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Lap shear strength and fatigue behavior of friction stir spot welded dissimilar magnesium-to-aluminum joints with adhesive

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ABSTRACT

Lightweighting is currently considered as an effective way in improving fuel efficiency and reducing anthropogenic greenhouse gas emissions. The structural applications of lightweight magnesium and aluminum alloys in the aerospace and automotive sectors unavoidably involve welding and joining while guaranteeing the safety and durability of motor vehicles. The objective of this study was to evaluate the lap shear strength and fatigue properties of friction stir spot welded (FSSWed) dissimilar AZ31B-H24 Mg alloy and Al alloy (AA) 5754-O in three combinations, i.e., (top) Al/Mg (bottom), Al/Mg with an adhesive interlayer, and Mg/Al with an adhesive interlayer. For all the dissimilar Mg-to-Al weld combinations, FSSW induced an interfacial layer in the stir zone (SZ) that was composed of intermetallic compounds of Al_3Mg_2 and $Al_{12}Mg_{17}$, which led to an increase in hardness. Both Mg/Al and Al/Mg dissimilar adhesive welds had significantly higher lap shear strength, failure energy and fatigue life than the Al/Mg dissimilar weld without adhesive. Two different types of fatigue failure modes were observed. In the Al/Mg adhesive weld, at high cyclic loads nugget pull-out failure occurred due to fatigue crack propagation circumferentially around the nugget. At low cyclic loads, fatigue failure occurred in the bottom Mg sheet due to the stress concentration of the keyhole leading to crack initiation followed by propagation perpendicular to the loading direction. In the Mg/Al adhesive weld, nugget pull-out failure mode was primarily observed at both high and low cyclic loads.

1. Introduction

Sustainable growth in the transportation sector for the next generation of motor vehicles will be increasingly contingent on the development of energy efficient products that economically use and conserve global resources whilst protecting the environment through reduced emissions [1,2]. The main challenge in terms of manufacturing in the aerospace and ground transportation sectors is to reduce the weight of the vehicle body via applying advanced lightweight materials without compromising reliability and safety. This has recently prompted the development and application of ultra-lightweight magnesium alloys due to their low density, high strength-to-weight ratio and superior damping capacity [3–7]. On the other hand, design and manufacturing with aluminum alloys are longstanding and increasingly significant in aerospace and automotive structures to take advantage of the light weight and proper combination of strength with ductility [8,9]. Co-existent applications of magnesium and aluminum alloys afford design freedom and manufacturing flexibility, but require the development of advanced joining processes, especially with due consideration of the challenges related to the conventional fusion welding to join magnesium-to-aluminum alloys.

Friction stir welding (FSW), a solid-state joining technology, developed by The Welding Institute of Cambridge, UK, in 1991, shows a considerable potential for assembly of sheet/plate materials as the low heat input and process temperatures (absence of melting) enable good retention of the baseline mechanical properties and high weld quality with relatively few defects. As a derivative of the FSW process, friction stir spot welding (FSSW) was later proposed and successfully applied to manufacture hood and rear doors of a sport vehicle [10]. For aluminum and magnesium alloys, conventional assembly by resistance spot welding presents some technical concerns, including weld porosity, electrode wear, high energy consumption, low production efficiency, and inconsistency in failure modes [11–15]. Thus alternative and novel technologies are of avid interest in the automotive industry. Recent research and development thrusts in joining aluminum-to-magnesium sheet materials are to explore methods such as structural adhesives, rivets and toggle-locks. The FSSW process is an emergent technology that may offer a potentially viable solution for dissimilar metal assembly without adding extra weight whilst enabling joint strength and weld

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quality with a reasonable operational cost [11]. Although a number of papers on the joining of Mg and Al alloys using FSSW have recently been reported [8,10,16,17], only limited studies have been done on lap shear strength and especially fatigue resistance of the dissimilar Al-to-Mg FSSW joints, a topic of vital importance for ensuring safe and reliable applications. Lin et al. [18] observed differences in the fracture path under quasi-static loading compared with cyclic loading for Al 6111-T4 alloy. The FSSWed joints of dissimilar Al-to-Mg alloys were observed to have different failure modes compared with the similar welds (i.e., identical alloys for the top and bottom sheets) [8,16,19]. Recently, some new kinds of hybrid welding techniques have been used to join dissimilar Al-to-Mg alloys, such as laser adhesive welding [20–23]. Liu and Ren [20] indicated that the lap shear strength increased in the MIG spot adhesive welded AZ31B-to-Al 6061 joints, while Wang et al. [23] observed that the addition of the adhesive also increased the weld penetration depth in the Al alloy side for Nd-YAG laser adhesive welds of dissimilar Mg-to-Al alloys.

In the present study, friction stir spot adhesive welding, an innovative derivative to FSSW and adhesive bonding, was envisaged for assembly of dissimilar Al-to-Mg alloys. While adhesives provide excellent uniform stress distribution over a large bonding area, the weld itself improves the peel resistance of the adhesive joints. However, the integrity and durability of FSSWed dissimilar Al/Mg and Mg/Al adhesive welds especially under cyclic loading have not been studied yet, since any lap shear strength and fatigue behavior of such adhesive welds in relation to the failure mode changes have not been reported in the literature. It is also unknown how large is the difference between the FSSWed dissimilar Al/Mg welds with and without the use of the adhesive. The main objective of the present study was, therefore, to identify the lap shear strength and fatigue behavior of the friction stir spot adhesive welded AZ31B-H24 alloy to AA5754-O alloy and compare the results with those for the FSSWed joints.

