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Failure mode and fatigue behavior of weld-bonded lap-shear specimens of magnesium and steel sheets

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ABSTRACT

Failure modes and fatigue behaviors of ultrasonic spot welds in lap-shear specimens of magnesium AZ31B-H24 and hot-dipped-galvanized mild steel sheets with and without adhesive were investigated. The spot welded specimens failed from the kinked crack growth mode. The adhesive-bonded specimens failed from the cohesive failure through the adhesive and the kinked crack growth through the magnesium sheet. The weld-bonded specimens failed from the cohesive failure through the adhesive, the interfacial failure through the spot weld, and the kinked crack growth through the magnesium sheet. The estimated fatigue lives for the adhesive-bonded and weld-bonded specimens failed from the kinked crack growth mode are lower than the experimental results.

1. Introduction

Lightweight materials such as advanced high strength steels, aluminum, and magnesium alloys have been replacing the traditional steel in the automotive industry to reduce the vehicle weight for better fuel efficiency. Since magnesium alloys are much lighter than the steels commonly used in vehicles, using magnesium alloys could result in a substantial weight reduction. One of the major issues for introducing magnesium alloys into vehicle structures appears to be joining magnesium components to the existing steel structures. Joining magnesium alloys to steels is especially difficult due to the extreme difference in their melting temperatures and immiscibility of magnesium and iron [1]. Melting magnesium alloys and steels together as might be done in resistance spot welding would vaporize magnesium and create unacceptable porosity in the weld nugget. Solid state joining of magnesium alloys and steels offers a potential solution as the melting is either avoided or minimized. Both friction stir spot welding (FSSW) and ultrasonic spot welding (USW) are capable of joining similar and dissimilar materials. A comprehensive review of FSSW on joining similar materials can be found in Pan [2]. The research works on joining dissimilar materials by FSSW were carried out mostly on joining aluminum and steel sheets, for example, see Gendo et al. [3]. Liyanage et al. [4] conducted research on joining magnesium to steel sheets by FSSW with tool penetration into the lower steel sheets by using a tungsten-based W-25Re tool. However, it would be difficult to implement the technology in the mass production due to tool wear.

For joining similar materials using USW for automotive applications, researchers conducted research on processing conditions of joining similar aluminum sheets, for example, see Hetrick et al. [5], Jahn et al. [6] and Wright et al. [7]. For joining dissimilar sheets by USW, Watanabe et al. [8] investigated the effects of the welding conditions and insert metal on the mechanical properties of dissimilar joints of aluminum and steel sheets. Santella et al. [1] investigated the effects of the zinc coating on joining magnesium to zinc-coated steel sheets by USW. Shakil et al. [9] conducted research on the effects of the welding parameters on microstructure and mechanical properties of dissimilar joints of aluminum and stainless steel sheets by USW. Matsuoka and Imai [10] conducted research on the effects of the welding parameters on joining aluminum and copper sheets by USW. The fatigue behavior of dissimilar ultrasonic spot welds in lap-shear specimens of magnesium AZ31B-H24 and hot-dipped-galvanized mild steel sheets was investigated by Franklin et al. [11]. For joining similar materials using ultrasonic weld bonding (USW + adhesive), Carboni and Moroni [12] conducted research on joining aluminum and magnesium sheets by ultrasonic weld bonding and found better fatigue performance than the ones made by USW alone.

The introduction of pre-cracks in the adhesive-bonded lap-shear specimen was motivated by the computational results

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reported by Heyes et al. [13], who intentionally introduced pre-cracks in their finite element models of the adhesive-bonded specimens to evaluate the *J* integrals for the pre-cracks. Their computational results show that the *J* integral for the pre-cracks can be used to correlate the fatigue lives of different types of specimens. In this investigation, pre-cracks were intentionally introduced in adhesive-bonded and weld-bonded lap-shear specimens. The existence of the stress and strain singularities near the pre-cracks benefits the fatigue life estimation in a way such that the fatigue initiation life can be assumed to be short and then neglected. The fatigue life can therefore be estimated by considering only the crack propagation life using the Paris law.

In this paper, the failure modes and fatigue behaviors of ultrasonic spot welded, adhesive-bonded, and weld-bonded lap-shear specimens of dissimilar magnesium AZ31B-H24 sheets and galvanized mild steel sheets are examined. Ultrasonic spot welded, adhesive-bonded, and weld-bonded lap-shear specimens were first made from dissimilar magnesium AZ31B-H24 sheets and galvanized mild steel sheets. These lap-shear specimens were then tested under quasi-static and cyclic loading conditions. Quasi-static and fatigue strengths of the three types of joints in lap-shear specimens were then obtained. Optical micrographs and SEM images of the failed joints after testing are also examined to identify the failure modes of the joints. Based on the failure modes, fatigue lives of the specimens failed in the kinked crack failure mode are estimated using the Paris law. Finally, conclusions are made based on the experimental results.

