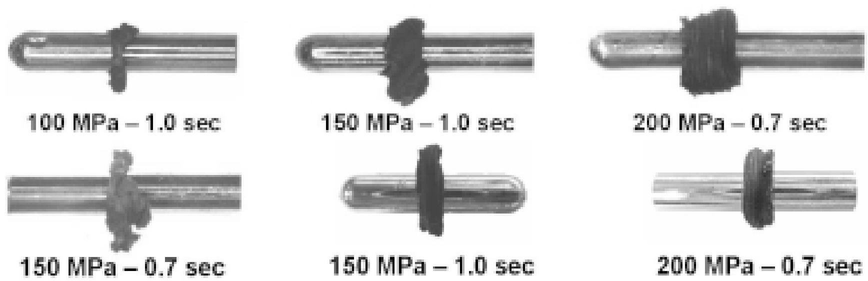


**Fig. 1.** Appearances of weld BMG specimens after the friction welding; (a) Similar BMG welding of $Cu_{45}Zr_{45}Ag_5Al_5/Cu_{45}Zr_{45}Ag_5Al_5$ alloys and (b) dissimilar BMG welding of $Cu_{45}Zr_{45}Ag_5Al_5/Zr_{55}Al_{10}Ni_5Cu_{30}$ alloys.

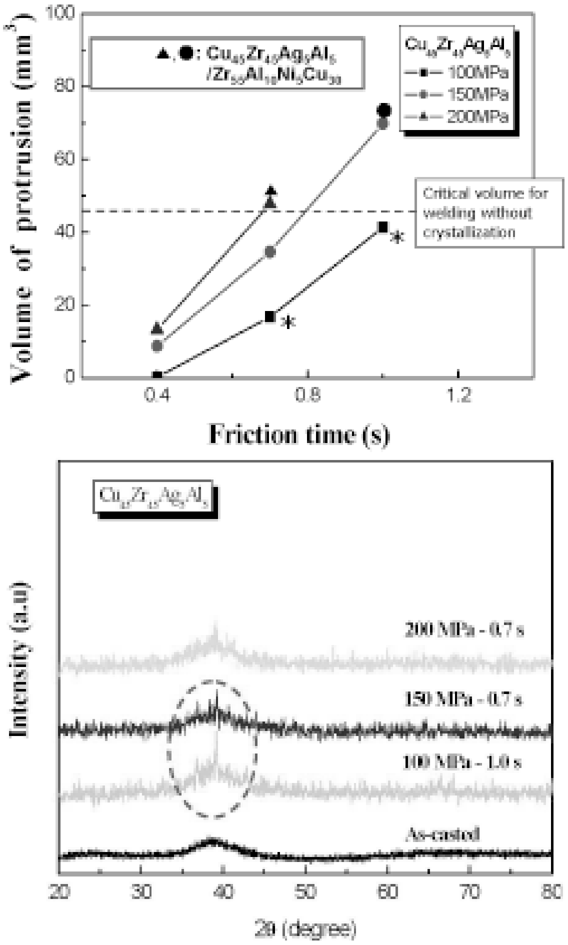


**Fig. 2.** (a) Changes in the protrusion volume with friction time and pressure and (b) X-ray diffraction traces on cross-section including welded interface in the friction welded similar $Cu_{45}Zr_{45}Ag_5Al_5$ BMG alloy.

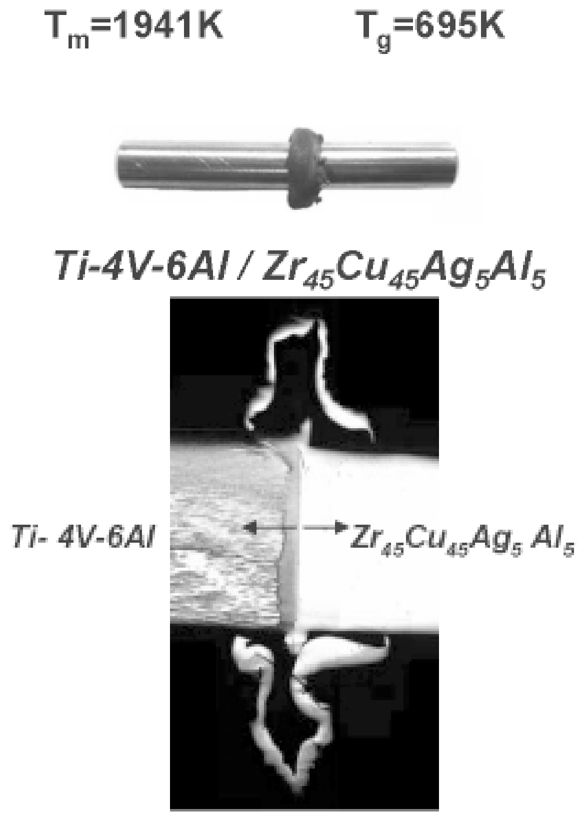


**Fig. 3.** (a) Appearance of dissimilar friction welding of $Zr_{45}Cu_{45}Ag_5Al_5$ BMG to Ti-alloys at the condition of 200 MPa - 1.0 sec and (b) optical micrograph of polished cross-section.

