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Effect of annealing temperature on joints of diffusion bonded Mg/Al alloys

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Abstract: To study the effect of annealing temperature on the joints between magnesium and aluminum alloys, and improve the properties of bonding layers, composite plates of magnesium alloy (AZ31B) and aluminum alloy (6061) were welded using the vacuum diffusion bonding method. The composite specimens were continuously annealed in an electrical furnace under the protection of argon gas. The microstructures were then observed using scanning electron microscopy. X-ray diffractometry was used to investigate the residual stresses in the specimens. The elemental distribution was analyzed with an electron probe micro analyzer. The tensile strength and hardness were also measured. Results show that the diffusion layers become wide as the heat treatment temperature increases, and the residual stress of the specimen is at a minimum and tensile strength is the largest when being annealed at 250 °C. Therefore, 250 °C is the most appropriate annealing temperature.

Key words: annealing temperature; diffusion bonding; diffusion layer; residual stress; tensile strength

1 Introduction

With the rapid development of the transportation, aerospace, and defense industries, magnesium alloys have received growing attention due to their low densities, high specific strengths, excellent casting ability, and outstanding vibrational energy absorption [1]. While the use of magnesium alloys allows the weight of components to be reduced, this material is easily corroded. Another group of materials used in a similar role are aluminum alloys, which have attractive mechanical and metallurgical properties including high strength and excellent corrosion resistance [2−5]. It is well-known that both magnesium and aluminum alloys are both widely used in the aerospace, mechanical, electrical, and chemical industries [6−9]. Furthermore, with the growing emphasis on energy economy and environmental concerns, Mg alloys have become a favored choice in the automobile field. If aluminum alloys can be bonded to magnesium alloy and form some kind of composite material, not only would the flexibility and availability of the material be substantially improved, but also the weight and cost would be reduced.

At present, there is much research into this topic. Many welding methods have been used to join Mg alloys and Al alloys. These methods include soldering, electron beam welding, resistance spot welding, explosive welding [10], laser welding, and the vacuum diffusion bonding. However, no matter which technique is used, brittle and hard intermetallic compounds, such as Al_3Mg_2 and $Mg_{17}Al_{12}$, form in the joints. This weakens the tensile strength of the joints. As was previously reported elsewhere, the tensile strength of bonded specimens was only 37 MPa [11], despite the Mg/Al alloy being welded with a Zn interlayer [12].

The process of annealing is always applied to plastically deformed metals and alloys in order to soften and restore the ductility and formability of materials [13]. Annealing can transform the structure of crystals and eliminate defects in microstructures, thereby reducing the brittleness and improving the mechanical characteristics of a material. In this work, in order to investigate these effects, annealing treatments were applied at different

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temperatures. In addition, the microstructures and their properties were investigated. This work represents one of the first attempts to study the effect of annealing temperature on the joints between magnesium and aluminum alloys. Based on the results of this work, the applications of the composite material formed by the diffusion bonding of aluminum alloy and magnesium alloy could be extensive. The composite materials formed by this process will lead to light-weight components, which will in turn lead to decreased depletion of resources and reduced energy usage, which can help mitigate environmental pollution.

2 Experimental

The chemical compositions of AZ31B magnesium alloy and 6061 aluminum alloy are given in Table 1 and Table 2.

Table 1 Composition of AZ31 Mg alloy (mass fraction, %)

Al	Zn	Mn	Ca	
2.5−3.5	0.5−1.5	0.2−0.5	0.04	
Si	Cu	Ni	Fe	Mg
0.1	0.05	0.005	0.005	Bal.

Table 2 Composition of Al6061 alloy (mass fraction, %)

Mg	Zn	Mn	Si	
0.9678	0.0005	0.0038	0.5527	
Cu	Fe	Ti	Cr	Al
0.2175	0.1401	0.0127	0.0718	Bal.

The principle impurities present in the alloys are Fe and Ni [14]. These impurities have an adverse effect on the uniformity of microstructures and the distribution of elements. Conversely, the presence of Mn elements can reduce the effect of impurities and refine the grain as well as improve the tensile strength of the diffusion layers. Si can improve the mechanical properties of the alloy at room temperature, and Cu can improve the strength at high temperature. Ca can refine the size of dendrites in $Mg_{17}Al_{12}$. Additionally, it will form the phase of Al_2Ca, which has a very high melting point [15]. Consequently, it can reduce the micro-hardness of the diffusion zone. The element Zn is present firstly for its own solid-solution strengthening and secondly because a small amount of Zn can increase the solubility of Al in Mg, thereby improving the solid solution strengthening effect of Al. Besides, Zn can also reduce the formation of intermetallic compounds [16]. Overall, Zn can reduce micro-hardness and increase the tensile strength of the diffusion layers.

The first step in the experimental procedure was to cut AZ31B magnesium alloy sheets and 6061 aluminum alloy sheets to the dimensions shown in Fig. 1.

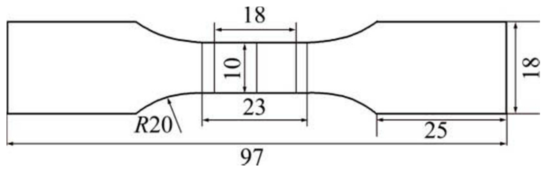

Fig. 1 Dimensions of specimen (unit: mm)

The oxide layers on the surface of the substrate were then polished with abrasive papers and the ground samples were wiped with acetone before joining. According to the Mg−Al phase diagram, the joining temperature was chosen as 440 °C. Specimens were successfully joined with a method called vacuum diffusion bonding under the protection of argon gas. After that, in order to refine microstructures and improve the properties of the bonding layers, annealing treatment was carried out. According to the Mg−Al phase graph and previous annealing experience, the samples were annealed using heat treatment temperatures of 200, 250 and 300 °C, and the holding time was 1 h. After heat treatment, samples were cooled to room temperature in an electric furnace.

For the purpose of studying the effect of annealing temperatures on microstructures and the properties of the interfaces, a series of specimens annealed at different conditions were cut across the diffusion zone. The cut sections were then inlaid into resin to facilitate the investigation of microstructures. Using a grinder and abrasive papers (Grit 240, 600, 800, 1200), the samples were ground and polished with a polishing compound.

The microstructures and elemental distribution of the joints were then studied using scanning electron microscopy (SEM) and an electron probe micro analyzer (EPMA). Using a tensile machine, the tensile strength was also investigated. The tensile speed used was 0.008 mm/s. After the measurement, the stress−strain graphs could be obtained. In order to investigate the distribution of residual stress of the specimens annealed at different temperatures, residual stress was measured by X-ray diffraction (XRD), based on the testing principle of residual stress and using X-ray of wavelength λ. Initially, the specimen was irradiated, and a diffraction angle 2θ was obtained which was later used to calculate the slope, M, of $2\theta-\sin^2\psi$. Generally, ψ was set to be 0°, 15°, 30° and 45°. This allowed us to obtain the relationship between 2θ and $\sin^2\psi$, and thus calculate the residual stress σ using the following equation:

$$\sigma=K\cdot\Delta 2\theta/\Delta\sin 2\psi=K\cdot M \quad (1)$$

K is the stress constant of XRD analysis, which can be expressed as