Materials Science & Engineering A 666 (2016) 139–148

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Ultrasonic spot welding of rare-earth containing ZEK100 magnesium alloy to 5754 aluminum alloy

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ARTICLE INFO

Article history:
Received 20 February 2016
Received in revised form
18 April 2016
Accepted 20 April 2016
Available online 21 April 2016

Keywords:
Magnesium alloy
Aluminum alloy
Ultrasonic spot welding
Microstructure
Tensile strength
Fatigue

ABSTRACT

The aim of this study was to examine the feasibility of joining a low rare-earth containing ZEK100 Mg alloy to 5754 Al alloy via solid-state ultrasonic spot welding (USW), and evaluate the interface microstructure, tensile lap shear strength, and fatigue life. A diffusion layer consisting of eutectic structure of α-Mg and $Al_{12}Mg_{17}$ intermetallic compound was observed to form at the interface during USW, and its thickness increased with increasing welding energy. The tensile lap shear strength first increased, reached a peak value and then decreased with increasing welding energy. The optimal average strength of ZEK100-Al5754 dissimilar joints arrived at ~78% of ZEK100-ZEK100 similar joints and ~55% of Al5754-Al5754 similar joints. The tensile lap shear test samples failed in an interfacial mode with partial cohesive failure through the interface diffusion layer and partial failure through Mg alloy, with Mg alloy sticking on the Al side. Fatigue life of samples welded at a welding energy of 500 J was longer than that at 1000 J at higher cyclic loading levels, and it became equivalent at lower cyclic loading levels. The bi-linear behavior of S-N curves corresponded well to the change in the failure characteristics. At higher cyclic loading levels interfacial failure prevailed, while the formation of transverse-through-thickness (TTT) crack at the nugget edge occurred at lower cyclic loading levels.

1. Introduction

Lightweighting has been regarded as a key strategy in the automotive industry to meet stringent corporate average fuel economy (CAFE) regulations and diminish anthropogenic climate-changing, environment-damaging, costly and human death-causing[1] emissions [1–5]. Magnesium (Mg) alloys with a high strength-to-weight ratio are attractive for the transportation industry to achieve vehicle lightweighting [6–8]. Although wrought (extruded, rolled) Mg alloys such as AZ31 and AZ61 show superior mechanical properties to the cast counterparts, their applications are limited by their poor room temperature formability due to the strong crystallographic texture, which also leads to the tension-compression yield asymmetry and mechanical anisotropy [9–11]. In recent years, it has been realized that the addition of rare-earth (RE) elements to Mg alloys along with Zn can soften or randomize the texture and improve their room temperature formability [10–14]. Moreover, the corrosion resistance of Mg alloys can also be effectively improved by the addition of RE elements [15,16]. Therefore, some new Mg alloys are being developed with a minimal addition of RE elements to reduce alloy cost and achieve better mechanical properties. One such Mg alloy is ZEK100, which contains only 0.2 wt% Nd. Several recent studies showed that ZEK100 Mg alloy exhibited superior room temperature formability [17,18] and fatigue resistance [19,20]. As a result, it is being considered as a promising candidate for structural and closure components in the automotive and aerospace sectors. These applications inevitably involve dissimilar joining of ZEK100 Mg alloy, especially with Al alloy to manufacture lightweight multi-material vehicle body structures and parts [21].

With increasing use of Al and Mg alloys in the automotive industry, there is a pressing need for technology to develop robust welding processes for producing a reliable and durable dissimilar Mg/Al joints. The major difficulty in the welding of Al and Mg alloys using conventional fusion processes is the formation of excessive intermetallic compounds (IMCs), which have a detrimental effect on the joint strength [22,23]. The key to increase the joint strength is to control the IMCs as less as possible during joining process. The three main approaches reported to eliminate or reduce the negative effect are to use (1) a lower welding

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[1] According to Science News entitled “Air pollution kills 7 million people a year” on March 25, 2014 at http://www.sciencemag.org/news/sifter/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.”

http://dx.doi.org/10.1016/j.msea.2016.04.060
0921-5093/

temperature and (2) a shorter welding time, and (3) add filler material in-between the joint [24,25]. Recently, solid-state welding techniques, e.g., ultrasonic spot welding (USW), friction stir welding (FSW), linear friction welding (LFW), and friction stir spot welding (FSSW), are gaining popularity for dissimilar joining applications due to their lower welding temperature, shorter reaction time and lower energy consumption, compared with fusion welding techniques. USW is an emerging and evolving spot welding technique with low energy consumption and higher efficiency for joining thin lightweight metal sheets compared with other spot welding techniques such as, RSW and FSSW, and therefore is of special interest for producing dissimilar Mg/Al joints [23,25–29]. During USW, high frequency (typically 20 kHz) shear vibration is applied to the work pieces through sonotrodes (welding tools), which are connected to transducers, under a small static normal clamping force. This induces the scrubbing of two metal sheets, leading to the breaking of surface oxide layers between contacting asperities, generating localized heat to soften the material at the weld interface, and eventually resulting in local adhesion and formation of microwelds, which expand over the entire weld interface [23,25–27].

