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Characteristics of friction stir spot welding of Zr-based bulk metallic glass sheets

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ABSTRACT

In this study, the friction stir spot welding (FSSW) of Zr-based BMG sheets has been investigated using an apparatus which was devised with a CNC milling machine to give a precise control of the friction time and the plunge depth. The variation of vertical load pressing the sheet specimens and the temperature history during friction stirring were measured which are closely related to the deformation behavior of BMG materials at the supercooled liquid region. A characteristic behavior during FSSW of BMG sheets was found. Influences of the plunge speed and plunge depth on the characteristic features of FSSW of BMG sheets were investigated. The micrographic observation and the tensile shear test were carried out to characterize the behaviors of FSSW of BMG sheets. The fractographic analysis at the fracture surfaces was done.

1. Introduction

The bulk metallic glasses (BMGs) have been developed for the expansion of structural applications utilizing their superior mechanical properties. However, the availability of various sizes to be used for engineering and structural application fields is still limited. In order to solve the size limit problem and to extend the application field of BMGs, it is necessary to develop a new joining technique applicable to parts having sheet in shape. There are reports that some studies on the friction welding of similar and dissimilar BMG rods had succeeded [1–3], but studies for application of friction stir welding (FSW) technique to BMG sheets have just started and limited [4–7]. In this study, the application of friction stir spot welding (FSSW) technique to the BMG sheets has been initially investigated and the characteristic feature observed was discussed based on the influences of plunge depth and plunge speed of the probe on it.

2. Experimental procedures

In this study, a Zr-based BMG having a composition of $Zr_{41.5}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (Vit-1) was supplied. The specimen was machined from a commercially available 7 mm thickness plate to a coupon-shape with dimensions of 100 mm × 10 mm × 1 mm in thickness. Thermal properties of the Vit-1 BMG measured using DSC are as follows; the glass transition temperature (T_g) and the crystallization temperature (T_x) are 623 and 705 K, respectively. And the supercooled liquid region ($\Delta T_x = T_x - T_g$) was 82 K.

Fig. 1(a) shows the apparatus for FSSW used in this study. The FSSW process of BMG sheets was carried out by plunging the rotating probe tool onto the single lapped BMG sheet specimen fixed using a jig on the bed of the small-scale CNC milling machine. By using the CNC milling machine, it is possible to control both plunge depth and plunge speed of the probe. Fig. 1(b) shows the probe tool used. The tool has a cylindrical shoulder and pin part. The diameters of the shoulder and the pin used were 4.0 and 1.5 mm, respectively. The depth of the probe pin is 1.2 mm, and the angle of chamfer within the shoulder end surface is 10°.

The process profile and test conditions for FSSW adopted in this study are shown in Fig. 2. In this study, a nominal plunge speed was used instead of the actually measured plunge speed although it showed a little bit smaller value than the nominal one. During FSSW, the temperature distribution around the shoulder on the upper specimen was measured by using an infrared imager (FLIR-ThermaCam SC-2000). In this case, the area of measured object was larger than 6 mm^2 including an error of ±3 K. Also, the vertical load pressing the specimens was measured using a loadcell installed under the jig. The fracture load of the FSSW weld BMG specimens was evaluated by a tensile–shear test. The fractographic observation has been done using optical microscope and SEM.

3. Experimental results and discussion

Fig. 3 shows appearances of friction stirred parts on the upper BMG specimen at each plunge depth. It could be seen that burr occurred along the outer circumference of the probe shoulder. Variations of the maximum temperature around the friction stirred part and the vertical load pressing the BMG specimen measured at the plunge depth of 1.7 mm during FSSW are shown in Fig. 4. During welding, it could be seen that the surface temperature increased with time up to about 500 K and held a nearly constant value until 18 s. Considering that the surface temperature of the upper BMG specimen sharply decreases with the distance from the probe pin and the average value across a small area beside the probe pin can be obtained when an infrared imager is used as mentioned in pre-

