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Influence of Cu coating thickness on interfacial reactions in laser welding-brazing of Mg to Ti

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ABSTRACT

Laser welding-brazing Mg/Cu-coated Ti in lap configuration using various coating thickness was performed with AZ92 Mg based filler. The thermodynamic calculation was conducted to help to analyze microstructure evolution. The brazed joint was divided into three regions. Only Ti_3Al interfacial layer was generated at the direct irradiation region and grew obviously when thicker Cu coating was adopted. The interfacial reaction layer evolved from Ti_3Al to Ti_3Al/Ti_2Cu to $Ti_3Al/Ti_2Cu + AlCu_2Ti$ at the middle region with the increase of Cu coating thickness. Ti_2Cu interfacial layer was observed at the weld toe region and grew evidently as Cu coating thickness increased. The calculation result of chemical potential in AZ92Mg-Cu-Ti system suggested that Cu could promote mutual diffusion between Ti and Al. Ti preferred to react with Al than Cu, indicating Al-Ti compounds were easily produced along the Ti surface. The maximum fracture load was 2314 N with coating thickness of 10.6 μm, which was 55% higher than that with bare Ti sheet and as high as 85% of Mg parent metal. The fracture occurred along the Mg/Ti interface at the direct irradiation region while the crack propagated in Mg-Cu eutectic structure near the interfacial layer at the middle region.

1. Introduction

Mg and Ti have enormous differences in their physical and metallurgical performance, thus they have limitation in achieving reliable metallurgical bonding. For instance, the melting point of Mg is 649 °C while the melting point of Ti is 1678 °C. The solubility of Mg in Ti is less than 2 at.%, and the solubility of Ti in Mg is slightly less than 0.1 at.% (Murray, 1986). Based on above, another intermediate element must be adopted to realize the metallurgical bonding between Mg and Ti.

From the current studies, aluminum (Al) element, nickel (Ni) element and copper (Cu) element which had mass of solid solubility in or could react with Mg or Ti base metals were employed, respectively. Cao et al. (2014) and Tan et al. (2016a) adopted Al element from Mg based filler by cold metal transfer (CMT) welding-brazing technique and laser welding-brazing (LWB) method to join Mg/Ti, respectively. Ti_3Al phase was found along the interface in both cases, suggesting that Mg/Ti metallurgical joining was realized successfully with the addition of Al element. In addition, Tan et al. (2016a) investigated the effect of different Al contents on joint mechanical properties. A remarkable 85% increase of the tensile-shear fracture load was obtained when substituting AZ91 filler for AZ31 filler during laser welding-brazing process. Aonuma and Nakata (2009) studied the influence of Al element on interfacial reaction and joint strength when using friction stir welding (FSW) to join Mg-Al-Zn alloy with Ti. $TiAl_3$ interfacial layer was produced at the Mg/Ti joint interface under all welding parameters. It was worth noting that the contents of Al element played a crucial part in joint strength. The increased Al content would reduce the tensile strength, and this result was contrary to the result of Tan et al. (2016a,b). In order to inhibit the growth of $TiAl_3$ and improve joint strength when joining Mg/Ti by FSW process (Aonuma and Nakata, 2009), Aonuma and Nakata (2010) used calcium (Ca) from AMCa602 alloy (6% Al and 2% Ca) base metal to react with Al. The formation of Al_2Ca suppressed the growth of $TiAl_3$ layer and resulted in better performance of joint strength. Atieh and Khan (2013, 2014a,b) employed Ni element during transient liquid phase (TLP) bonding, Ni/Ti interface produced solid diffusion and liquid eutectic reaction occurred at the Mg/Ni interface. Higher tensile-shear fracture load was obtained by Ni coating than Ni foil in the experiment (Atieh and Khan, 2014b). Atieh and Khan (2014a) then adopted Ni coating dispersed with nanoparticles Ni or Cu and maximum joint strength was acquired when using Cu nanoparticle. Tan et al. (2017) also adopted Ni coating when using LWB to join Mg/Ti. The results indicated that Ti_3Al interfacial phase and Mg-Al-Ni interfacial intermetallic compounds formed.

Considering the works above, adding alloying element was an

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effective way to realize metallurgical joining of Mg to Ti, and the content of alloying element played a significant role in microstructure development and mechanical properties. The effect of Cu element was investigated only in the TLP bonding in the form of nanoparticles mixed in the Ni coating (Atieh and Khan, 2014a). Therefore, Cu element was selected as the intermediate element in this work. The electroplating method was adopted for the precise control of Cu content. The influence of varying Cu coating thicknesses on microstructural evolution and fracture loads of Mg/Cu-coated Ti joints was evaluated. The element diffusion and joining mechanism were elucidated with the assistant analysis of thermodynamic calculation.

2. Experimental procedure

2.1. Materials and electrodeposition process

Commercially available magnesium alloy AZ31B (Mg-3%Al-1%Zn) and titanium alloy Ti-6Al-4 V (Ti-6%Al-4%V) were used as base metals, which were cut into rectangle shape with 100-mm length, 55-mm width, 1.5-mm thickness and 100-mm length, 55-mm width, 1.0-mm thickness, respectively. AZ92 Mg based filler (Mg-9%Al-2%Zn) with a diameter of 1.6 mm was used as filler metal. Before electrodeposition, the joining surface of Ti alloy was degreased and oxide film was removed in acid (5% HF, 15% HCl and 80% distilled water) bath for 3 min, and then Ti sheet was rinsed under tap water for 1 min. The electrodeposition of Cu coating on Ti was carried out in plating solution and its composition was listed in Table 1. The plating current density was maintained at 0.5 A/dm^2, the temperature was set as 35 °C, and the magnetic stirrer was keep at 200 rpm during plating process. The corresponding schematic diagram of electrodeposition was provided as Fig. 1 showed. The coating thickness was controlled by altering coating time, and the averages of five readings for coating thickness were measured by scanning electron microscopy (SEM) and the corresponding SEM morphologies were shown in Fig. 2(a)–(e). The relation between coating thickness and coating time was established as presented in Fig. 2(f).

