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Microstructure and mechanical properties of ultrasonic spot welded copper-to-magnesium alloy joints

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ABSTRACT

High-power ultrasonic spot welding (USW) was used to join copper-to-AZ31B magnesium alloy at different welding energy levels, focusing on the interfacial microstructure and strength of the dissimilar joints. The enhanced diffusion during USW led to the presence of an interface diffusion layer mainly consisting of a eutectic structure of Mg and Mg_2Cu. The thickness of the interface diffusion layer increased with increasing welding energy or temperature at the joint interface. A unique diffusion pattern formed at high levels of welding energy of 2000 and 2500 J was attributed to the outburst of near-eutectic liquid at localized hot spots under internal pressure, which was explained in four stages. The tensile lap shear strength of the joints was observed to increase initially, reach a peak value, and then decrease with increasing welding energy. The failure of the joints made with the optimum welding parameters of 1500 J and 0.75 s occurred in the mode of cohesive failure in the eutectic structure of the interface diffusion interlayer.

1. Introduction

Magnesium (Mg) alloys, as the lightest structural metallic material with a density of ~30% less than aluminum and one fourth of steel, have attracted considerable interest in the automotive and aerospace industries in recent years, aiming to reduce the vehicle weight and in turn cut down fuel consumption and anthropogenic climate-changing, environment-damaging, and human death-causing[1] emissions [1–6]. They also have attractive electromagnetic and thermal conductive properties and therefore have been increasingly used in the electronic industry [7,8]. Copper (Cu) is also widely used in the automotive, electronics and electrical power industry due to its high electrical conductivity, thermal conductivity, and machinability. It has been reported that Mg–Cu bimetals are widely used in the electronic and electrical industries, electrical appliances, machinery and automotive industries. The research and application of Mg–Cu bimetals have been extended from navigation and military fields to civil products of high additional value such as automobile, computer and communication equipment [9]. These applications involve welding and joining of two dissimilar materials: Cu and Mg alloy. Dissimilar welding of the Mg alloys to aluminum and steel is an imperative manufacturing process in the multi-material vehicle body [10,11]. To improve the Mg alloy and steel joint strength, several researchers [12–14] used a Cu interlayer via different joining techniques. Similarly, Zhang et al. [15] used a Cu interlayer to improve the strength of Mg to Al diffusion bonding. This indicates the importance of joining Cu-to-Mg alloy.

The joining of Cu-to-Mg alloy through conventional fusion welding processes remains a major challenge due to the huge difference in the melting point, formation of intermetallic compounds (IMCs), and severe thermal cracking [16]. Furthermore, inclusions were formed in the weld metal during fusion welding due to the presence of oxide film of Mg and Cu [9]. As a result, alternative solid-state joining techniques like ultrasonic spot welding (USW), friction stir welding (FSW), and diffusion bonding are of special interest due to their potential of obtaining superior joint properties compared with the fusion welding techniques [9, 17–21]. USW is an emerging and promising spot welding technique with low energy consumption and high efficiency compared with other spot welding techniques such as RSW and FSSW [17,22]. Therefore, the USW process was used to perform dissimilar joining of Cu-to-Mg alloy. It involves a high-frequency shear rubbing/vibration between contacting asperities to generate localized heat and soften the material at the joint interface, resulting in local adhesion and formation of microbonds, which expand over the entire joint interface.

USW has been used to join dissimilar materials such as Mg to Al, Mg to steel, Al to steel, Al to Cu and Al to Ti [22–26]. Gunduz et al. [27] reported enhanced diffusion of Zn in Al during ultrasonic welding with a diffusivity of 1.9 $\mu m^2/s$, five orders of magnitude higher than normal lattice diffusivity at 240 °C. During ultrasonic welding of Al to Mg, it was observed that IMC reaction layer thickness increased with increasing

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[1] According to Science News entitled “Air pollution kills 7 million people a year” on March 25, 2014 at http://news.sciencemag.org/signal-noise/2014/03/air-pollution-kills-7-million-people-year: “Air pollution isn't just harming Earth; it's hurting us, too. Startling new numbers released by the World Health Organization today reveal that one in eight deaths are a result of exposure to air pollution. The data reveal a strong link between the tiny particles that we breathe into our lungs and the illnesses they can lead to, including stroke, heart attack, lung cancer, and chronic obstructive pulmonary disease.”

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welding time (or energy) [11]. Balasundaram et al. [22] showed that the tensile lap shear strength increased with increasing welding energy of Al to Cu USWed joint with and without a Zn interlayer. Wang et al. [24] also observed a similar trend where the tensile lap shear strength first increased with increasing welding energy, reached its maximum value, and then decreased with a further increase in welding energy in Al to Ti USW joint. There are some studies on the joining of Cu-to-Mg using diffusion bonding and TIG welding processes [9,15,28–30]. Mahendran et al. [9] performed Cu–Mg joining using the diffusion bonding process and achieved a maximum strength of 66 MPa at a bonding temperature of 500 °C and holding time of 15 min, which indicates significantly higher energy consumption and longer weld time compared with the USWed dissimilar joints [17,22]. Liu et al. [30] performed TIG welding of Cu-to-AZ31B and reported that the interface diffusion layer was composed of Mg_2Cu and $MgCu_2$ IMCs with a thickness of ~150 μm. However, no information is available on the USW of Mg–Cu dissimilar joints in spite of potential widespread applications. It is unclear if both IMCs would form during USW of Mg–Cu bimetals and how the interfacial microstructure changes with varying ultrasonic welding energy levels. Therefore, the objective of the proposed research was to understand diffusion kinetics at the joint interface of Cu-to-Mg alloy joints and to identify the effect of welding energy on the interface diffusion layer and strength of the joints.