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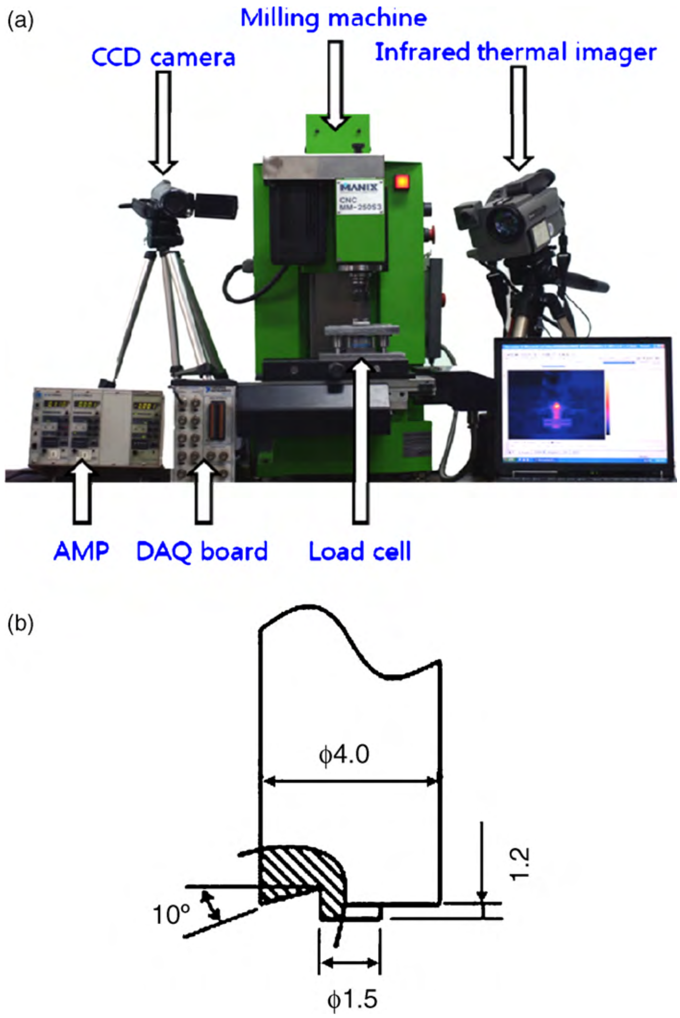
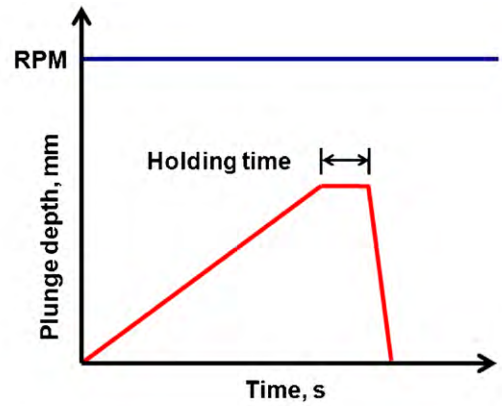


Fig. 1. (a) Apparatus and (b) shape of probe tool used for friction stir spot welding of BMG sheets.



Parameter	Test condition
Rotation speed (rpm)	2,700
Plunge depth (mm)	1.5, 1.7, 1.9
Plunge speed (mm/min)	3, 5, 7
Holding time (sec)	3

Fig. 2. Process profile and test conditions for friction stir spot welding.

vious section, it can be inferred that the real temperature around the probe pin inserted into the specimen reaches the T_g of the BMG while the temperature measured just showed about 500 K. When the friction time elapsed over the 18 s, which corresponds to the period the probe shoulder plunges into the upper BMG specimen, the temperature starts to increase again.

