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Joining of bulk metallic glass to brass by thick-walled cylinder explosion

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This paper reports the development of a thick-walled cylinder explosion technique to weld a typical Zr-based bulk metallic glass (Vitreloy 1 (Vit 1)) to a commercial Cu-based crystalline alloy (brass). It is shown that a strong metallurgical bonding between the Vit 1 and the brass is achieved, which is due to significant atomic diffusion across the welding interface and shock wave propagation in the weldment. The dissimilar joining of the noncrystalline to crystalline alloy extends the application of bulk metallic glasses as structural and functional materials.

Keywords: Bulk metallic glass; Thick-walled cylinder technique; Explosive welding; Diffusion; Shock wave

Bulk metallic glasses (BMGs), due to their unique atomic structures and intriguing properties [1–7], have shown wide potential applications [8–12], in which weldability is an important factor. However, the metastable nature of BMGs against relaxation and crystallization is still a huge challenge for most techniques that are suitable for joining crystalline materials. Many welding methods for BMGs have been developed, including friction, pulse-current, electron-beam, laser, explosive and thermoplastic welding [13–20]. Among these methods, explosive welding shows a significant advantage, because a large area of atomic-scale joint is achieved within a short duration and the glassy structures of BMGs can be preserved [19–20]. It is worth noting, however, that the key question of what happens near the welding interface has not been satisfactorily answered. Thus, the underlying mechanism for explosive welding of BMGs deserves further investigations. In particular, it is essential to scrutinize how a shock wave facilitates the interface joining in such a dynamic process. In this paper, we developed a thick-walled cylinder explosion technique, which has been successfully applied in welding a typical Zr-based BMG (Vitreloy 1 (Vit 1)) to a commercial Cu-based crystalline alloy (brass). The distribution of alloy elements was examined across the interface of explosive joints, and in addition the wave propagation was investigated in the Vit 1 and brass as well as at their interface.

We chose Vit 1, with a nominal composition of $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10.0}Be_{22.5}$ (at.%), as the welding material due to its good glass-forming ability and high thermal stability [21]. The Vit 1 was suction-drawn into a copper mold to form a tube of 50 mm in height with an inner diameter of 14 mm and an outer diameter of 20 mm, as shown in the inset of Figure 1. The glassy nature of the prepared tube was checked by X-ray diffraction (XRD) in a Philips PW 1050 diffractometer with Cu K_a radiation. The XRD pattern (see Fig. 1) shows only broad diffraction maxima, and there are no visible peaks of crystalline phases, indicating an amorphous structure.

The thick-walled cylinder explosion technique, proposed and developed by Nesterenko et al. [22,23], has been widely used to study multiple shear banding behaviors in various materials from porous matter to metal alloys [24–26]. In the present work, this technique was modified for the explosive welding of the Vit 1 BMG to a brass ($Cu_{62}Zn_{38}$, at.%). As illustrated in Supplementary Figure 1, the Vit 1 tube was sandwiched between a thick-walled cylinder and a stopper rod. The brass was selected as the thick-walled cylinder, and a 4.2 mm gap between the brass cylinder and the Vit 1 tube was specially designed for a proper collision velocity. The welding surfaces, including the inner surface of the brass cylinder and the outer surface of the Vit 1 tube, were polished with #2000 sandpaper to remove oxides. A stainless steel (ss316) was adopted as the stopper rod. The Vit 1

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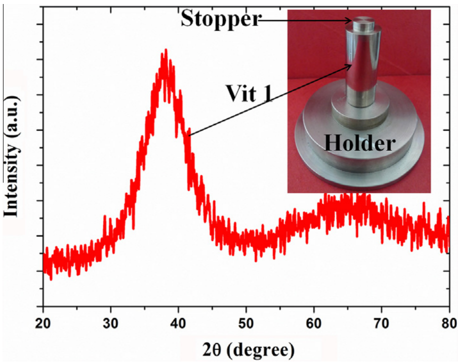

Figure 1. The XRD pattern of an as-cast Vit 1 BMG tube, where inset shows a stainless steel stopper rod enveloped by the Vit 1 tube.

tube and the stopper rod were heavy force fit to avoid the extra rarefaction wave reflected from the free interface between them. A specially prepared explosive (with a density of ~1 g cm^{-3} and a mass ratio of RDX to epoxy of 68:32) was placed coaxially with the brass cylinder. The detonation of the explosive was triggered at the top by an electric detonator. The explosive energy produces the implosion of the brass cylinder at an initial collapse velocity of about 5500 m s^{-1}, which drives the brass cylinder into the Vit 1 tube. At the collision point, it is predicted that the pressure and temperature will be so high that the brass and the Vit 1 BMG weld together. The welding area was examined by scanning electron microscopy (SEM) in an FEI Sirion microscope equipped for energy-dispersive spectrometry (EDS; Oxford INCA).