2. Experimental procedure

Commercial AZ31B-H24 Mg and AA5754-O Al alloy sheets with a thickness of 2 mm were selected for FSSW. The nominal chemical composition was Mg-3Al-1Zn-0.6Mn-0.005Ni-0.005Fe for the AZ31B-H24 and Al-3.42Mg-0.23Sc-0.22Zr for the AA5754-O. The Mg and Al alloy sheets were cut into small coupons of 35 mm × 100 mm with the loading axis along the rolling direction. Two coupons were overlaid over an area of 35 mm × 35 mm between which Terokal 5089 adhesive had been applied and cured at a temperature of 170 °C for 20 min. FSSW was then performed at the center of the overlapped area. Three types of dissimilar material combinations, i.e., (top) Al/Mg (bottom), (top) Al/Mg (bottom) with adhesive, and (top) Mg/Al (bottom) alloys with adhesive, were used. The FSSW tool fabricated from H13 tool steel consisted of a scrolled shoulder with a diameter of 13 mm and a left-hand threaded pin with a diameter of 5 mm. FSSW was performed using a MTS I-STIR FSW machine with the process parameters that consisted of a pin length of 2.8 mm, tool rotational rate of 2000 rpm, tool plunge rate of 3 mm/s, tool removal rate of 15 mm/s, shoulder plunge depth of 0.2 mm and dwell time of 2 s. The welded samples were carefully sectioned using a low speed diamond blade to extract specimens for microstructural examination and weld integrity analysis. Metallographic preparation of the specimens involved cold mounting followed by grinding with SiC papers to 1200 grit, polishing to a 0.05 μm finish and etching the Mg alloy side with acetic picral (10 ml acetic acid (99%), 4.2 g picric acid, 10 ml H_2O, 70 ml ethanol (95%)) and the Al alloy side with Keller's reagent (2.5 ml nitric acid, 1.5 ml hydrochloric acid, 1 ml hydrofluoric acid and 100 ml distilled water). The microstructure was observed with an optical microscope equipped with Clemex quantitative image analysis software. Vickers microhardness measurements across the weld were obtained using a computerized Buehler microhardness tester operated at a load of 100 g with a dwell time of 15 s. It is noteworthy that according to ASTM: E384-11e1, the spacing between two adjacent indentations must be at least three times the diagonal length of the indentation. Hence, the spacing between two adjacent indentations during microhardness testing was suitably selected to avoid any potential effect of the strain fields caused by adjacent indentations. To evaluate the mechanical strength of the joints, lap shear tensile tests of the welds were conducted in air at room temperature (RT) using a fully computerized United tensile testing machine at a crosshead displacement speed of 10 mm/min.

Fatigue tests were carried out using a fully computerized Instron 8801 servo-hydraulic testing system under load control at RT and different load amplitudes. A load ratio of R (P_{min}/P_{max}) equal to 0.2, sinusoidal waveform, and a frequency of 50 Hz were applied for all the tests. At least two samples were tested at each load level. The fracture surfaces of the FSSWed joints after fatigue testing were examined using a JSM-6380LV scanning electron microscope (SEM) equipped with Oxford energy dispersive X-ray spectroscopy (EDS) system and three-dimensional (3D) fractographic analysis capacity. Additionally, a multifunctional PANalytical X-ray diffractometer was used to identify the formation of potential intermetallic compounds in the dissimilar Mg-to-Al adhesive welds from the fracture surface (Mg side) after fatigue testing. X-ray diffraction (XRD) was conducted using CuK_α radiation (wavelength $\lambda = 0.15406$ nm) at 45 kV and 40 mA. The diffraction angle (2θ) at which the X-rays hit the sample varied from 20° to 110° with a step size of 0.05° and 3 s in each step.

3. Results and discussion

3.1. Microstructure

Typical base metal (BM) microstructures for the AZ31B-H24 Mg alloy and the AA5754-O Al alloy are shown in Fig. 1(a) and (b), respectively. As shown in Fig. 1(a), elongated and pancake-shaped grains with varying sizes were observed in the BM of the Mg alloy due to both the deformation of the 2 mm thick sheet by rolling and incomplete dynamic recrystallization (partial annealing) [24–26].

Typical optical images at the interface of the dissimilar Al/Mg and Mg/Al adhesive welds are shown in Fig. 1(c) and (d), respectively. For the Al/Mg weld, the interface was marked by the presence of an interfacial layer which covered most of the boundary but the thickness of the interfacial layer varied. However, it was different for the Mg/Al adhesive weld where the interface was marked by both the adhesive and interfacial layer. Fig. 2(a) shows an SEM image of the interface taken from the cross-section of an Al/Mg weld. A distinguishable interlayer with a thickness up to ~20 μm was observed at the interface between the Mg (at the left side in Fig. 2(a)) and the Al (at the right side in Fig. 2(a)) alloys. The EDS line analysis revealed the mutual presence of Al and Mg across the reaction layer, suggesting that the intermetallic compound (IMC) layer formed at the Al/Mg interface during FSSW. As shown by the corresponding EDS line analysis of the image in Fig. 2(b), the presence of the adhesive in the Mg/Al adhesive weld interface decreased the thickness of the IMC layer. An X-ray diffraction pattern obtained from the fracture surface of the Mg/Al adhesive weld (Mg alloy side) is shown in