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Monotonic and Fatigue Behavior of Mg Alloy Friction Stir Spot Welds: An International Benchmark Test in the "Magnesium Front End Research and Development" Project

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Abstract

This paper presents the experimental results of benchmark coupon testing of monotonic and cyclic conditions on friction stir spot welded coupons of Mg AZ31alloy. The results presented here are a product of a collaborative multinational research effort involving research teams from Canada, China, and the United States. Fatigue tests were conducted in load control at R=0.1 at two different maximum loads: 1kN and 3kN. Good agreement was found between the participating labs regarding the number of cycles to failure. Differences in the failure modes were observed for the two different loading conditions tested. At the higher load, fatigue failure was caused by interfacial fracture. However, at the lower load, fatigue cracks formed perpendicular to the loading direction, which led to full width separation. For additional comparison, the monotonic and cyclic results of the friction stir spot welds are compared to resistance spot welded coupons of similar nugget size.

Introduction

The continued push for more fuel efficient automobiles designs is motivation for ongoing research in lightweight metals. Through lightweight designs comes the need to explore alternatives to traditional metals like aluminum and steel currently used in the manufacturing of automobiles. As such, a collaborative multinational research effort involving researchers from Canada, China, and the United States and joined by Chrysler, Ford, and General Motors, is underway with the goal of developing the ability to build a front end of an automobile constructed of magnesium alloys. Magnesium alloys, with a density of 1.74g/cm^3, weigh less than a quarter of steel and two-third of aluminum, and with abundant reserves on the earth, are attractive substitutes for steel and aluminum for vehicle body structures [1–4]. Replacing the largely steel structure of a vehicle's front end with magnesium can also move the vehicle center of gravity away from the front, improving vehicle drivability.

This research project, called the Magnesium Front End Research and Development program, or MFERD, has already yielded several fatigue characterizations of wrought magnesium alloys [cf. 5-7]. In order to fully meet the project's objectives, characterization of mechanical properties of potential joining techniques is also needed. As such, friction stir spot welding is targeted as a possible joining technique in the fabrication of a front end of an automobile using magnesium alloys.

Friction stir welding has steadily been gaining more wide spread use when high integrity and strength are required. Friction stir spot weld is a recent variant of friction stir welding and is an attractive welding technique due to the solid state nature of the process and the lack of stress relieving that is typically needed. A recent literature review of the friction stir spot friction process can be found in [8]. The solid state nature and the ability of joining dissimilar metals have made friction stir spot welding an attractive welding process.

The fatigue behavior of a friction stir spot weld (FSSW) is highly dependent on process parameters employed to create the weld [9,10]. These parameters include speed, depth of plunge, dwell time, and tool configuration. Up to this point, a majority of studies of the nature of fatigue of FSSW's have been almost exclusively focused on aluminum alloys [9-12]. With regards to FSSW's made of aluminum alloys, the failure modes of quasi-static and cyclic loads of FSSW coupons vary based on the load level [9]. Differences have been observed in the fracture path for quasi-static loads compared to fatigue loads for aluminum alloys [9]. In this study[9-10], FSSW coupons failed by interfacial fracture under quasi-static loading, whereas, under cyclic loading, fatigue cracks initiated and grew from several locations including the interfacial tip and outside the weld zone. In addition, fatigue failure modes of aluminum FSSW made using various tooling were also observed to differ based on the shape of the tooling used to make the weld [10]. Also, fatigue of FSSW's of dissimilar aluminum alloys were observed to have different failure modes compared to FSSW's with identical alloys for the top and bottom sheets [11]. The fatigue failure modes of dissimilar metals (aluminum and steel) were also observed to vary compared with joints made of all aluminum alloys [12]. While the FSSW joining technique of magnesium alloys is documented [13-16], limited published literature exists on the fatigue properties of FSSW coupons of magnesium alloys. Mallick and Agarwal [17] were the first to quantify the fatigue behavior of FSSW's made of a magnesium alloy. However, their characterization of the failure mechanisms under cyclic loading was limited in its presentation.

Resistance Spot Weld (RSW), on the other hand, is currently the most common joining process in the automotive industry and hence is the manufacturers' preferred joining technique. Thus, as have been performed for steel [18-22] and aluminum alloys [23-27], characterization of FSSW and RSW techniques and comparing their monotonic and cyclic behavior, provide the motivation for these types of studies. As such, the purpose of this research is the characterization of FSSW'ed sheets of AZ31B magnesium alloy through a round-robin experimental program and also evaluating its mechanical behavior by a comparative analysis to RSW of the same alloy.

