

Failure Mode and Fatigue Behavior of Ultrasonic Spot Welds with Adhesive in 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 are investigated. Ultrasonic spot welded, adhesive-bonded, and weld-bonded lap-shear specimens were made. These lap-shear specimens were tested under quasi-static and cyclic loading conditions. The ultrasonic spot weld appears not to provide extra strength to the weld-bonded lap-shear specimen under quasi-static and cyclic loading conditions. The quasi-static and fatigue strengths of adhesive-bonded and weld-bonded lap-shear specimens appear to be the same. For the ultrasonic spot welded lap-shear specimens, the optical micrographs indicate that failure mode changes from the partial nugget pullout mode under quasi-static and low-cycle loading conditions to the kinked crack growth mode under high-cycle loading conditions. For the adhesive-bonded lap-shear specimens, the optical micrographs indicate that failure mode changes from the cohesive failure mode near the interfaces under quasi-static and low-cycle loading conditions to the kinked crack growth mode under high-cycle loading conditions. For the weld-bonded lap-shear specimens, the optical micrographs indicate that failure mode changes from the cohesive failure mode near the interfaces through the adhesive and interfacial failure mode through the spot weld under quasi-static and low-cycle loading conditions to the kinked crack growth mode under high-cycle loading conditions.

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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. 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 applications regarding joining dissimilar materials by FSSW are done 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] conducted research on joining aluminum and steel sheets. Santella et al. [1] conducted research on joining magnesium to zinc-coated steel 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. [9].

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

EXPERIMENT

Magnesium AZ31B-H24 and hot-dip-galvanized (HDG) mild steel sheets with the thicknesses of 1.6 mm and 0.8 mm, respectively, are used in this investigation. Ultrasonic spot welded (USW), adhesive-bonded, and ultrasonic spot welded and adhesive-bonded (weld-bonded) lap-shear specimens were prepared for this study. Each lap-shear specimen was made by using a 30 mm $\times$ 100 mm magnesium sheet and a 30 mm $\times$ 100 mm HDG steel sheet with a 30 mm $\times$ 40 mm overlap area.

Figure 1(a) shows the top views of the USW, adhesive-bonded, and weld-bonded lap-shear specimens from the top to the bottom. Figures 1(b), 1(c), 1(d) show schematics of the top and 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 Figures 1(c) and 1(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 $\times$ 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. Figure 1(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].

For the adhesive-bonded lap-shear specimens, the magnesium and steel sheets were bonded by BETAMATE™ 73305, a heat curing epoxy adhesive. Prior to applying the adhesive, two tapes were placed on the magnesium and steel sheets to form two pre-cracks between the sheets and the adhesive, as shown in Figure 1(a). The locations of the tape tips are indicated in Figure 1(c). As shown in the figure, the tape tips are 5 mm from the edges of the overlap region. The adhesive thickness is controlled by placing a few 0.3-mm zirconia balls on the bonded surfaces. Hence the final adhesive thickness is 0.3 mm. The specimen was then heated to the curing temperature to join the sheets. The area joined by the adhesive is 30 mm $\times$ 30 mm which is smaller than the overlap area of the two sheets.

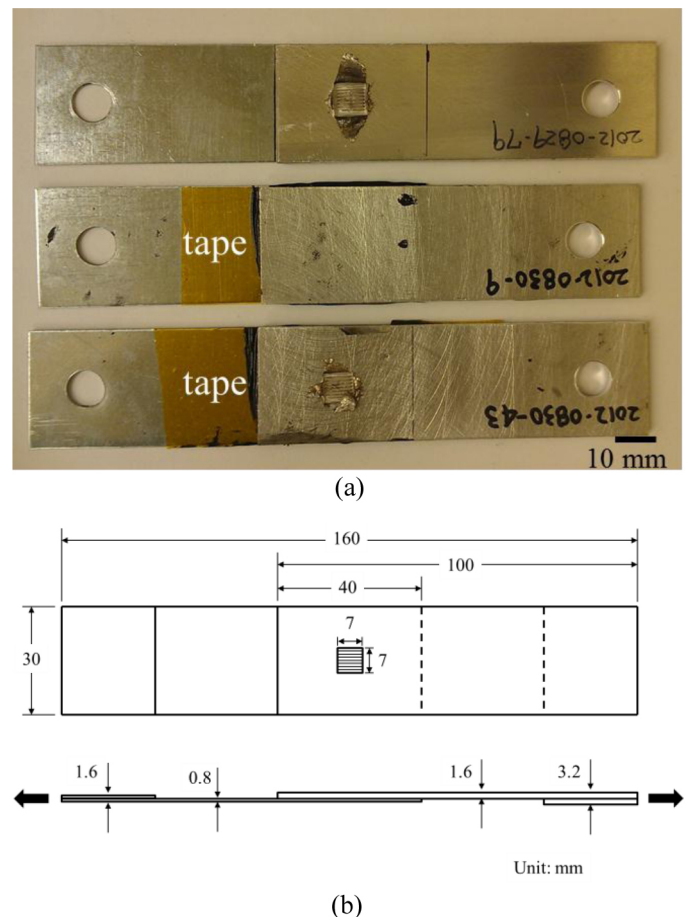
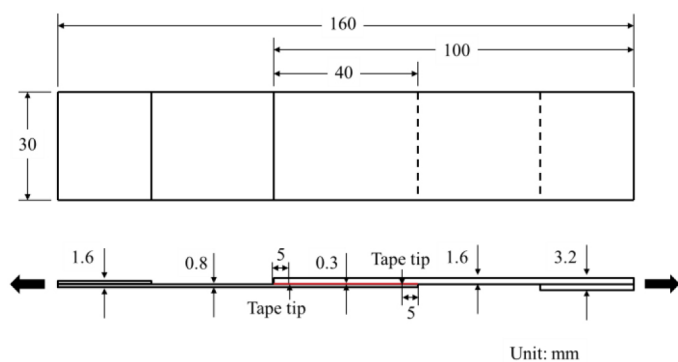
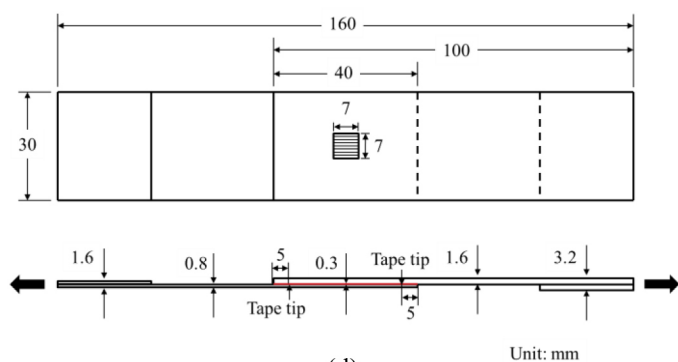