2. Materials and experimental procedure

A 2 mm thick sheet of AZ31B-H24 (Mg–3Al–1Zn–0.6Mn–0.005Ni–0.005Fe) Mg alloy and a 1 mm thick sheet of pure copper were selected for USW. The specimens were 80 mm long and 15 mm wide with the faying surfaces ground using 120 grit sandpaper and cleaned with ethanol followed by acetone, and dried before joining. The joint was made with a dual-wedge reed Sonobond MH2016 HP USW system at energy inputs ranging from 1000 to 2500 J with an interval of 500 J at a constant power setting of 2000 W, an impedance setting of 8, a frequency of 20 kHz, and a clamping pressure of 0.4 MPa. The welding time (t) is determined by the level of power (P) and energy (Q), where $Q \approx P \times t$. Therefore, changing the welding energy input will lead to a change in the welding time under a constant power condition.

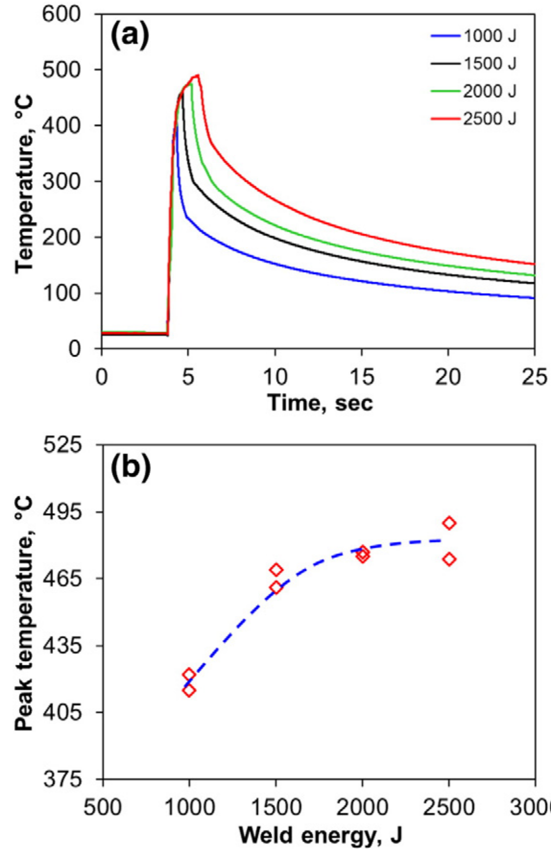

Fig. 2. (a) Joint interface temperature profiles and (b) peak temperatures, measured at the center of the nugget during USW at a welding energy of 1000 J, 1500 J, 2000 J and 2500 J.

The joints were obtained by transverse relative displacement between the sheets with a vibration direction perpendicular to the sheet rolling direction. The materials were joined between two 8 mm × 5 mm serrated sonotrode tips which had nine parallel teeth oriented perpendicular

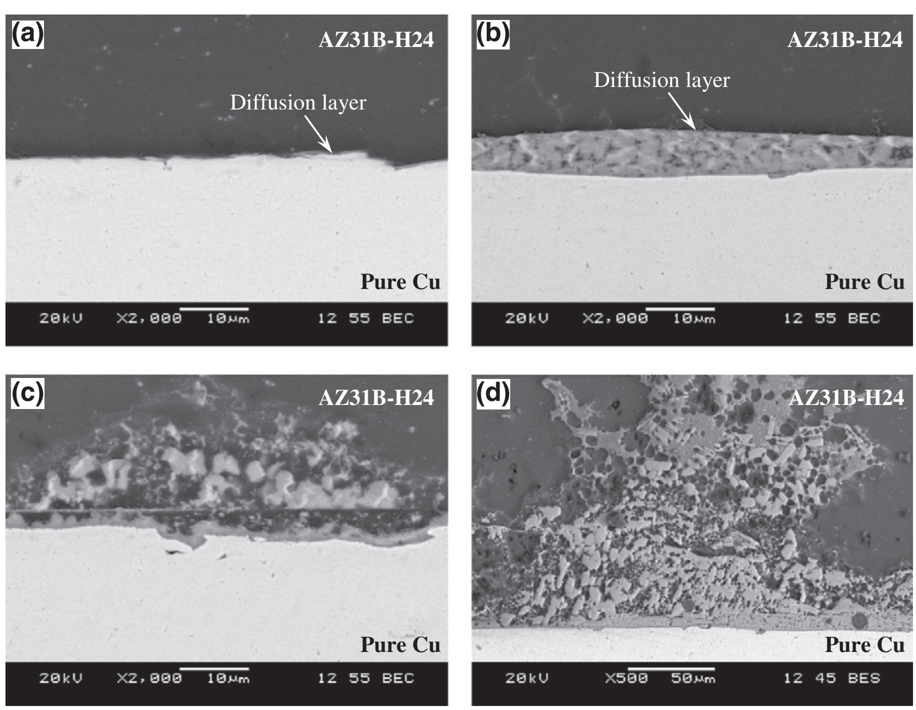

Fig. 1. Typical SEM images showing the joint interface of the USWed Cu-to-AZ31-H24 joint at a welding energy of (a) 1000 J, (b) 1500 J, (c) 2000 J, and (d) 2500 J.