Materials

Magnesium AZ31B alloy sheets of 2.0mm thickness are chosen for the present study. Coupons were welded in lap configuration. The individual sheet dimensions were: length 100mm, width 38mm and were welded on an overlap area of 38 × 38 mm. The FSSW tool was made from standard tool steel (H13) material, having a shoulder with diameter 12 mm, pin length of 3.2 mm and left hand threads (M5). The shoulder was a concave profile with the angle of concavity of 10 deg. The welding process parameters were: tool rotation speed 750 RPM, tool plunge speed of 20mm/min, shoulder plunge depth of 0.1mm and a dwell time of 2.5 sec. In regards to the bonded area in FSSW, the welding process produces an annulus shape, and the average inner and outer diameters in this study were found to be 6.5mm and 9.7mm, respectively. During the welding process, the interface between the upper and lower sheet is formed into a hook like shape due to the penetration of the FSSW tool into the bottom sheet.

For comparison purposes, resistant spot weld (RSW) coupons were made of the same alloy as for the FSSW. The thickness of the sheet as well as the specimen configuration and dimensions were similar to the FSSW. Additionally, the weld nugget was approximately the same. The RSW parameters were: welding current of 34 kA, welding time of 8 cycles (8/60 sec), electrode force of 4 kN, and holding time of 30 cycles (0.5 sec). Figure 1 shows general dimensions for FSSW and RSW coupons employed in this study.

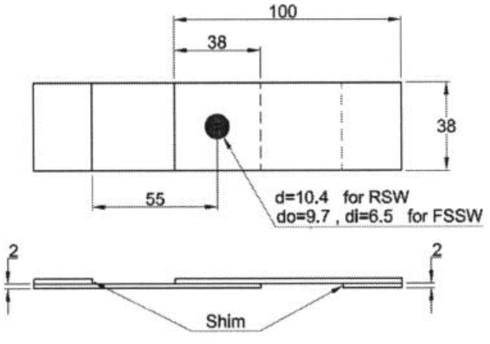

Figure 1. Configuration of friction stir and resistant spot welds single-weld lap-shear coupons. Dimensions are in mm.

Experiments

Mississippi State University (MSU), Ryerson University (RU), University of Waterloo (UW), and the Institute of Metal Research (IMR), all participated in round-robin fatigue testing of lap-shear FSSW coupons. Each institution conducted six (6) load control tests consisting of three (3) specimens conducted at each of the two (2) P_{max} load levels: 3kN and 1kN. The tests were run at $R = \frac{P_{min}}{P_{max}} = 0.1$, and a frequency of 5 Hz. All tests were conducted at ambient temperature and humidity. The test set-up also included certain specifications for mounting including careful attention to grip alignment, grip distance, and use of shims or offsets. The grip-to-grip distance was maintained at 110 mm at each of the labs. In addition, UW also tested RSW coupons under the same conditions as stated for the FSSW coupons.

Results and Discussion

Monotonic Tests

Monotonic tests were performed on a servo-hydraulic load frame under uniaxial displacement rate of 1 mm/min. The test results show that the FSSW coupons exhibited an average ultimate tensile-shear load (UTSL) of 4650±10N. All specimens tested failed in a consistent manner with a partially interfacial failure mode, as shown in Figure 2.

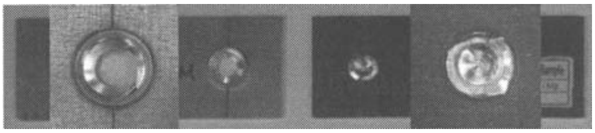

Figure 2. Failure mode in friction stir spot welded coupons under monotonic tensile-shear loading.

Similar to studies on steel FSSW [22] and aluminum FSSW [27], comparing the static and cyclic behavior of emerging FSSW joining technique and commonly used RSW is of interest. Recent research [28] has studied the monotonic and fatigue behavior of RSWs of AZ31B-H24 Mg alloy, and showed that the highest UTSL is achieved using the welding current of 34 kA, and the welding time of 8 cycles. The same welding parameters were utilized in this study, and a solid circular nugget with an average diameter of 10.4 mm was obtained which is close to outer diameter of FSSW (9.7 mm). It should be noted that although FSSW and RSW are of a similar outer diameter, the bonded area are very different (40 mm^2 in FSSW and 85 mm^2 in RSW), due to the different shapes of bonded region. However, comparing the mechanical behavior of these specimens is sound from the application perspective, as the area of coupons contributing in the joints is almost the same in FSSW and RSW specimens. Monotonic testing of tensile-shear RSW specimens yielded an average UTSL of 7620±48N with interfacial failure mode, as shown in Figure 3.

