

Fatigue Behavior of Dissimilar Ultrasonic Spot Welds in Lap-Shear Specimens of Magnesium and Steel Sheets

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ABSTRACT

Fatigue behavior of dissimilar ultrasonic spot welds in lap-shear specimens of magnesium AZ31B-H24 and hot-dipped-galvanized mild steel sheets is investigated based on experimental observations, closed-form stress intensity factor solutions, and a fatigue life estimation model. Fatigue tests were conducted under different load ranges with two load ratios of 0.1 and 0.2. Optical micrographs of the welds after the tests were examined to understand the failure modes of the welds. The micrographs show that the welds mainly fail from kinked fatigue cracks growing through the magnesium sheets. The optical micrographs also indicate that failure mode changes from the partial nugget pullout mode under low-cycle loading conditions to the transverse crack growth mode under high-cycle loading conditions. The closed-form stress intensity factor solutions at the critical locations of the welds are used to explain the locations of fatigue crack initiation and growth. A structural stress model based on the closed-form structural solution and the stress-life data for magnesium sheets is adopted to estimate the fatigue lives due to kinked crack growth. The fatigue live estimations based on the structural stress model are lower than the experimental results under high load ranges and are in better agreement with the experimental results under low load ranges.

INTRODUCTION

The automotive industry has increased the use of lightweight materials such as aluminum and magnesium alloys to reduce the weight of the vehicle. Aluminum and magnesium alloys are lighter than the steels commonly used in vehicles. Using

magnesium alloys extensively in a vehicle could result in a significant reduction of weight. An important challenge for introducing more 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) can be used to join dissimilar materials. Many researchers used FSSW to joint similar metals. A comprehensive review of FSSW can be found in Pan [2]. For joining dissimilar sheets by FSSW, most researchers conducted research 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 environment due to tool wear. For joining similar materials by 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] conducted research on joining

aluminum and steel sheets. Recently, Santella et al. [1] conducted research on joining magnesium to zinc-coated steel sheets by USW.

Fatigue behavior of these similar and dissimilar solid state spot welds needs to be thoroughly understood and design tools should be developed for life prediction during product development. Many researchers investigated the processing conditions of FSSW and USW and the strength of the spot welds, but few have conducted research on the fatigue behavior of these solid state welds. A comprehensive review of the fatigue research on similar and dissimilar friction stir spot welds can be found in Tran et al. [9] and Tran and Pan [10]. Tran et al. [9,11] adopted the kinked fatigue crack growth model and the structural stress model to correlate their fatigue data successfully based on the closed-form and computational stress intensity factor solutions for spot welds in lap-shear and cross tension specimens. For the similar and dissimilar ultrasonic spot welds, limited research data on the fatigue behavior are available in the literature. A load-life curve for ultrasonic spot welds in lap-shear specimens of similar aluminum sheets can be found in Hetrick et al. [5].

In this paper, the fatigue behavior of dissimilar ultrasonic spot welds in lap-shear specimens of magnesium AZ31B-H24 and galvanized mild steel sheets are examined under cyclic loading conditions. The lap-shear specimens with ultrasonic spot welds were tested under quasi-static and cyclic loading conditions. Optical micrographs of the welds after testing are used to examine the failure modes of the welds. Analytical closed-form stress intensity factor solutions at the critical locations of spot welds in lap-shear specimens of Tran and Pan [12] are presented. The stress intensity factor solutions are used to correlate the experimental observations of the locations of fatigue crack initiation and growth. The fatigue lives due to kinked crack growth are then estimated based on a structural stress model. The estimated fatigue lives due to kinked crack growth are finally compared with the experimental results.