There are some studies on the joining of Mg to Al using USW in recent years. Panteli et al. [30] studied the growth behavior of Mg-Al IMCs under various welding energy levels (or welding times) and clamping pressures for USWed AZ31-Al6111 dissimilar joints, and observed that the IMC growth rate was over twice faster than under static condition. Patel et al. [23,25] also evaluated the effect of welding energy on the microstructure and strength of the USWed AZ31-Al5754 dissimilar joints and showed that the addition of a tin interlayer improved the strength by eliminating IMCs with the formation of a Mg-Mg_2Sn eutectic layer. To the authors' knowledge, all of the above studies involved AZ31 Mg alloy; there are no reports on the dissimilar welding of Al to the low RE-containing ZEK100 Mg alloy. It is unknown if the bonding strength of ZEK100 to an Al alloy via USW would be enhanced due to its improved ductility and formability. Furthermore, it was reported that the interdiffusion coefficient in Mg-Al system was a function of composition [31], it would thus be of interest to ascertain how the IMC will grow during USW of ZEK100 to Al5754 alloy. The present investigation was, therefore, aimed to study the feasibility of joining ZEK100 Mg alloy to 5754 Al alloy via USW and identify the effect of a key welding parameter (i.e., welding energy) on the microstructure, tensile properties and fatigue life of the dissimilar joints.

2. Materials and experimental procedure

The materials used for USW were 2.0 mm thick sheet of ZEK100-O Mg alloy supplied by Magnesium Electron North America, Inc. via Magna International Inc. and University of Waterloo and 1.5 mm thick sheet of Al5754-O Al alloy supplied by General Motors, USA. The chemical composition of both alloys are listed in Table 1. Test coupons of 80 mm × 15 mm strips were initially cut to prepare joints. A 2.5 kW dual wedge reed Sonobond-MH2016 HP-USW system operated at 20 kHz was used to perform welding. The welding tools used were 8 × 5 mm flat serrated sonotrode tips having nine parallel teeth to ensure good grasping of top and bottom sheets so as to eliminate the relative motion between the sonotrode tip and sheet. The test coupons were ground with 120 grit sand paper, cleaned with ethanol followed by acetone prior to welding. The joints were achieved by a transverse relative displacement between the sheets with a 20 mm overlap having vibration direction perpendicular to the rolling direction. The welding was performed in an energy mode, where different weld energy levels ranging from 250 to 2000 J with a constant power setting of 2 kW, an impedance setting of 8, and a clamping pressure of 0.4 MPa. Here, the weld energy (Q, in J) is determined by the level of power (P, in kW) and weld time (t, in s), i.e., $Q \approx P \times t$. For example, 1000 J at 2 kW is equivalent to ~0.5 s

Table 1
Chemical composition of the ZEK100-O Mg alloy and 5754-O Al alloy.

Material	Zn	Zr	Nd	Mn	Sc	Mg	Al
ZEK100 Mg alloy	1.3	0.25	0.2	0.01	–	Bal.	–
5754 Al alloy	–	0.22	0.21	0.63	0.23	3.42	Bal.

The joints were sectioned across their center, parallel to the vibration direction by a slow speed diamond cutter for scanning electron microscope (SEM) observations. The samples were then cold-mounted in epoxy and mechanically polished using abrasive papers, diamond paste and colloidal silica. Tensile lap shear tests of the joints were conducted to measure the failure load using a fully computerized United testing machine in air at room temperature with a constant crosshead speed of 1 mm/min. X-ray diffraction (XRD) was carried out on both matching interfaces of Mg alloy and Al alloy sides after tensile lap shear tests using Cu K_α radiation at 45 kV and 40 mA. The diffraction angle (2θ) at which the X-rays were incident on the samples varied from 20° to 100°, with a step size of 0.05° and 2 s in each step. Fatigue tests were performed using a fully computerized Instron 8801 servo-hydraulic testing system under load control at different maximum loads. A load ratio of R (P_{min}/P_{max}) equal to 0.2, sinusoidal waveform, and frequency of 50 Hz were used in all the tests. In the tensile lap shear testing and fatigue testing, restraining shims or spacers were attached at both ends of the specimen to minimize the phase angle and therefore, bending moment. The polished samples, tensile failed samples, fatigue failed samples were examined using a JSM-6380LV SEM equipped with Oxford EDS, EBSD, and 3D surface/fractographic analysis capacity.

3. Results and discussion

3.1. Microstructure characterization

The commonly observed bonding mechanisms during USW of metals were metallurgical adhesion, interface diffusion, localized melting, and mechanical interlocking. During USW oxide film would first break locally at asperities allowing metal-to-metal contact, where interdiffusion would occur, allowing the formation of intermetallic products under a sufficiently rapid kinetic reaction at the interface. Fig. 1 shows typical interfacial microstructures of welds made at welding energy levels of 250 J, 500 J, and 1000 J. It can be seen that at a welding energy of 250 J the diffusion at the initially touched asperities resulted in the formation of non-uniform and isolated diffusion layer islands indicated by an arrow (Fig. 1(a)). The non-uniform and discontinuous nature of the diffusion layer was attributed to a non-uniform temperature distribution along the interface within a short welding time [32]. As the welding energy increased to 500 J, a thin continuous diffusion layer was formed as seen from Fig. 1(b) due to an increase in temperature and strain rate at the interface. Further increase in the welding energy to 1000 J (Fig. 1(c)) resulted in the thickening of diffusion layer.

The elemental distribution across the interface of the joints was determined via EDS line analysis. Fig. 2 shows typical results of EDS line scan at a welding energy of 250 J, 500 J and 1000 J, respectively. The concentration of Mg and Al at 250 J as shown in Fig. 2(a) indicated no significant diffusion across the interface except at localized asperities. Fig. 2(b) shows a change in the