Figure 3. Failure mode in resistant spot welded coupons under monotonic tensile-shear loading.

Load-displacement curves, shown in 4, illustrate that the RSW coupons have higher UTSL compared to FSSW coupons. Higher UTSL of RSW specimens is mainly attributed to the smaller bonded area in FSSW specimens. As mentioned before, RSWs have a solid circular, and FSSWs have an annulus-shaped weld region. Therefore, even for the same outer diameter, a higher UTSL is expected for RSWs.

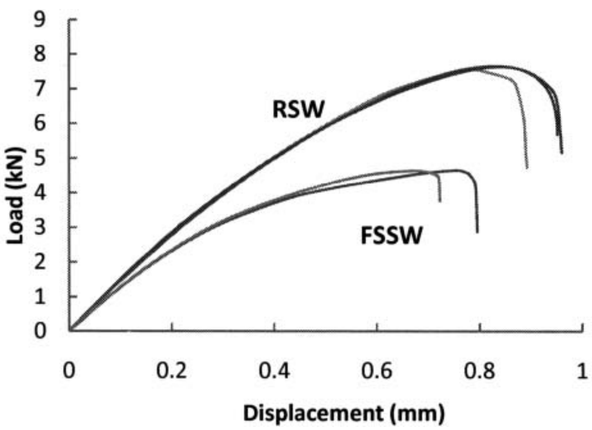

Figure 4. Load-displacement curves for friction stir spot weld and resistance spot weld tensile-shear specimens under quasi-static loading.

Fatigue Tests

Figure 5 displays the round-robin fatigue results of the FSSW from the four institutions. The first observation based on the fatigue life results was the overall good correlation between all of the laboratories. Fatigue failure for this particular study was defined as complete separation of the lap-joint. However, there were some outliers in both sets of load levels tested. One of the tests MSU conducted at the 3kN load level failed much earlier than the rest of the tests compared to the other institutions. At the 1kN level, several specimens tested at IMR failed much later compared to the rest of the group of coupons. However, the variation in the fatigue results overall is fairly consistent compared to other published round-robin fatigue testing programs. It is important to point out that at the higher fatigue load level (3kN), the load is above the elastic limit based on the monotonic load-displacement curve shown in Figure 4. At the 1kN load level, the load is within the elastic range. The number of cycles to failure for the FSSW coupons presented here are in the same order of magnitude of similar FSSW [9-12,17]

For further comparisons, the fatigue life of the FSSW coupons are compared to the fatigue life of the RSW. Fatigue results show that the RSW exhibited better fatigue life at the lower load level (1kN) compared to the FSSW coupons. However at the higher load level (3kN), the FSSW coupons exhibited better fatigue resistance compared to the RSW coupons. For the lower load level (1kN), where we have the same failure modes in FSSW and RSW specimens (coupon width separation, Fig. 7.a), higher fatigue life of RSW could be attributed to larger nugget size which causes lower stress concentration and hence smaller hot spot stress and retardation of crack initiation. However, at the higher load level (3kN), the better fatigue performance of FSSW is due to the different failure modes in FSSW and RSW specimens. FSSW specimens failed in interfacial mode (Fig. 7.b), while coupon failure perpendicular to the loading direction (Fig. 7.a) was observed in RSW specimens. The reason why the fatigue strength in interfacial mode is higher than coupon failure is, in both cases, the mode I stress intensity factor (K_I) is the main factor for fatigue crack propagation. The load component contributing to K_I in interfacial failure mode is normal to the coupon surface at the joint, and the load component contributing to K_I in coupon separation is parallel to the coupon surface or normal to the coupon thickness at the joint. And because the load component parallel to the coupon is larger than the one normal to the coupon surface (as bending rotation in coupon at the joint is less than 45 deg), the coupon separation mode is more critical than interfacial failure. However, this still needs more investigations.

