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Effect of Zn alloy interlayer on interface microstructure and strength of diffusion-bonded Mg–Al joints

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The diffusion-bonding of Mg–Al without and with Zn alloy interlayer has been investigated. The addition of Zn alloy interlayer improves the microstructure of Mg–Al joints. The intermetallic phases exist in the form of dispersive particles and a thin layer of about 1 μm thickness. The shear strength of joints is doubled by using the Zn alloy interlayer.
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Magnesium is the lightest metal. The weight of structure components can be reduced by using magnesium alloy. The joining of Mg alloys and other metals is of great significance [1]. Especially for automotive industries, reducing vehicle weight is the best way to meet the needs of energy economy and environmental protection. The welding assemblies of favorable performance in which Mg alloys partially substitute for Al alloys can reduce vehicle weight greatly. It has resulted in the welding of Mg–Al dissimilar metals becoming a focal subject. Fusion welding methods, such as electron beam welding [2] and resistance spot welding [3], and solid-state bonding, such as diffusion-bonding [4], have been used to join magnesium and aluminum; however, the results were not ideal. The major problem is the formation of much more Mg–Al intermetallic compounds with a very high hardness and brittleness, which lie between magnesium and aluminum as an interlayer. These hard intermetallic compounds act preferentially as the source of microcracks in the mechanical property tests [5]. Friction-stir welding [6–8] of Mg–Al can achieve relatively high joining strength comparing other methods, but for the direct contact of base Mg and Al, there are also Mg–Al intermetallic compounds in the joints. In addition, the specific requirements for the shape of substrate limits the application of this method [9]. Eliminating or improving Mg–Al intermetallic phases has become the key to achieve firm joints of Mg–Al. Some exploring work has been done, for example, laser weld bonding of Mg–Al [10,11] and laser-TIG hybrid welding of Al alloy and Mg alloy with Ce as an interlayer [5].

Diffusion-bonding with a right interlayer is an effective solution to join dissimilar metals. But no study has been reported about the diffusion-bonding of Mg–Al with an interlayer. The present work investigates diffusion-bonding of Mg–Al without and with a Zn alloy interlayer. By analyzing the microstructure changes of the both joints, the effect of a Zn alloy interlayer on interface microstructure and strength of diffusion-bonded of Mg–Al joints is represented.

The base materials used for diffusion-bonding were Mg alloy AZ31B and Al alloy 6061, which were cut into samples of size 60 mm × 13 mm × 3 mm. The chemical composition of Mg alloy AZ31B was Al-3.0, Zn-1.0, Mn-0.4, Si-0.1 (wt.%); Al alloy 6061 was Mg-0.9678, Si-0.5527, Cu-0.2175, Fe-0.1401 (wt.%), and Zn alloy interlayer was Al-4.0, Ce-0.1 (wt.%).

Zn alloy interlayer was prefabricated firstly on the surface of Al base sample by hot-dipping at 450 °C with a thickness of about 60 μm. Then all the bonding surfaces of samples were ground flat by 200 #, 400 #, 600 # grit SiC paper and cleaned in ethanol or acetone prior to diffusion-bonding. The thickness of Zn alloy interlayer after grinding is about 30 μm.

The cleaned sample was carefully assembled into a sandwich type, fixed by clamps and then placed in a traditional furnace with an argon gas shield. The processing temperature was monitored with an R type

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Pt/Rh thermocouple fixed on the sample's upper surface. The optimized technological parameters of Mg–Al joints diffusion-bonded without Zn alloy interlayer were: heating speed of 110 °C min^{-1}, bonding temperature of 447 °C, holding time of 3 s. The optimized technological parameters of Mg–Al joints diffusion-bonded with Zn alloy interlayer were: heating speed of 90 °C min^{-1}, bonding temperature of 360 °C, holding time of 3 s. After bonding, the above samples were taken out of the chamber and cooled with water.

The cross-sections of the bonded joints were prepared by standard polishing techniques and then etched in picric acid solution. The microstructure was observed by scanning electron microscopy (SEM) equipped with an energy-dispersive X-ray spectroscopy (EDXS) analysis system. The element distributions and contents of the joints were measured by EPMA-1600 electron probe micro analyzer. Shear strength of the joints was tested using a material testing machine of type CSS-2205. The phase constitution of broken joint was analyzed by X-ray diffraction (XRD) fracture analysis.

