Interfacial Microstructure of Aluminum/Metallic Glass Lap Joints Fabricated by Magnetic Pulse Welding

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Magnetic pulse welding was applied to the lap joining of crystalline pure aluminum and metallic glass (Zr48Cu36Al14Ag5 and Cu60Zr42.5Al7.5) and interfacial microstructure was examined. The metallic glass fractured in brittle manner in conventional plate layout. However, Al/metallic glass joints were successfully obtained without fragmentation of brittle metallic glass by setting a soft aluminum plate as a shock absorber behind the metallic glass. The welding interface exhibited characteristic wavy morphology as well as that of metal/metal joints. Thin layer with medium chemical composition of the metallic glass and Al was also produced at the welding interface. No chemical composition change took place in the area of 2 μm and more away from each matrix/intermediate layer interface. Also, no hardness change of Al matrix was detected in the area of 2 μm and more away from Al/intermediate layer interface. Hardness of metallic glass matrix close to the welding interface was not constant, however, TEM observation revealed that the metallic glass matrix retained the amorphous structure after the welding. These obtained results are considered to indicate that the metallic glass did not crystallize after the magnetic pulse welding.

Keywords: dissimilar materials welding, pure aluminum, metallic glass, magnetic pulse welding, welding interface

1. Introduction

Magnetic pulse welding is classified as one of the solid-state welding processes. The impact energy is induced by electromagnetic force, which is generated by interaction among discharge pulse running through the coil, induced magnetic flux around the coil, and eddy current produced at the plate surface. The welding between two metal plates is normally achieved within 10 μs with a negligible temperature increase. This welding process can be applied for metal couples widely differing in physical and mechanical properties such as melting point, heat conductivity, and hardness to produce a wide variety of similar and dissimilar metal joints.

The present authors have examined microstructure and mechanical properties of the magnetic pulse welded lap joints such as Al/Al, Cu/Cu, Al/steel, Al/Ni, Al/Cu, Cu/Ni, and Cu/Fe.1–4) The bonding strength was extremely high and they seldom failed at the welding interface in tensile-shear tests. The welding interface exhibited characteristic wavy morphology. In the Al/steel, Al/Ni, and Al/Cu joints, intermediate phase layer consisting of amorphous phase and fine crystal grains was produced at the welding interface. However, microstructural change such as grain morphology was limited to the area within several μm from the welding interface.5) This indicates that extremely little thermal effect on original microstructure is expected for the magnetic pulse welding compared to that of other welding methods.

Metallic glasses are known to have many unique properties such as high strength, high hardness, and high corrosion resistance. This is attributed to the random atomic arrangement like those in a liquid. Recently, some bulk metallic glasses with several tens millimeters thickness were produced directly from the melt with low cooling rates of the order of 10⁵ K/s to 10⁶ K/s.6–9) The metallic glasses with such properties are worth for engineering materials. Therefore, weldability of the metallic glass to other engineering materials is of great interest when we seek the usage of the metallic glass. The metallic glasses have been successfully welded to metals by several kinds of welding methods.10–17) However, their reports did not investigate in detail the microstructure close to the welding interface.

In the present study, aluminum/metallic glass lap joints were fabricated using the magnetic pulse welding and welding interface and the microstructure close to the welding interface were examined.

2. Experimental Procedures

2.1 Materials

A crystalline pure aluminum (99.50 mass%Al, hereafter Al) plate (100 mm × 50 mm × 0.5 mm) and a Zr48Cu36Al14Ag5 and a Cu60Zr42.5Al7.5 metallic glass were used. Size of the metallic glasses was 10 mm × 50 mm × 10 μm. Figure 1 shows X-ray diffraction pattern of both metallic glass samples. The pattern of the both samples consisted of only broad diffraction maxima without any sharp Bragg peaks.

2.2 Magnetic pulse welding

A discharge circuit as shown in Fig. 2(a) is used for the magnetic pulse welding. The circuit consists of a capacitor for a supply of electrical energy, a discharge gap switch, and a special E-shaped one-turn flat coil. Two plates are set over the coil, with a little gap between them. The plate close to the coil is termed “flyer plate” and another plate above it, which is fixed firmly in place, is referred to as “parent plate”.