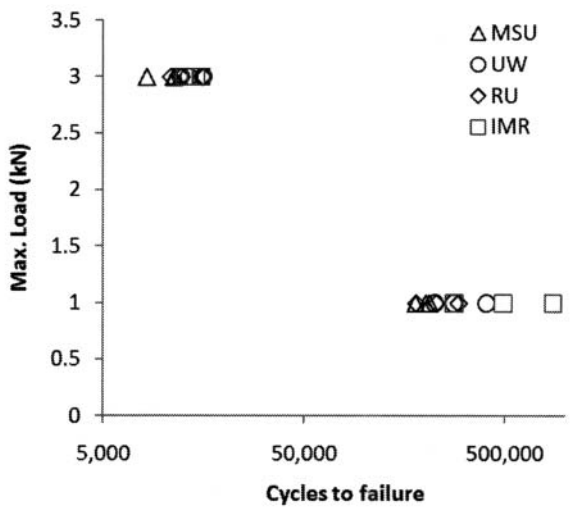

Figure 5. Comparison of Mg AZ31 friction stir spot welds fatigue results from the four universities: Mississippi State University (MSU), Ryerson University (RU), University of Waterloo (UW), and Institute for Metal Research (IMR). Fatigue tests were conducted in load control at R=0.1, at a frequency of 5 Hz and at room temperature.

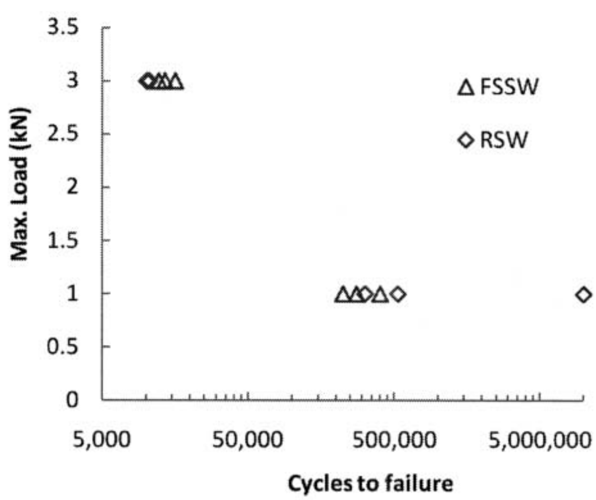

Figure 6. Comparison of fatigue results of the magnesium AZ31 alloy friction stir spot welds to the resistance spot welds tested at University of Waterloo (UW). Fatigue tests were conducted in load control at R=0.1, at a frequency of 5 Hz and at room temperature.

Fractography

The failure modes under cyclic loading were observed to vary for the different load levels tested in the round-robin testing program. All four laboratories reported that the failure mode at the lower cyclic load level of 1 kN was different compared to the higher cyclic load level of 3 kN. That is, the failure at the lower load level occurred perpendicular to the loading direction, while the failure at the higher load level exhibited interfacial fracture, as shown in Figure 7(a) and (b), respectively. The interfacial failure observed for the 3 kN load level likely occurred because as the crack propagated circumferentially around the nugget, the shear/tensile stress in the remaining net area of the nugget increased with each advancement of the crack front. Once the crack had propagated around approximately half of the nugget diameter, the shear/tensile stresses acting on the net area were such that the remaining cross section failed under shear/tensile overload. The other type of fatigue failure occurred at the load level of 1kN. Once the crack had propagated circumferentially around the nugget, the crack then propagated outward through the sheet material.

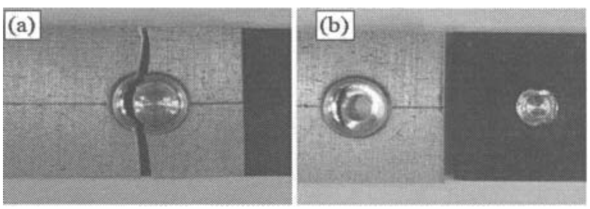

Figure 7. Macroscopic images of friction stir spot weld coupons of magnesium AZ31 alloy samples fatigued at a load level of (a) P_{max}=1 kN, and (b) P_{max}=3 kN (R=0.1, 5 Hz, sine waveform, room temperature).