2.2. Laser welding-brazing process

Fig. 3 shows the schematic illustration of LWB process. Lap configuration with Ti sheet at the bottom was adopted in this work. The welding was carried out by a fiber laser of YLS-6000 model (IPG company) with 6-kW maximum output power, 1070-nm laser beam wavelength, 8-mm mrad beam parameter product and 0.6-mm-diameter focused beam which was focused by a mirror with 300-mm focus length. Before welding, the oxide layer at the bonding surface of AZ31B Mg alloy was wiped off by stainless steel wire brushing. Both Ti and Mg base metals were cleaned by ultrasonic with acetone. Continuous laser beam irradiated the junction vertically between the two base metals. Argon gas was used as shielding gas (20 l/min of flow rate). The detailed welding parameters were presented in Table 2.

2.3. Analysis methods

The cross-sectional observations of welding region were taken by optical microscope (OM) and scanning electron microscope (SEM) with energy dispersive spectrometer (EDS). Micro X-ray diffraction (XRD) was conducted to confirm the phases produced at the Mg/Cu-coated Ti surface. The specimens for tensile-shear testing were prepared with 10-mm width. In order to guarantee parallel between joint interface and loading direction, shims were used at the end of specimens as shown in Fig. 3(b). The cross-head speed of 1 mm/min was adopted when using universal material testing machine (model Instron 5967) at room temperature. The average fracture loads of joints were calculated through three specimens.

Table 1
The Cu electroplating solution composition (g/L).

Composition	$K_4P_2O_7{\cdot}3H_2O$	$C_6H_{17}N_3O_7$	$CuSO_4{\cdot}5H_2O$	$Na_2HPO_4{\cdot}12H_2O$
value	220	20	48	24

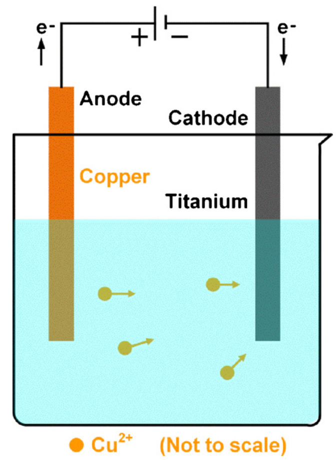

Fig. 1. Schematic of Cu electroplating onto Ti alloy surface.

2.4. Thermodynamic analysis

Thermodynamic calculation was performed by MATLAB to analyze the atomic diffusion and dissolution, assisting in analyzing the element reaction based on the Miedema model (Miedema, 1973) and Toop model (Toop, 1965). In this work, only small region near the Ti interface where the stirring and flow of pool was weak was taken into consideration. Additionally, the starting point of the calculated stage was not coincided with that of welding process. The situation was employed that atomic distribution had been in relative stabilization process when Cu, Al, Mg and Ti atoms existed in liquid phase and in solid phase, respectively.

The formation enthalpy of binary system could be expressed as:

$$\Delta H_{1,2} = f_{1,2}\frac{x_1[1+\mu_1 x_2(\varphi_1-\varphi_2)]x_2[1+\mu_2 x_1(\varphi_2-\varphi_1)]}{x_1V_1^{2/3}[1+\mu_1 x_2(\varphi_1-\varphi_2)]+x_2V_2^{2/3}[1+\mu_2 x_1(\varphi_2-\varphi_1)]} \quad (1)$$

$$f_{1,2} = \frac{2pV_1^{2/3}V_2^{2/3}[q/p(\Delta n_{WS}^{1/3})^2-(\Delta\varphi)^2-a(r/p)]}{(\Delta n_{WS}^{1/3})_1^{-1}+(\Delta n_{WS}^{1/3})_2^{-1}} \quad (2)$$

Where, ΔH was the formation enthalpy of binary alloys; x_i was the molar fraction of components; φ, V and n_{ws} were the electronegativity, molar fraction and electron density parameters of component; q, r, μ, a, p were experimental constants determined by Miedema and coworkers.

Toop model (1965) was developed from Miedema model (1973) and Toop model (1965) was the basis of quaternary system. Corresponding excess Gibbs free energy G^E and chemical potential μ_i could be calculated by following formula:

$$\begin{aligned} G^E = {} & \frac{x_2}{1-x_1}G_{12}^E(x_1, 1-x_1) + \frac{x_3}{1-x_1}G_{13}^E(x_1, 1-x_1) + \frac{x_4}{1-x_1}G_{14}^E(x_1, 1-x_1) \\ & + (x_2+x_3)^2G_{23}^E\left(\frac{x_2}{x_2+x_3}, \frac{x_3}{x_2+x_3}\right) \\ & + (x_2+x_4)^2G_{24}^E\left(\frac{x_2}{x_2+x_4}, \frac{x_4}{x_2+x_4}\right) \\ & + (x_3+x_4)^2G_{34}^E(\frac{x_3}{x_3+x_4}, \frac{x_4}{x_3+x_4}) \end{aligned} \quad (3)$$

$$G_m = G^{ID} + G^E \quad (4)$$