On the other hand, the variation of vertical load pressing the specimens showed an interesting phenomenon. The vertical load initially increased up to ∼600 N similarly with the case of temperature (the plunge depth corresponds to 0.2 mm), then it suddenly decreased to 50 N and showed a low load until the 18 s. When the friction time was over 18 s, similarly with the case of temperature, the vertical load increased again but the peak value of the load was different depending on the test condition. This behavior of vertical load will be a characteristic feature of FSSW of BMG; When the plunge depth of the probe pin exceeded 0.2 mm, the stirred zone around the probe pin was already in the supercooled liquid region which represents a superplastic deformation behavior of Newtonian viscous flow in that region [8–10]. Therefore a sudden drop of the stirring resistance of the BMG within the supercooled liquid region occurred, which made to reduce significantly the vertical load applied to the specimen. When the probe pin plunged completely the upper BMG specimen, the temperature did not increase and kept a thermal equilibrium. However, when the probe pin plunged into the lower BMG specimen, the vertical load started to increase and a consecutive plunging of the probe shoulder into the upper BMG specimen produced a further increase in the vertical load pressing specimens located under the probe.

The effect of plunge depth on the strength of weld part after FSSW of BMG sheets was also evaluated by the tensile–shear test and shown in Fig. 5. The case of 1.9 mm plunge depth showed the

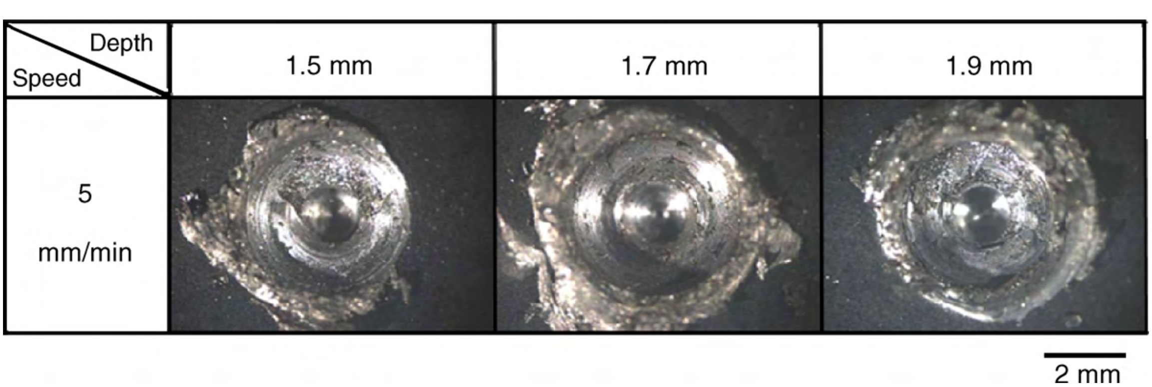


Fig. 3. Appearances on upper BMG sheet after friction stir spot welding at each plunge depth.

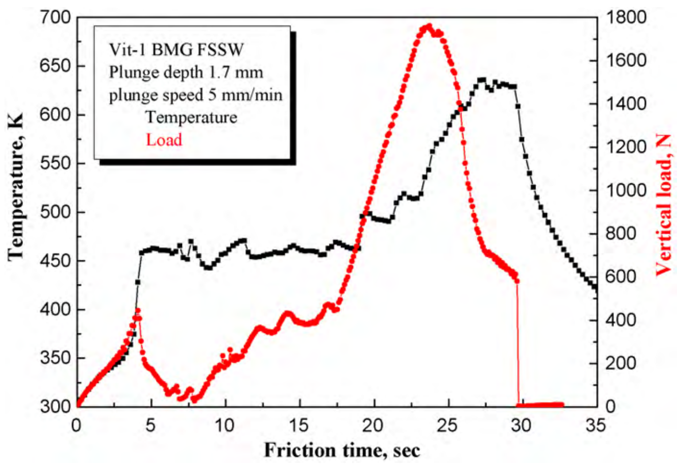


Fig. 4. History of temperature and vertical load pressing weld specimen during friction stir spot welding of BMG sheets at the plunge depth of 1.7 mm.

