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Microstructure, mechanical properties and mechanism of ultrasound-assisted rapid transient liquid phase bonding of magnesium alloy in air

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ABSTRACT

An ultrasound-assisted transient liquid phase (U-TLP) bonding process for magnesium alloy has been developed to shorten the bonding time and operate in air. The optimized joint shear strength can reach 109.3 MPa, which is 100% of base metal. The mechanism of this rapid U-TLP process has been investigated based on the microstructure evolution, phase composition, mechanical properties, and fracture path. The results indicate that the surface oxide films were successfully removed by ultrasonic. The intermetallic compounds (IMCs) in the joint were decreased by increasing bonding temperature. A full solid solution joint interface without IMCs or pores was obtained by applying a two-step U-TLP process: first ultrasonic at 370 °C and second ultrasonic at 490 °C. The time needed for isothermal solidification process was significantly shortened to several seconds, due to liquid squeezing out and accelerated diffusion.

1. Introduction

Magnesium (Mg) alloy is receiving great interests in automotive and aerospace industries due to its low density and high specific strength [1]. To enhance the application of magnesium alloy from single component to assembled system level, reliable and efficient welding technologies are required. A variety of welding methods, including fusion welding [2,3], brazing [4–7], friction stir welding [8,9], friction stir spot welding [10,11] and transient liquid phase (TLP) bonding [12–17] have been applied to join magnesium alloy. Above all, TLP bonding has the advantage of obtaining the joint microstructure and mechanical properties close to the base material [16]. Previous literatures had demonstrated the possibility of obtaining high strength magnesium alloy joints using TLP bonding technique with Al [12,13], Ag [14], Cu [15,16] and Ni [17] interlayer, respectively. The time required for the bonding process was long (30–120 min) and a vacuum environment was needed, limiting the application of this bonding method [18].

The completion time of the TLP process depends on the diffusion and reaction between interlayer and substrate. Zn has the similar crystal structure and electrode potential with Mg, which is used as an alloy element in the brazing filler metals for Mg alloy [4–6]. However, the high vapor pressure of Zn damages the purity and cleanness of the vacuum furnace, making Zn not suitable for the traditional TLP process. Many literatures reported that ultrasound had successfully assisted the brazing process without flux in air, because the surface oxide films were removed and the wettability was enhanced by ultrasonic cavitation effect [19–21]. In this paper, ultrasound-assisted TLP bonding of Mg alloy using Zn interlayer was developed, aiming at shortening bonding time, operating in air and lowering cost comparing with the traditional TLP bonding. A series of technological processes were designed and the mechanism was different from the ultrasonic assisted spreading and wetting. The microstructure evolution, mechanical properties and fracture path were also investigated.

2. Experimental procedures

ME20M Mg alloy was used with nominal chemical composition of 1.8 wt.% Mn, 0.3 wt.% Zn, 0.25 wt.% Ce and Mg balance. The ME20M Mg alloy sheet was cut to 16 mm × 16 mm × 3 mm and 20 mm × 20 mm × 3 mm. The pure Zn foil with ~50 μm thickness was used as U-TLP interlayer. Prior to U-TLP bonding process, the specimens were ground by SiC paper up to 1000 grit and ultrasonically cleaned in acetone for 15 min. The assembly was fixed in an overlap configuration

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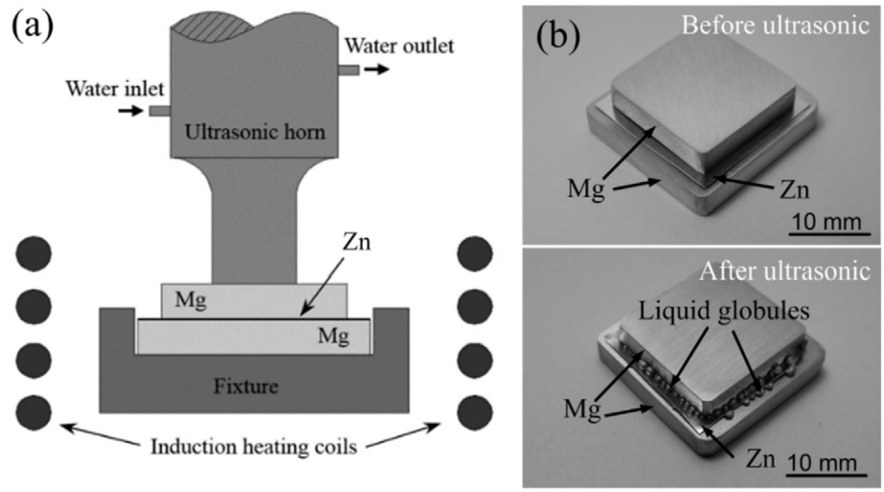