Figure 1. (a) A top view of USW, adhesive-bonded, and weld-bonded lap-shear specimens, from the top to bottom. (b)-(d) Schematics of the top and side views of the USW, adhesive-bonded, and weld-bonded specimens with the loading directions shown by the arrows. The red line represents the adhesive position.



(c)



(d)

Figure 1. (cont.) (a) A top view of USW, adhesive-bonded, and weld-bonded lap-shear specimens, from the top to bottom. (b)-(d) Schematics of the top and side views of the USW, adhesive-bonded, and weld-bonded specimens with the loading directions shown by the arrows. The red line represents the adhesive position.

For the weld-bonded lap-shear specimens, the adhesive was first applied and then the sheets were ultrasonic spot welded. The ultrasonic spot welding procedure is the same as that for the USW lap-shear specimens. Figure 1(a) also shows the indentation of the sonotrode tip on the upper magnesium of the weld-bonded specimen. Two tapes were also placed on the magnesium and steel sheets to form two pre-cracks between the sheets and the adhesive, as those for the adhesive-bonded specimen. Each welded specimen is then heated to the curing temperature to further join the rest of the overlap region.

Prior to testing, all three types of lap-shear specimens were sectioned through the center line parallel to the loading direction to observe the cross sections of the bonded regions. The lap-shear specimens were first tested with doublers under quasi-static loading conditions by using a MTS testing machine at a displacement rate of 5 mm per minute. The average failure loads, defined as the average of the maximum loads of the load-displacement curves obtained from three lap-shear specimens, are listed in Table 1. The failure loads were used as the reference loads to determine the applied

loads for the fatigue tests. The lap-shear specimens were then tested with doublers under cyclic loading conditions using an Instron servo-hydraulic fatigue testing machine with the load ratio of 0.1. The test frequency was 10 Hz. The tests were terminated when specimens were separated or transverse cracks from the welds became clearly visible. Figure 2 shows the load range as a function of the fatigue life for the lap-shear specimens under cyclic loading conditions.

Table 1. Failure loads of the lap shear specimens tested under quasi-static loading conditions at a displacement rate of 5 mm/min.

	Failure load (N)
USW	4040 ± 13
Adhesive-bonded	6524 ± 65
Weld-bonded	6403 ± 61

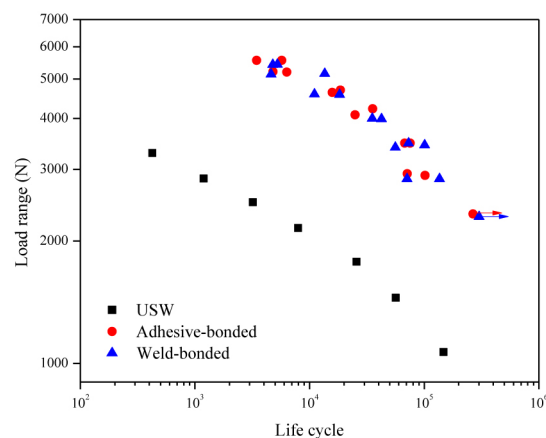


Figure 2. Experimental results of the fatigue tests for USW, adhesive-bonded, and weld-bonded lap-shear specimens at the load ratio of 0.1.

QUASI-STATIC AND CYCLIC LOADING TEST RESULTS

The results of the quasi-static tests indicate that the failure load per bonded area for USW lap-shear specimens is higher than that for adhesive-bonded lap-shear specimens. However the adhesive-bonded and weld-bonded lap-shear specimens have almost the same failure load. This means the ultrasonic welds do not provide significant extra strength to the weld-bonded joints. This is possibly due to the poor strength of the USW because of the thickness of the adhesive layer was controlled and limited by the zirconia balls at the interface between the magnesium and steel sheets. Under cyclic loading conditions, the adhesive-bonded specimens have better fatigue properties than the USW specimens. However, adhesive-bonded and weld-bonded lap-shear specimens appear to have the same fatigue properties. This further confirms that the ultrasonic spot weld in weld-bonded lap-shear specimen does not contribute to the bond strength.