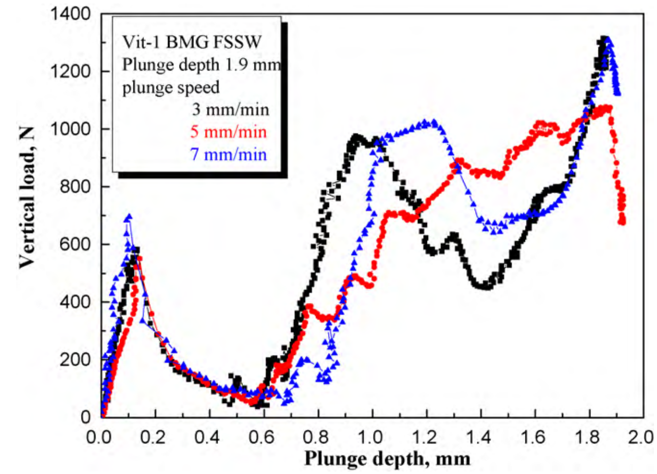


Fig. 6. Influence of plunge speed on vertical load variation during FSSW of BMG sheets.

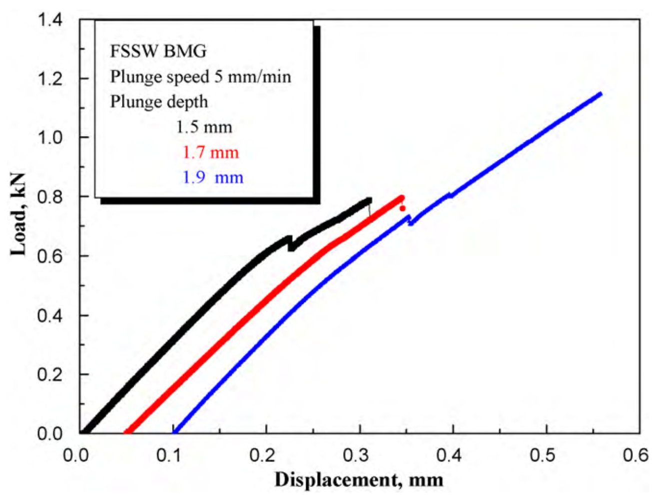


Fig. 5. Load–displacement curves obtained at each plunge depth by tensile–shear test after FSSW of BMG sheet.

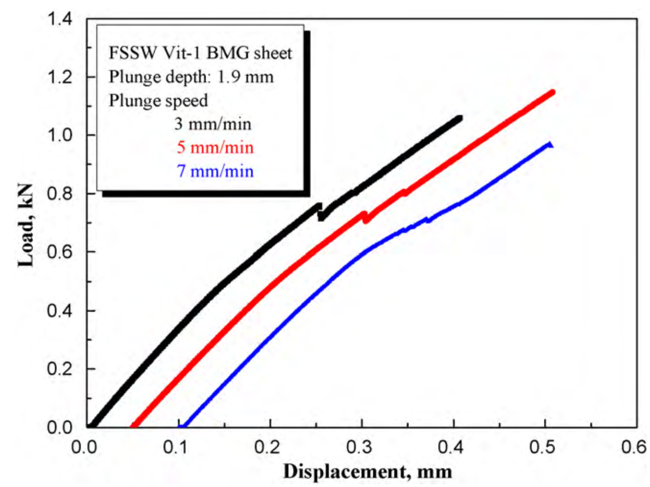


Fig. 7. Load–displacement curves obtained at each plunge speed after FSSW of BMG sheets.