EXPERIMENT

The materials used in this investigation are magnesium AZ31B-H24 sheets with a thickness of 1.6 mm and hot-dip-galvanized (HDG) mild steel sheets with a thickness of 0.8 mm. The machine used for the ultrasonic spot welding was a Sonobond CLF 2500 single-transducer, wedge-reed ultrasonic welder. The sonotrode tip has a square face of 7 mm × 7 mm and the face has a grooved pattern on it. The spot welding was done with a power of 1500 W, an impedance setting of 6 and a welding time of 1 s. Figure 1(a) shows a lap-shear specimen with an ultrasonic weld. Figure 1(a) also shows the indentation of the sonotrode tip on the upper magnesium sheet. The lap-shear specimen was made by using a 30 mm × 100 mm magnesium sheet and a 30 mm × 100 mm coated steel sheet with a 30 mm × 75 mm overlap

area. The spot weld was centered in the overlap area. The microstructures of the sheets, the specimen preparation procedure and the processing conditions were detailed in Santella et al. [1]. Figure 1(b) shows a schematic of a lap-shear specimen with an ultrasonic weld. In the figure, the loading direction is shown by the arrows. Note that Santella et al. [1] used the same processing parameters to investigate the effects of the welding time on the formation of the welds and the strength of the welds under lap-shear loading conditions.

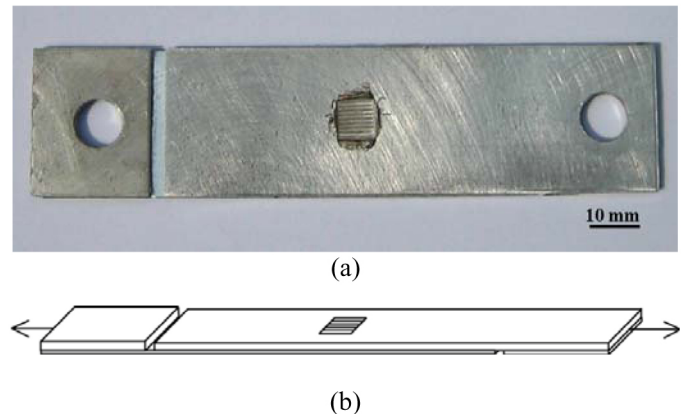


Figure 1. (a) A top view of a lap-shear specimen with an ultrasonic spot weld and (b) a schematic of a lap-shear specimen with an ultrasonic weld with the loading direction shown by the arrows.

Prior to testing, a specimen was sectioned through the weld perpendicular to the vibration direction. Figure 2 shows an optical micrograph of the cross section along the symmetry plane of the weld in the lap-shear specimen. As marked in the figure, the upper sheet is the AZ31 and the lower sheet is the steel. During the welding, the sonotrode tip indented into the top sheet and forced the AZ31 material under the tip to flow outward. The flash can be seen on both side of the tool indentation. The weld reaches just outside of the visibly indented region. On the right side, a gap and a visible Mg-Zn eutectic layer between the magnesium and steel sheets can be seen. On the left side, the Mg-Zn eutectic layer between two sheets is quite thin and the gap between the magnesium and steel sheets can barely be seen. The uneven distribution of the Mg-Zn eutectic layer is possibly due to lack of constraint of the fixture and the upper sheet of the specimen.

The lap-shear specimens were first tested without using doublers under quasi-static loading conditions by using a MTS testing machine at a displacement rate of 10 mm per minute. The average failure load, defined as the average of the maximum loads of the load-displacement curves obtained from three lap-shear specimens, was 4.19 kN. The failure load was used as the reference load to determine the applied loads for the fatigue tests. The lap-shear specimens were then tested with doublers under cyclic loading conditions by using