Figure 2a is a typical macroscopic cross-section of the weldment obtained by the thick-walled cylinder explosion technique. It can be seen that the gap disappears between the Vit 1 BMG tube and the brass cylinder, indicating that the two materials are well joined together. There are no visible defects or pores at or near their interface. In Figure 2b, the SEM micrograph of the welded materials shows a clear interface with a characteristic wave-like profile. Such a profile usually implies a perfect and strong metallurgical bonding [20,27], which can be well explained by the hydrodynamic instability [28,29]. During the explosive welding process, the materials near the collision point behave in a manner similar to liquids of low viscosity [28,29]. The inset of Figure 2b presents the XRD pattern of the Vit 1 near the interface after the explosive welding. Compared to its as-cast state, the welded Vit 1 exhibits no significant structural changes, and maintains its original glassy structure. The result is consistent with a previously microscopic observation by Liu et al. [20]. In their work, it is revealed that, during the explosive welding process, the maximum temperature of the Vit 1 at the collision point can reach 911 K, close to its melting point. However, the cooling rate (~10^{8} K s^{-1}) of the Vit 1 is much higher than the critical cooling rate (~1–10 K s^{-1}) of its glass formation. This explains why the Vit 1 can preserve the glassy structure, even through the maximum temperature exceeds its crystallization point.

Figure 2c shows a high-magnification SEM image in the welding interface region. A precise scan was performed along an arbitrary straight line (e.g. the black line in Fig. 2c) normal to the interface by using the EDS, which allows us to identify the distribution of the alloy elements across the interface. As shown in Figure 2d, the light element Be in the Vit 1 BMG cannot be determined. It is found that in regions far away from their interface, both brass and Vit 1 retain their original atomic ratios, and all component elements are uniformly distributed along the scan line. However, near the welding interface, the content of component elements shows a gradual transition from one side to the other. This demonstrates that there is a mutual diffusion of atoms between the crystalline brass and non-crystalline Vit 1. The diffusion behavior occurs

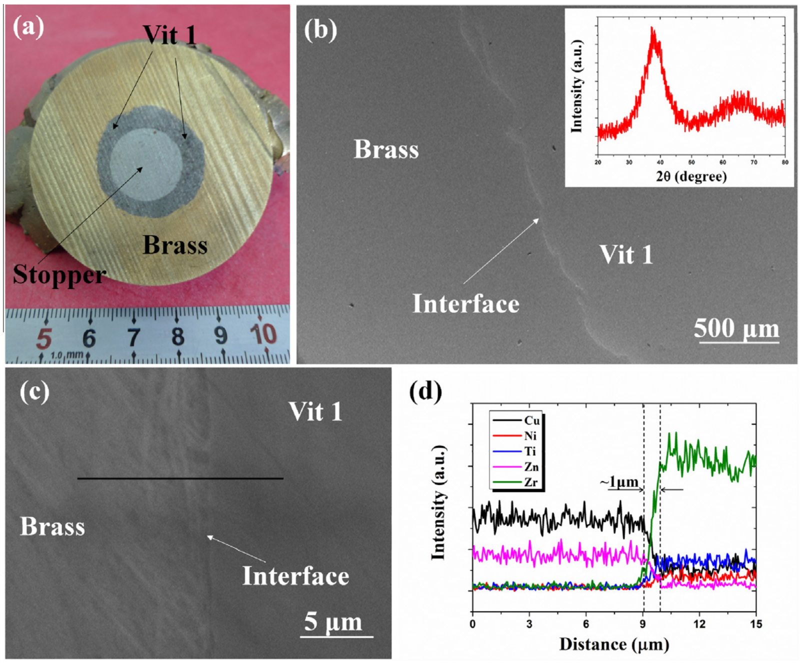

Figure 2. (a) Macroscopic cross-view of the weldment. (b) SEM image of the welded materials and their interface, where the inset shows a XRD pattern of Vit 1 after explosive welding. (c) High-magnification SEM image of the interface region. (d) The EDS result of the distribution of alloy elements across the interface (along the marked line in (c)).

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