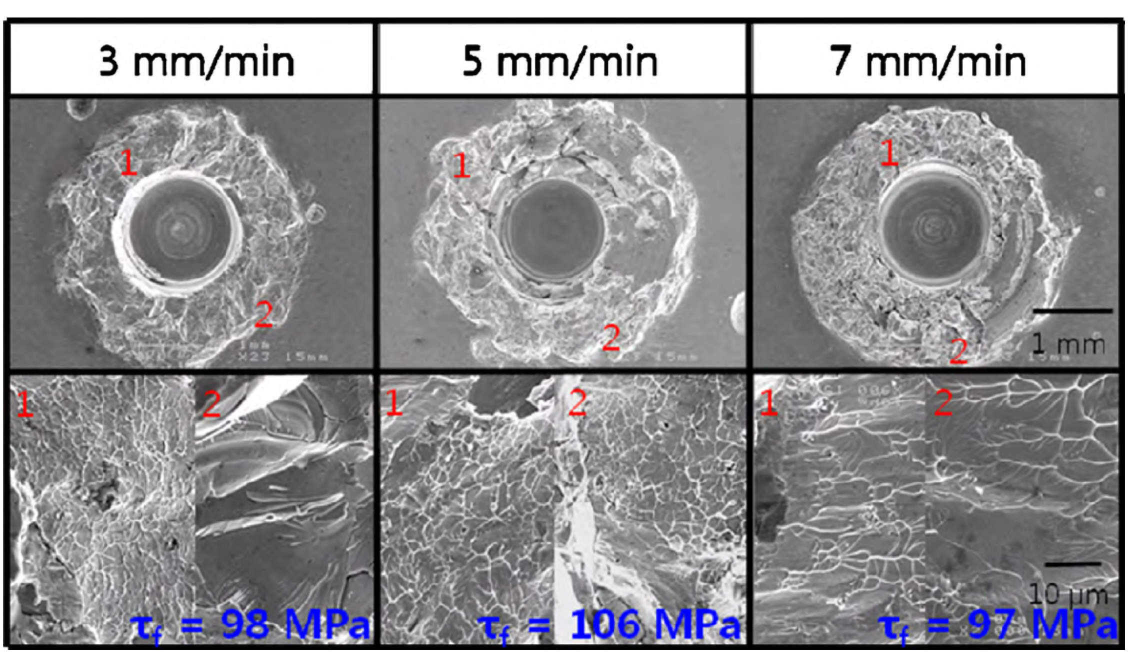


Fig. 8. Fractographic views on the lower BMG sheet induced by tensile–shear tests.

highest fracture load. Although in the case of 1.7 mm plunge depth, the peak of vertical load increased up to 1.8 kN as shown in Fig. 4, it showed a lower fracture load than the case of 1.9 mm plunge depth. Because the high value in the vertical load was resulted from the increase of deformation resistance due to the insufficient temperature rise in the stirring region of BMG sheets representing the stir zone was not formed within the supercooled liquid region, eventually resulting in a relatively low fracture load.

The influences of plunge speed on the characteristic feature during FSSW of BMG sheets were examined. The variations of vertical load against the plunge depth are shown in Fig. 6. It could be found that the plunge speed did not affect the characteristic feature of the vertical load variation during FSSW of BMG sheets. The temperature measured at the upper BMG sheet specimen also showed a similar behavior regardless of plunge speed. The influences of plunge speed on the fracture load obtained at each plunge depth are shown in Fig. 7. Little difference on the load–displacement curves could be seen in the tested plunge speed range, representing a fracture load of nearly 1 kN. At around 0.7 kN, on the load curve, a pop-in phenomenon existed which is thought as the occurrence of shear band at weld part during tensile–shear test. Further efforts are needed to clarify this phenomenon.

Fig. 8 shows fractographic micrographs of fracture surfaces induced on the lower BMG specimen after tensile–shear tests. Fractured parts have almost similar area regardless of plunge speed. From magnified views of marked spots on the SEM micrographs shown in Fig. 8, it could be found that some parts of fracture surface was consisted of BMG characteristic vein-like patterns, but others were brittle and plastic deformation due to insufficient joining. Comparison of FSSW to the electric resistance spot welding of BMG sheets is still needed [7].

4. Summary

The characteristic features occurred during the application of the friction stir spot welding (FSSW) technique to BMG sheets were investigated and the effects of plunge depth and plunge speed of probe tool on it were discussed. During FSSW of BMG sheets, a characteristic behavior could be observed; the vertical load pressing the specimen dropped dramatically when the temperature around the tool pin entered into the supercooled liquid region due to the heat generation by the stir friction between the pin and the BMG specimen. In that time, the temperature around the weld interface held almost a constant value. The fracture load after FSSW of BMG sheets increased with the plunge depth of the tool, but it was not influenced by the plunge speed. The application of FSSW technique to the BMG sheets produced a good joining and a high fracture load when the stir zone was well formed in the supercooled liquid region.

Acknowledgement

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