The principle of generation of electromagnetic force is explained by using Fig. 2(b) which shows a close-up around a middle section of the coil. When a discharge pulse passes
through the coil, high density magnetic flux lines generated around the coil. The generated magnetic flux lines intersect with the flyer plate, and eddy currents are excited in the surface of the flyer plate adjacent to the coil by Lentz’s law. Since the discharge pulse is high-frequency, the eddy current is mainly generated at the plate surface due to the so-called surface effect. The eddy currents and the magnetic flux induce an electromagnetic force upward by Fleming’s left-hand rule. The generated electromagnetic force drives the flyer plate to the parent plate at a high velocity and the collision takes place between two plates. Metal plates with high electrical conductivity such as Al and Cu are suitable for the flyer plate because they can generate large electromagnetic force. In the present study, an Al plate was applied as the flyer plate and a metallic glass was applied as the parent plate.

The initial gap between the Al plate and the metallic glass was fixed to be 1.0 mm. The discharge energy was 2.5 kJ. The Al plate hits the metallic glass at a velocity of several hundred m/s. When the conventional plate layout, as shown in Fig. 2 was used for welding, the metallic glass fractured in a brittle manner as shown in Fig. 3. In the present study, in order to prevent such brittle fracture of the metallic glass, a 0.5 mm thick softened Al plate was set over the metallic glass as a shock absorber, as shown in Fig. 4. In order to prevent welding of the shock absorber and the metallic glass, an insulator (polyimide sheet) was inserted between them.

2.3 Microstructural observation of welding interface

Interfacial microstructure was examined using a scanning electron microscope (SEM) and a transmission electron microscope (TEM). TEM foils were fabricated by using a focused ion beam facility (FIB). TEM observation was carried out by a high-voltage electron microscope (HVEM) operated at 1000 kV.

2.4 Chemical composition analysis and hardness measurement

In order to examine the extent of alloying due to the welding, composition profile across the welding interface was measured for each element by electron probe micro-

![Fig. 1 X-ray diffraction patterns of Zr$_{48}$Cu$_{36}$Al$_{8}$Ag$_{8}$ and Cu$_{50}$Zr$_{42.5}$Al$_{7.5}$ alloy.](image1)

![Fig. 2 Schematic illustrations of welding process of magnetic pulse welding. (a) Set-up of the lapped plates over the E-shaped one-turn coil. (b) Principle of the magnetic pulse welding.](image2)

![Fig. 3 Macroscopic appearance of Al plate and metallic glass after welding without a shock absorber.](image3)

![Fig. 4 Schematic illustration of set-up of a shock absorber.](image4)
analyzer (EPMA). Spot size of the electron beam was about 3 μm in diameter.

Hardness change close to the welding interface was investigated by a nano-indentation method with a load of 100 mgf. The measurement was carried out in the area (30 μm × 30 μm) including the welding interface. The measurement intervals were 3 μm to the perpendicular direction of the interface and 5 μm to the parallel direction.

3. Results and Discussion

3.1 Interfacial microstructure of the lap joints

Figure 5 shows an external appearance of the front (Al side) and back (metallic glass side) surface of the Al/Zr₄₈Cu₃₆Al₈Ag₈ lap joint. A part of the Al plate bulged toward the Zr₄₈Cu₃₆Al₈Ag₈ metallic glass along the longitudinal direction of the coil, as shown in Fig. 5(a). The shock absorber of soft Al plate worked effectively. The metallic glass was not broken and welded to the Al, as shown in Fig. 5(b). The same result was obtained for Al/Cu₅₀Zr₄₂.₅Al₇.₅ joint.

The upper bright contrast side is metallic glass and the lower dark contrast side is Al. The welding interface exhibited characteristic wavy morphology, as well as that of metal/metal joints.¹⁻⁴ Thin layer with medium contrast of the metallic glass matrix and Al matrix was also observed at the welding interface. The medium contrast of the thin layer suggests that this layer has intermediate chemical composition of the metallic glass and Al.