Figure 1 shows the SEM images of interfacial structure of Mg–Al joints diffusion-bonded directly at 447 °C for 3 s. It can be seen that the interfacial structure of Mg–Al joint consists of hoar phase marked with A zone next to the base Al and dark eutectic phase marked with B zone next to the base Mg. The narrowest part of A zone exceeds 20 μm. The elemental analysis was conducted in the A zone and B zone. The A zone consists of 40.63 at.% Mg and 59.37 at.% Al. The stoichiometric proportion of Mg to Al is approximately 2:3. The selected area XRD has shown that the A zone is composed of the Al_3Mg_2 compound. The B zone is a eutectic zone composed of 68.97 at.% Mg and 31.03 at.% Al. Combining with the phase diagram of the binary Al–Mg systems, the B zone was estimated to consist of $Al_{12}Mg_{17}$ and Mg solid solution. The existence of these constituents in the B zone has also been identified by selected-area XRD.

Shear strength tests were carried out on samples at the same joining conditions as the above joint. The maximum shear strength of Mg–Al joints using diffusion-bonding directly is 41.3 MPa and it is not good. By XRD analysis, the fracture always occurs in the interface between base Al and intermetallic compound layer.

To increase the strength of Mg–Al joint, Zn alloy interlayer is adopted. The interlayer is prepared by alloying zinc with Al and Ce. Adding Al to base Zn makes Al occupy the Zn crystal lattices and decrease the amount of base Mg into Zn interlayer, aim to reduce Mg–Zn intermetallics. Addition of Ce attempts to improve the intermetallic patterns. Figure 2 shows the SEM images of Mg–Al joints diffusion-bonded at 360 °C for 3 s with a Zn alloy interlayer. It can be seen from Figure 2a that there are a great deal of white second-phase particles marked with B dispersed in the base of the bond region marked with A and near to Al side there is a second-phase thin layer with a thickness of about 1 μm which is marked with C (the zone showed between the two black lines). Figure 2b is the high magnification of the bond region of the joint. It can be seen that the base of bond region is a kind of single-phase. The average size of the second-phase particles is less than 1 μm. The second-phase thin layer and the second-phase particles precipitated on top of it combine and form a continuous layer which the maximal thickness is less than 5 μm (showed as the black arrows).

Figure 3 shows a back-scattered electron image and elemental distributions of the cross-section of Mg–Al joint diffusion-bonded with a Zn alloy interlayer. The bond region can be divided into three zones: 1, 2 and 3. The concentration profiles of major elements (Al, Mg, Zn, Ce) across the bond region marked with white lines in Figure 3a are shown in Figure 3b.

Zn and Al elements diffuse from interlayer to the base Mg. The concentration profile of Al is flat in zone 1 and 2, while there is an increase from zone 2 to zone 3. The concentration of Zn decreases gradually from zone 3 to zone 1. The distribution of Mg is similar to Al in zone 1 and 2. But there is almost no Mg in zone 3. The concentration profile of Ce fluctuates regularly in all zones. It shows that Ce is distributed dispersedly in the bond region. In the heating process of diffusion-bonding, the elements of contact surfaces of Mg–Zn begin to interdiffuse. At some temperature approaching 360 °C, the low-melting eutectic liquid appears which speeds up elements diffusion from solid base into the liquid and the liquid region is widened continuously, which forms 1 zone in the cooling process. At the same time the elements in the liquid diffuse to the solid. But the element diffusion rate in solid is far lower than that in liquid and the contacting time between the liquid and the solid in this study is very short, the Mg elements

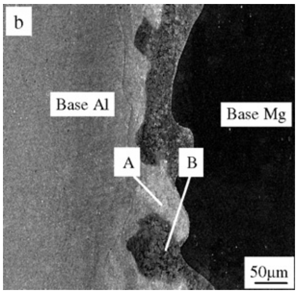

Figure 1. Interfacial microstructures (SEM) of Mg–Al joints diffusion-bonded directly at 447 °C for 10 s.

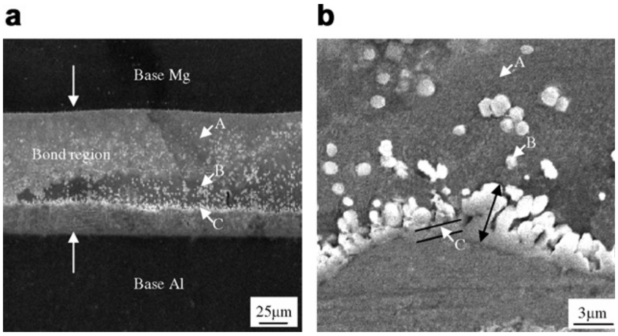

Figure 2. SEM images of Mg–Al diffusion-bonded with a Zn alloy interlayer at 360 °C for 3 s: (a) cross-section of the whole bond region; (b) high magnification of the bond region of the joint.

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