2. Experiment

Magnesium AZ31B-H24 and hot-dip-galvanized (HDG) mild steel sheets with the thicknesses of 1.6 mm and 0.8 mm, respectively, were used in this investigation. First, tensile tests were conducted using a MTS Insight testing machine with a 10 kN load cell at the University of Michigan. An extensometer was used for all specimens with a gauge length of 50.8 mm. The ASTM E8/E8M-11 tensile specimen standard for sheet materials was adopted. Fig. 1(a) shows a schematic of a tensile specimen with the dimensions. Fig. 1(b) shows the tensile specimens of the magnesium and steel sheets from the top to the bottom, respectively. The displacement rate was set at 2.54 mm/min (nominal strain rate of 0.00085 s^{-1}) for all tensile specimens. Three specimens were tested for each material. The stress–strain curves of the magnesium and steel sheets are shown in Fig. 2. It is noted that the magnesium shows low strain hardening after yielding. The total elongation ranges from 13% to 22% for the three specimens. The steel sheet shows higher strain hardening after yielding. However, due to the extension limit of the extensometer, the tests were conducted up to the nominal strain of 40% for the steel sheets. Table 1 lists the elastic moduli, yield stresses, and tensile strengths of the magnesium and steel sheets.

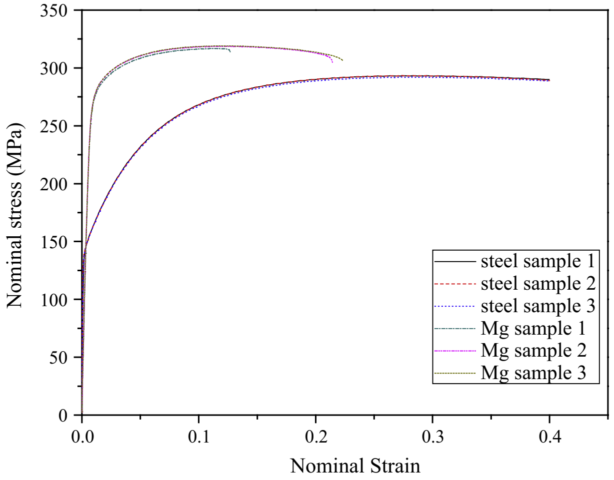


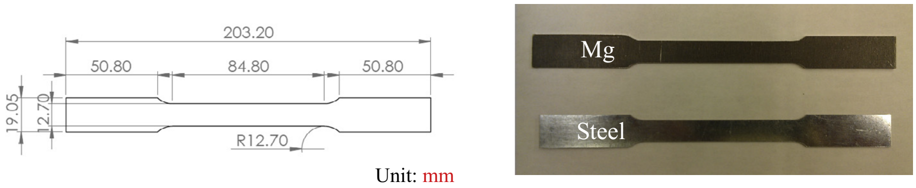
Fig. 2. Nominal tensile stress–strain curves of the magnesium and steel sheets tested at a displacement rate of 2.54 mm/min (nominal strain rate of 0.00085 s^{-1}).

Table 1
Elastic moduli, yield stresses, and tensile strengths of the magnesium and steel sheets tested under quasi-static loading conditions at a displacement rate of 5 mm/min.

	Elastic modulus (GPa)	Yield stress (MPa)	Tensile strength (MPa)
AZ31	45	260	318
HDG mild steel	210	145	293

Ultrasonic spot welded (USW), adhesive-bonded, and weld-bonded (ultrasonic spot welded and adhesive-bonded) lap-shear specimens were prepared for this study. Each lap-shear specimen was made by a 30 mm × 100 mm magnesium sheet and a 30 mm × 100 mm HDG steel sheet with a 30 mm × 40 mm overlap area. Fig. 3(a) shows the top views of the USW, adhesive-bonded, and weld-bonded lap-shear specimens from the top to the bottom. Fig. 3(b)–(d) shows schematics of the top and the side views of USW, adhesive-bonded, and weld-bonded lap-shear specimens with doublers. In the figures, the loading direction is shown by the arrows. The adhesive is shown as the red lines in Fig. 3(c) and (d) for the adhesive-bonded and weld-bonded lap-shear specimens.

For the USW lap-shear specimens, a Sonobond CLF 2500 single-transducer, wedge-reed ultrasonic welder was used for the ultrasonic spot welding. The sonotrode tip has a square face of 7 mm × 7 mm and the face has a grooved pattern. The ultrasonic spot welding was done with a power of 1500 W, an impedance setting of 6, and a welding time of 2.1 s. The spot welding was centered in the overlap area. Fig. 3(a) shows the indentation of the sonotrode tip on the upper magnesium of the USW specimen. The microstructures of the sheets, the specimen preparation procedure, and the processing conditions for the USW lap-shear specimens were detailed in Santella et al. [1].



(a) (b)

Fig. 1. (a) A schematic of a tensile specimen with the dimensions (ASTM E8/E8 M-11) and (b) a picture of the tensile specimens of the magnesium and steel sheets with the thicknesses of 1.6 mm and 0.8 mm, respectively, from the top to the bottom.