Chemical composition of the intermediate layer was investigated by EPMA. The line analysis was performed across the intermediate layer, as shown in Fig. 7(a) and 7(b). The left-hand side is metallic glass and the right-hand side is Al. Figures 7(c) and 7(d) show composition profiles of Zr, Cu, Al, and Ag elements. The area between the broken lines is corresponded to the intermediate layer (IML) region. In the area of 2 μm and more away from the broken lines, chemical composition of each element was almost constant. On the other hand, in the intermediate layer region, composition of each element exhibited gradual change. We need to mention that each plot in these figures does not always indicate local chemical composition at the corresponding position. This is because the spot size of electron beam was larger than the thickness of the intermediate layer in the present case. Therefore, in spite that we could know that some alloying

Fig. 5 Macroscopic appearance of Al/Zr₄₈Cu₃₆Al₈Ag₈ lap joint welded using a shock absorber. (a) Al side. (b) Zr₄₈Cu₃₆Al₈Ag₈ metallic glass side.

Fig. 6 Backscattered electron images of the welding interface. (a) Al/Zr₄₈Cu₃₆Al₈Ag₈ joint. (b) Al/Cu₅₀Zr₄₂.₅Al₇.₅ joint.
took place at the welding interface and this resulted in the intermediate layer formation, determination chemical composition of the intermediate layer was difficult.

3.2 Characteristic hardness change close to the welding interface

Figures 8(a) and 8(b) show backscattered electron images of the welding interface in Al/Zr$_{48}$Cu$_{36}$Al$_{8}$Ag$_{8}$ and Al/Cu$_{50}$Zr$_{42}$:5Al$_{7}$:5 joints and locations of hardness measurement. The size of each indentation was so small that each location was indicated by a circle. Figures 8(c) and 8(d) show the relationship between Berkovich hardness value and distance from the interface. The left-hand side is metallic glass and the right-hand side is Al. The 0 point on the horizontal axis in each figure indicates the location of the interface between the intermediate layer and matrix. Black square marks at both sides of the figure indicate hardness value of the each matrix. The average hardness value of Zr$_{48}$Cu$_{36}$Al$_{8}$Ag$_{8}$, Cu$_{50}$Zr$_{42}$:5Al$_{7}$:5, and Al matrices was 776$\sim$851 mgf$\mu$m$^{-2}$, 543$\sim$621 mgf$\mu$m$^{-2}$, and 68$\sim$83 mgf$\mu$m$^{-2}$, respectively. In the Al side, at the area of 2$\mu$m and more away from the interface, hardness was constant and equal to that of the Al matrix. In contrast, at the area within 2$\mu$m from the interface, hardness increased remarkably. In addition, in the metallic glass side, the hardness was not constant and scattered widely. However, the scatter of hardness value was small for the metallic glass matrix, as indicated by the black square marks.

The remarkable hardness increase in the Al matrix only close to the welding interface was also observed in the other magnetic pulse welded dissimilar metals joints. Remarkable grain refinement was observed close to the welding interface. Therefore, hardness increase of Al matrix is considered to be due to the combined effect of work hardening and grain refinement.

In the metallic glass matrix, there was a large scatter in hardness. Bhowmick produced Zr/Zr$_{41}$Be$_{23}$Ti$_{14}$Cu$_{12}$Ni$_{10}$ metallic glass using electron beam welding method and investigated hardness of area close to the welding interface. They reported that nanocrystals of Zr$_2$Cu phase were produced in the metallic glass matrix close to the welding interface. In the present study, lower hardness value compared to that of metallic glass matrix was detected in the metallic glass matrix close to the welding interface. This local reduction of hardness is considered to be attributed to the local crystallization of the metallic glass. Microstructure observation using a TEM will be useful to prove it.