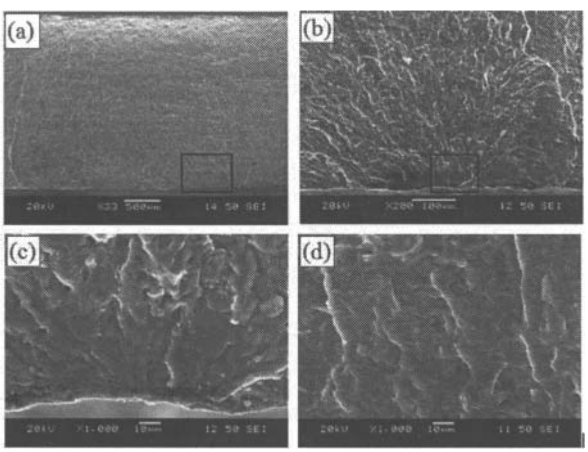

Figure 8. Scanning electron microscope images of fracture surfaces of friction stir spot weld coupons of magnesium AZ31 alloy fatigued at a load level of P_{max}=1 kN, (a) low magnification image near the center of the sample, (b) initiation site in the boxed region in (a), (c) magnified view of the boxed region in (b), and (d) crack propagation area near the center of the sample thickness.

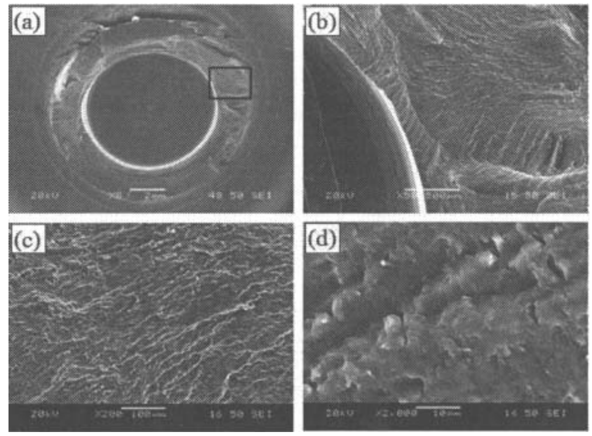

Figure 9. Scanning electron microscope images of fracture surfaces of friction stir spot weld coupons of magnesium AZ31 alloy fatigued at a load level of P_{max}=3 kN, (a) overall view of interfacial fracture of the sample, (b) initiation site in the boxed region in (a), (c) magnified view near the initiation site, and (d) crack propagation area at a higher magnification.

Fracture surfaces of the fatigued specimens were examined under scanning electron microscope (SEM). Figure 8(a-d) and Figure 9(a-d) show the typical SEM images of the coupons tested at P_{max}=1 kN and P_{max}=3 kN, respectively. The low magnification image shown in Figure 8(a) was taken near the center of the sample fractured at P_{max}=1 kN, while 9(a) showed an overall view of interfacial fracture of the sample tested at P_{max}=3 kN. Figure 8(b) and Figure 9(b) showed the boxed region in Figure 8(a) and 9(a), respectively, indicating the crack initiation site. While the failure mode was different (see Figure 7), the fatigue crack initiation at both load levels occurred from the surface. Figure 8(c) and 9(c) showed the higher magnification images near the fatigue crack initiation sites for both load levels. Figure 9(d) shows the fatigue crack propagation area with some striation-like features perpendicular to the crack propagation direction.

Conclusions

A summary of the main conclusions of this work are as follows:

1. The resistant spot weld lap-shear coupons exhibited better monotonic strength compared to the friction stir spot weld coupons with similar specimen dimensions and outer nugget diameter.
2. Friction stir spot weld and resistant spot weld coupons both failed in the interfacial mode under monotonic loading.
3. The fatigue results from the four different testing labs demonstrated consistent fatigue results on the friction stir spot weld lap-shear coupons.
4. Different failure modes were observed for the friction stir spot weld coupons for the two cyclic load levels tested. At the high cyclic load level (3kN), the coupons failed by interfacial fracture. At the lower cyclic load level (1kN), the coupons failed by full width separation.
5. Striations-like features were observed on fracture surfaces of specimens tested at 3kN.

6. The fatigue life the friction stir spot weld coupons were observed to compare closely to the fatigue life of the resistant spot weld coupons. At the higher cyclic load (3kN), the friction stir spot weld coupons exhibited better fatigue life, compared to the resistant spot weld coupons. However, at the lower cyclic load (1kN), the resistant spot weld coupons exhibited better fatigue resistance compared the friction stir spot weld coupons.

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