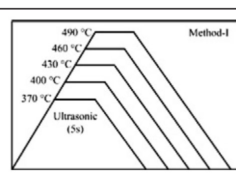
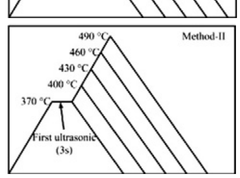
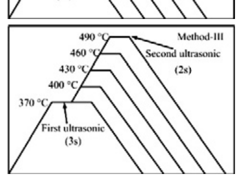
Fig. 1. (a) Schematic diagram of the ultrasonic-assisted TLP process and (b) The typical morphology of the Mg/Zn/Mg assembly.

with smaller Mg sheet on the top of larger one. The Zn foil was sandwiched as an interlayer between the two Mg sheets. A constant bonding pressure of 0.15 MPa was applied. The schematic diagram of U-TLP bonding process was shown in Fig. 1(a). A high-frequency induction system equipped with temperature feedback control was used to heat the sample at constant heating rate of ~20 °C/min. The ultrasound head was 500 W and 20 kHz in frequency. The typical morphology of the Mg/Zn/Mg assembly after ultrasonic was shown in Fig. 1(b).

Three bonding methods were designed as following and were listed in Table 1. Method-I: applying 5 s ultrasonic once reaching the bonding temperature (named as: T + 5 s, where T = 370 °C, 400 °C, 430 °C, 460 °C and 490 °C, respectively). Method-II: applying 3 s ultrasonic at 370 °C, then heating to bonding temperature but without applying a second ultrasonic (named as: 3 s + T, where T = 400 °C, 430 °C, 460 °C and 490 °C, respectively). Method-III: applying the first ultrasonic for 3 s at 370 °C, then heating to bonding temperature and applying a second ultrasonic (named as: 3 s + T + 2 s, where T = 400 °C, 430 °C, 460 °C and 490 °C, respectively).

The microstructures of the joints cross sections were observed by a Quanta 200F scanning electron microscopy (SEM) equipped with an Oxford energy dispersive X-ray spectrometer (EDS). The phase constitution of the joint was analyzed by a D/max 2500 X-ray diffraction (XRD). Hardness testing was performed on a FM-800 hardness tester using a 10 g indentation load and 15 s holding time. Specimens for shear tests were cut from the joints and had a uniform dimension of 5 mm × 10 mm × 6 mm. A specially testing fixture was designed to determine bond shear strength [14], which was schematically shown in Fig. 2. The shear strength test was carried out by a ZWICK-Z020 material test system at a speed of 1 mm/min. Three tests were carried out at each condition. The fracture path of the joint was observed by optical microscope (OM).

Table 1
The technological processes for U-TLP bonding.

	First ultrasonic (s)	Bonding temperature (°C)	Second ultrasonic (s)	Schematic of the process
Method-I	–	370	5	
	–	400	5	
	–	430	5	
	–	460	5	
	–	490	5	
Method-II	3	370	–	
	3	400	–	
	3	430	–	
	3	460	–	
	3	490	–	
Method-III	3	370	2	
	3	400	2	
	3	430	2	
	3	460	2	
	3	490	2	

3. Results

3.1. Technological process design for U-TLP bonding

To investigate the effect of bonding temperature in U-TLP process, three bonding methods were designed, as described above. Fig. 3 shows the typical microstructure of the joints made by method-I (T + 5 s). The joints contain Mg–Zn intermetallic compounds (IMCs) in the center which were detrimental to the joint strength [18]. The width of IMCs layer (indicated by the red dashed line in Fig. 3) was ~35 μm, ~32 μm, ~30 μm and ~17 μm when the joints were made by method-I at 370 °C, 400 °C, 430 °C and 460 °C, respectively. At 490 °C, IMCs layer became discontinuous and replaced by Mg(Zn) solid solution matrix. However, pores were found at the joint interface when the

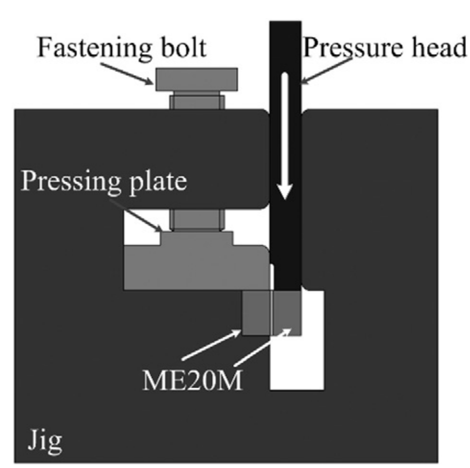


Fig. 2. Schematic diagram of the shear test fixture.