3.3 Microstructural change close to the welding interface

Figure 9(a) shows a bright-field image of the welding interface of the Al/Zr$_{48}$Cu$_{36}$Al$_{8}$Ag$_{8}$ joint. The upper dark contrast side is Zr$_{48}$Cu$_{36}$Al$_{8}$Ag$_{8}$ metallic glass and the
lower bright contrast side is Al. Careful tilt experiments revealed that no crystalline contrast was observed in the Zr$_{48}$Cu$_{36}$Al$_{8}$Ag$_{8}$ matrix. Figure 9(b) shows selected area diffraction patterns taken from Zr$_{48}$Cu$_{36}$Al$_{8}$Ag$_{8}$ metallic glass matrix. The size of selected area aperture is about 500 nm in diameter. The diffraction pattern taken from Zr$_{48}$Cu$_{36}$Al$_{8}$Ag$_{8}$ metallic glass matrix close to the welding interface consisted of only halo ring. This suggests that the Zr$_{48}$Cu$_{36}$Al$_{8}$Ag$_{8}$ metallic glass retains the amorphous structure after welding. Figures 9(c) and 9(d) show a bright-field image of Al matrix close to the welding interface and selected area diffraction pattern taken from grain indicated an arrow in Fig. 9(c). Original elongated grains were observed at region over about 1 µm from the welding interface, as shown in Fig. 9(a), however, Al matrix close to the welding interface consisted of extremely fine Al grains.

Figure 10(a) shows a bright-field image taken from another location of the same interface. The diffraction pattern taken from Zr$_{48}$Cu$_{36}$Al$_{8}$Ag$_{8}$ metallic glass matrix consisted of only halo ring, as shown in Fig. 10(b). This indicates that no crystallization occurred in the Zr$_{48}$Cu$_{36}$Al$_{8}$Ag$_{8}$ metallic glass matrix. On the other hand, particles of submicron size were observed in the Al matrix, as shown by the double arrows in Fig. 10(a). Figure 10(c) shows the selected area diffraction pattern taken from the particles. The diffuse halo ring indicates that the particles are amorphous phase. The Al matrix close to the welding interface consisted of fine grains including dispersed fine amorphous particles.

In the magnetic pulse welded Al/steel, Al/Cu, and Al/Ni dissimilar metals joints, fragments of the parent plate metal were observed in the intermediate phase layer. It is considered that surface of the parent plate metal was fragmented by high-speed oblique collision of the flyer plate and fragments were embedded in the intermediate phase layer. The size of fragments was range from several hundred nm to several µm. Size of the observed amorphous particles is corresponded to that of fragments produced at the dissimilar metals joints. Therefore, the amorphous particles observed in Al matrix close to the welding interface were considered to be broken pieces of the metallic glass.

4. Conclusions

Lap joining of a crystalline Al plate and metallic glasses (Zr$_{48}$Cu$_{36}$Al$_{8}$Ag$_{8}$ and Cu$_{50}$Zr$_{42.5}$Al$_{7.5}$) was carried out using the magnetic pulse welding. Interfacial microstructure of the joints was examined and the following findings were obtained.
(1) By using a soft aluminum plate as a shock absorber, fragmentation of metallic glass foils was suppressed and brittle metallic glass foils were magnetic pulse welded to the Al plate successfully with a very limited damage.

(2) The welding interface of Al/metallic glass joint exhibited characteristic wavy morphology. Backscattered electron image (composition image) revealed that the wavy interface was traced by the thin layer with intermediate chemical composition of metallic glass and Al matrix.

(3) Chemical composition determination of the intermediate layer was considered to be difficult by EPMA since the spot size of the analysis beam was large compared to the intermediate layer thickness. However, it was confirmed that no chemical composition change took place in the area of both matrixes which is 2 µm and more away from each matrix/intermediate layer interface.

(4) Nano-indentation test revealed that no hardness change of Al was detected in the area of 2 µm and more away from Al/intermediate layer interface. In contrast, in the area within 2 µm from Al/intermediate layer interface, hardness increase of Al was detected. Hardness of metallic glass was not constant close to the welding interface.

(5) No structural change was observed at metallic glass close to the welding interface. In contrast, the Al matrix close to the welding interface consisted of fine grains including dispersed fine amorphous particles.

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Fig. 10 (a) Bright-field image of the welding interface in the Al/Zr_{48}Cu_{36}Al_{8}Ag_{8} joint. (b) Selected area diffraction pattern taken from the Zr_{48}Cu_{36}Al_{8}Ag_{8} metallic glass matrix close to the welding interface. (c) Selected area diffraction pattern taken from the particles of submicron size observed at the Al matrix close to the welding interface.