**Table 1**. Thermal properties of $Cu_{45}Zr_{45}Ag_5Al_5$ and $Zr_{55}Al_{10}Ni_5Cu_{30}$ alloys.

| | $T_g$ (K) | $T_x$ (K) | $\Delta T_x(=T_x - T_g)$ |
|---|---|---|---|
| $Cu_{45}Zr_{45}Ag_5Al_5$ | 695 | 781 | 86 |
| $Zr_{55}Al_{10}Ni_5Cu_{30}$ | 680 | 762 | 82 |

Fig. 1 shows appearances of specimens friction welded under each test condition; (a) represents cases of similar BMG welding of $Cu_{45}Zr_{45}Ag_5Al_5/Cu_{45}Zr_{45}Ag_5Al_5$ and (b) cases of dissimilar BMG welding of $Cu_{45}Zr_{45}Ag_5Al_5/$

$Zr_{55}Al_{10}Ni_5Cu_{30}$. Protrusions are formed from both parts on the interface of welded similar and dissimilar BMG combinations. Depending on the adopted friction pressure - friction time, the protrusion shape and volume formed are different. As the friction pressure and friction time increases, the heating up above the glass transition temperature ($T_g$) of the interface due to friction results in the lower viscosity of the interface. Then a significant protrusion is formed around the whole welded interface because the interface region is protruded outward due to the superplastic deformation behavior when friction pressure is applied, discharging the oxide film at the interface in the form of protrusion. In the case of dissimilar BMG welding, successful friction welding could be achieved since the difference of $T_g$ in coupled BMG alloys was small [2,3].

Fig. 2a shows the change of the volume of protrusion as a function of friction time at each friction pressure level in the cases of similar BMG welding. The volume of protrusion increases linearly with friction time. It can be seen that the influence of friction pressure on protrusion formation appears significantly as the friction times increases.

In the friction welding process, the conditions should be selected to avoid crystallization to occur on the interface during friction welding. XRD measurements were carried out to confirm the occurrence of crystallization during friction welding. XRD traces measured at selected conditions are shown in Fig. 2b. The specimens tested at the "*" marked condition exhibit a diffraction peak of crystalline phase, but the specimen tested above the minimum protrusion volume plotted as a dotted line which is corresponding to about 45 mm$^3$, exhibits a halo pattern showing the existence of only the glassy phase [5]. From this result, it can be found that when the protrusion volume formed is insufficient, partial crystallization occurs at the interface. In addition, the protrusion volumes obtained from the dissimilar friction welding of $Cu_{45}Zr_{45}Ag_5Al_5$/$Zr_{55}Al_{10}Ni_5Cu_{30}$ BMG combinations are added into Fig. 2a, where the protrusion volume formed is almost the same as with the case of similar BMG welding.

On the other hand, a friction welding of $Cu_{45}Zr_{45}Ag_5Al_5$ BMG to the crystalline material of Ti-4V-6Al alloy was tried. A successful joining can be achieved at the condition of 150 MPa – 1.0 sec, shown in Fig. 3a. Fig. 3b shows the cross-sectional view of the weld interface. It can be seen that the joining was done firmly at the interface, although the protrusion formed from the BMG side which has a quite low $T_g$ when compared with the temperature corresponding to the plastic flow of Ti-alloy. In order to examine the weldability of Cu-based BMG to dissimilar welding cases, further efforts including weld strength evaluation are needed.

When the protrusion volume exceeds a critical value, the Cu-based BMG alloy produced successful welding without any crystallization at the interface regardless of similar or dissimilar BMG friction welding.

## 4. SUMMARY

Using a newly devised friction welding apparatus which incorporates a pneumatic actuator and gripper to give a precise control of the friction time and pressure, the friction welding of $Cu_{45}Zr_{45}Ag_5Al_5$ BMG alloy to similar and dissimilar BMG was accomplished. Through the measurements of protrusion volume at the welded interface during friction welding and XRD measurements after welding, it was confirmed that crystallization did not occur at the conditions of longer friction time-higher friction pressure. When the protrusion volume exceeded a critical value, the Cu-based BMG alloy produced successful welding without crystallization at the interface regardless of similar or dissimilar BMG friction welding.

## ACKNOWLEDGEMENTS

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