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Control of Mg_2Sn formation through ultrasonic-assisted transient liquid phase bonding of Mg to Al

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ABSTRACT

The formation of Al/Mg intermetallic compounds (IMCs) of Al_3Mg_2 and $Al_{12}Mg_{17}$ was successfully avoided through ultrasonic assisted transient liquid phase bonding Mg/Al using pure Sn interlayers. A new IMC of Mg_2Sn formed in the joints. Different bonding parameters were used to control the formation of Mg_2Sn. The optimum joint shear strength of 60.0 MPa was obtained at the temperature of 220 °C, ultrasonic power of Mode I and ultrasonic time of 4 s. The thickness of Mg_2Sn should be depressed to less than 15% of the joint width. Joints were fractured through the Mg_2Sn layer.

1. Introduction

The energy crisis and environment problems in the world have promoted the use of lightweight materials. Al and Mg are two of the lightest metals that are commonly used today. Al, Mg and dissimilar Al/Mg joints are always used to fabricate steering wheels, wheel boss, and other structural component. Therefore, the joining of dissimilar Al/Mg alloys has attracted extensive attention from researchers. To obtain Al/Mg joints with high strength, scholars have used various welding methods, such as fusion welding, diffusion welding, inertia friction welding, and friction stir welding. Islam et al. (2017) found that because of substrate melting, intermetallic compounds (IMCs) of Al_3Mg_2 and $Al_{12}Mg_{17}$ easily form in fusion welding joints. Guo et al. (2017a) reported similar IMC problems resulting from the different crystal structures, atom diameters, and electronegativities of Al and Mg in diffusion bonding. Although friction stir welding is a solid-state joining method, peak temperatures during welding easily exceed the eutectic temperatures of Al and Mg (Mohammadi et al., 2015 and Ji et al., 2016). Therefore, IMCs cannot be completely avoided.

Ultrasonic-assisted transient liquid phase bonding (UATLP) is a newly developed joining method, that utilizes the low-temperature eutectic reactions between substrates and interlayers. Using a Zn interlayer, Lai et al. (2016) joined AZ31 Mg alloys and achieved a shear strength of 106.4 MPa after 120 s of ultrasonic time. Xiao et al. (2013) reported that ultrasonic vibration exerts a grain refinement effect when joining 1060 Al with Zn-14Al interlayer. Guo et al. (2017b) obtained a joint with a full solid solution of < alpha > -Al with an ultrasonic time of 60 s and a holding time of 3 min at 400 °C. Given the presence of interlayers, UATLP can avoid the direct contact of Al/Mg alloys and thus serves as a good method to avoid Al_3Mg_2 and $Al_{12}Mg_{17}$.

To avoid Al/Mg IMCs, we used UATLP to join dissimilar Mg/Al alloys in this work. Using a pure Sn interlayer, we optimized the joint strength by controlling IMCs.

2. Experimental

The substrates used in this work were 1060 pure Al and AZ31B Mg alloys. Their thicknesses were both 3 mm. Before bonding, Al sheets were cut into dimensions of 14 mm × 14 mm, and Mg sheets were cut into dimensions of 10 mm × 10 mm. The interlayer was pure Sn with a thickness of 0.5 mm. The Sn interlayer was cut into dimensions of 12 mm × 12 mm. All substrates and interlayers were polished using # 800 emery papers and then ultrasonically cleaned in acetone for 10 min. During bonding, the substrates and interlayers were sandwiched in place in a specific fixture, as shown in Fig. 1. The Mg sheet served as the upper sheet. The joining equipment was the self-designed ultrasonic system UPM-U-P1010A01. A constant pressure of 0.4 MPa was applied. A high-frequency induction heating device equipped with temperature feedback control was used. The sonotrode was operated at 20 kHz. The ultrasonic vibration system had a maximum rated power (Pm) of 1000 W. Three modes of power output were used, namely, 1/3 Pm (Mode I), 2/3 Pm (Mode II), and Pm (Mode III). The bonding parameters are shown in Table 1.

After bonding, metallographic specimens were cut using an electrical discharge cutting machine. Following a standard polishing procedure, microstructures of the joints were observed with a ZEISS

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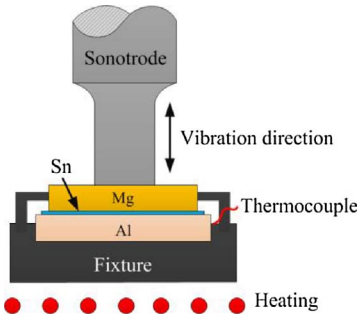

Fig. 1. Schematic of UATLP in this work.

Table 1
Bonding parameters.

No.	Temperature (°C)	Ultrasonic power (W)	Time (s)
1	205	Mode I	4
2	215	Mode I	4
3	220	Mode I	4
4	225	Mode I	4
5	235	Mode I	4
6	245	Mode I	4
7	225	Mode II	4
8	225	Mode III	4
9	225	Mode I	1
10	225	Mode I	6

scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectrometer (EDS). The phases of the joints were analyzed via a D8A25 X-ray diffraction (XRD). The hardness of the joint was tested on a HVS-1000 machine using a 10 g indentation load and 10 s holding time. Shear tests were performed on an electromechanical material testing machine (Instron-5569) using a speed of 1 mm/min. No less than 3 specimens were tested for each condition. The fracture positions and fracture surfaces of the joints were then observed by SEM.