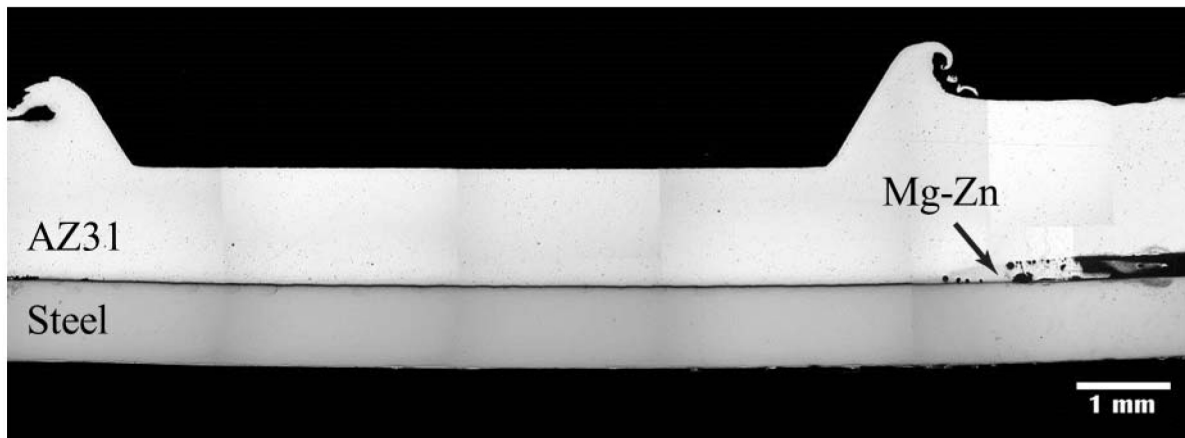


Figure 2. An optical micrograph of the cross section along the symmetry plane of a weld in a lap-shear specimen.

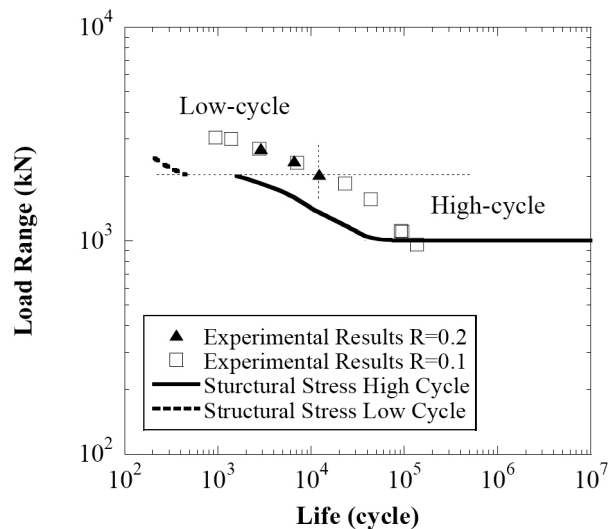


Figure 3. Experimental results and fatigue life estimations for ultrasonic spot welds in lap-shear specimens.

an Instron servo-hydraulic fatigue testing machine with the load ratios of 0.1 and 0.2. The test frequency was 10 Hz. The tests were terminated when specimens were separated or transverse cracks from the welds became clearly visible. [Figure 3](#) shows the load range as a function of the fatigue life for the welds in lap-shear specimens under cyclic loading conditions. The fatigue life estimations shown in the figure based on the structural stress model will be discussed later in the paper.

FAILURE MODE

Under quasi-static loading conditions, the experimental observations indicate that the welds mostly failed in an interfacial failure mode. It should be noted that the fracture path was in the magnesium near the interface. Some failed welds have small partial nuggets of the upper magnesium left on the lower steel sheets. [Figure 4\(a\)](#) shows a failed weld with a small partial nugget left on the lower steel sheet under

quasi-static loading conditions. Under cyclic loading conditions, the experimental observations indicate that the welds failed in a partial nugget pullout mode for the fatigue lives from 10^3 to 10^4 cycles (low-cycle loading conditions). [Figure 4\(b\)](#) shows a failed weld with a large partial nugget left on the lower steel sheet at the fatigue life of 2.8×10^3 cycles under a load range of 2.690 kN. The experimental observations indicate that the specimens failed in a transverse crack growth mode for the fatigue lives from 2×10^3 to 10^5 cycles (high-cycle loading conditions). [Figure 4\(c\)](#) shows a failed specimen at the fatigue life of 9.1×10^4 cycles under a load range of 1.112 kN. As shown in the figure, two transverse through cracks grew through the upper magnesium sheet. Note that the low-cycle and high-cycle loading conditions in this study are defined only for convenient presentation of the experimental results.