3. Results and discussion

3.1. Mg_2Sn formation

According to the Mg–Sn binary phase diagram in the work of Meng et al. (2010), the eutectic liquid phase forms at about 203.5 °C (Fig. 2).

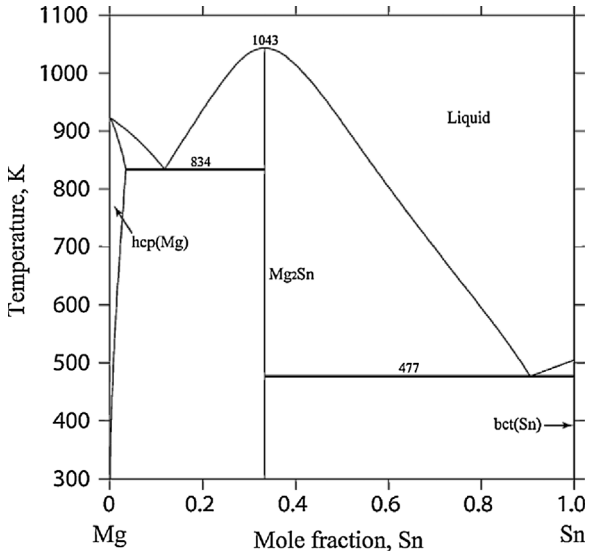

Fig. 2. Phase diagram of the Mg-Sn binary system in the work of Meng et al. (2010).

Fig. 3a shows the joint cross section at 205 °C. The ultrasonic time was 4 s, and the ultrasonic power was Mode I. At 205 °C, only a small amount of Mg–Sn eutectic liquid phase formed at the Mg/Sn interface. Under the action of ultrasonic vibration, a part of the liquid phase was squeezed out. Hence, the joint had a width of about 410 μm. Fig. 2d shows a diffusion layer with 120 μm thickness. The interlayer only partially melted and thus retained its original morphology. Adjacent to the Mg side, the oxide film was incompletely removed because a small amount of the liquid phase was insufficient to produce intense ultrasonic cavitation. The oxide film was only broken due to its plasticity mismatch with the substrate caused by ultrasonic vibration. The EDS results showed that the gray IMC layer was composed of 62.8% Mg, 36.7% Sn and 0.5% Al (at.%). The possible IMC was Mg_2Sn. No effective metallurgical bonding formed at the Al/Sn interface, which showed a rigid unbonded interface (Fig. 3e). After bonding, the joint directly failed at the Al/Sn interface and almost showed no shear strength.

As the temperature was increased to 215 °C, more Mg–Sn eutectic liquid phase was formed and accordingly squeezed out from the joint. Therefore, the joint width of about 340 μm was smaller than that obtained at 205 °C. Mg dissolved into the whole seam, as shown in Fig. 3b. At the Mg/Sn interface shown in Fig. 3f, large, blocky Mg_2Sn was formed. The Mg_2Sn exhibited a discontinuous morphology and a maximum thickness of about 20 μm. No crack was observed inside Mg_2Sn, although it did have high brittleness. At the Al side, the wavy interface indicated that effective bonding was formed. The oxide film was partially broken, as shown in Fig. 3c. The incomplete oxide removal can be attributed to the relatively weak cavitation and plasticity mismatch between the oxide film and the Al substrate caused by the short ultrasonic time of 4 s. During the shear test, the joint showed an average shear strength of 29.6 MPa and failed at the Al/Sn interface.

3.2. Joint formation mechanism

Based on the microstructures presented in Fig. 2, the schematic of the joint formation mechanism was concluded as follows (Fig. 4). After ultrasonic vibration broke the oxide film at the Mg/Sn interface, a large amount of Mg–Sn eutectic liquid phase formed rapidly when the temperature exceeded 215 °C. A large amount of Mg dissolved into the liquid phase. However, the temperature remained lower than the eutectic temperature of Al/Sn according to the Al/Sn binary phase diagram in the work of Smetana et al. (2012). As previously discussed and shown in Fig. 2d, the plasticity mismatch between the oxide film and the Al substrate only partially broke the oxide film. Hence, we speculated that the oxide film removal at the Al/Sn interface mainly depended on ultrasonic cavitation. As Fig. 3b shows, intense ultrasonic vibration occurred in the Mg-Sn eutectic liquid phase. Cavitation bubbles emerged and collapsed continuously under ultrasonic vibration. Micro-jets, acoustic streaming and shock waves impacted both the Mg and Al substrates. After a certain vibration time, cavitation erosion occurred on the Mg substrate, and the oxide film on the Al substrate became completely broken and was finally removed. At this point, some Al atoms dissolved into the liquid phase, although the solubility of Al in Sn was rather low, this result was the same as that obtained by Li et al. (2012). After the ultrasonic vibration, numerous Mg and Sn atoms formed Mg_2Sn near the Mg/Sn interface (Fig. 4c). Some blocky Mg_2Sn phases and Al were also observed inside the joint. The typical element distribution after bonding is shown in Fig. 4d.

As shown in Fig. 3, before the oxide film at the Al/Sn interface was completely removed, some Mg_2Sn phases have already formed at the Mg/Sn interface. With the further increase in the ultrasonic time or temperature, the oxide film at the Al/Sn interface was completely removed, and effective metallurgical bonding was formed. At this moment, a large amount of Mg_2Sn phase formed at the Mg/Sn interface and inside the joint. Therefore, we can conclude that the at Mg_2Sn phase at Mg/Sn interface cannot be completely avoided to form Al/Mg joint in this work. Mg_2Sn is the IMC that easily forms when soldering