

Fatigue Behavior of Spot Friction Welds in Cross-Tension Specimens of Aluminum 6061-T6 Sheets

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ABSTRACT

Failure modes of spot friction welds in cross-tension specimens of aluminum 6061-T6 sheets are first investigated based on experimental observations. Optical and scanning electron micrographs of the welds before and after failure under quasi-static and cyclic loading conditions are examined. Experimental results show that the failure modes of the welds under quasi-static and cyclic loading conditions are quite different. Under quasi-static loading conditions, the failure mainly starts from the necking of the upper sheet outside the weld. Under low-cycle loading conditions, the dominant fatigue cracks are the kinked cracks growing into the upper sheet from the crack tips; hence, the upper nugget pullout failure mode can be seen. Under high-cycle loading conditions, the dominant fatigue cracks are kinked cracks growing into the lower sheet from the crack tips; subsequently, the lower nugget pullout failure mode can be seen. A fatigue crack growth model based on the paths of the dominant kinked fatigue cracks is then adopted to estimate the fatigue lives of the spot friction welds. The accurate global and local stress intensity factors for finite kinked cracks based on the three-dimensional finite element computations and the Paris law for fatigue crack propagation are utilized in the fatigue crack growth model. The fatigue life estimations based on the fatigue crack growth model correlate well with the experimental results.

INTRODUCTION

Resistance spot welding is widely used for joining body-in-white parts made of steel sheets. However, resistance spot welding of aluminum sheets is likely to produce poor welds due to numerous voids and defects inside the nugget. A new spot friction welding (SFW) process for joining aluminum sheets has recently been developed by Mazda Motor

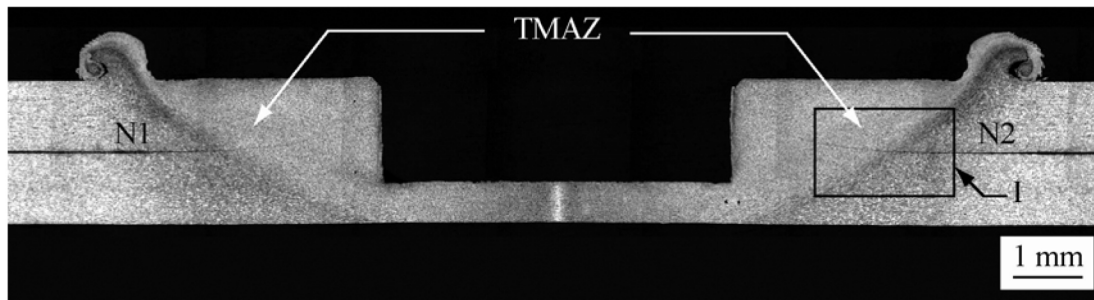
Corporation and Kawasaki Heavy Industry [1,2]. Importantly, in contrast with conventional welding processes, the spot friction welding process makes joints without melting the base metal. A comprehensive literature review for spot friction welding process can be found in Pan [3].

Mechanical behaviors of spot friction welds under quasi-static and dynamic loading conditions were studied, for example, Lin et al. [4] and Tran et al. [5]. Fatigue behaviors of spot friction welds between similar and dissimilar sheet materials were investigated by experiments [6,7,8,9,10]. For fatigue life estimations, the kinked crack growth model of Newman and Dowling [11] and Lin et al. [12] was adopted to estimate the fatigue lives of spot friction welds in lap-shear specimens [6,7,8,9,10]. Additionally, Tran et al. [8, 10] developed a structural stress model to estimate the fatigue lives of spot friction welds. Notably, lap-shear and cross-tension specimens are commonly used to investigate the mechanical properties of spot friction welds under shear and tensile dominant loading conditions, respectively. However, most of the literature is only available for the fatigue behaviors of spot friction welds in lap-shear specimens. The fatigue behaviors of spot friction welds between similar sheet materials in cross-tension specimens have not been investigated. Therefore, spot friction welds in cross-tension specimens of aluminum 6061-T6 sheets were tested under quasi-static and cyclic loading conditions in this work.

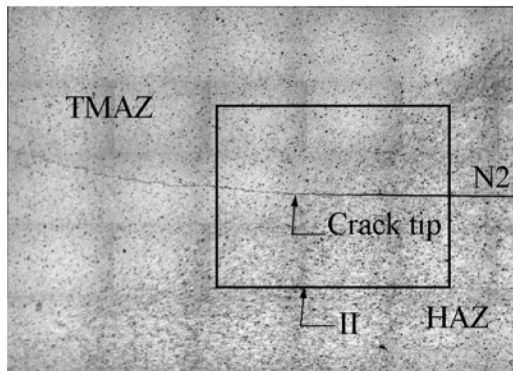
This work presents failure modes of spot friction welds in cross-tension specimens of aluminum 6061-T6 sheets investigated by experimental observations. Optical and scanning electron micrographs of welds before and after failure under quasi-static and cyclic loading conditions are first examined. Failure behaviors of spot friction welds under quasi-static, low-cycle and high-cycle loading conditions are then investigated. The dominant fatigue cracks under

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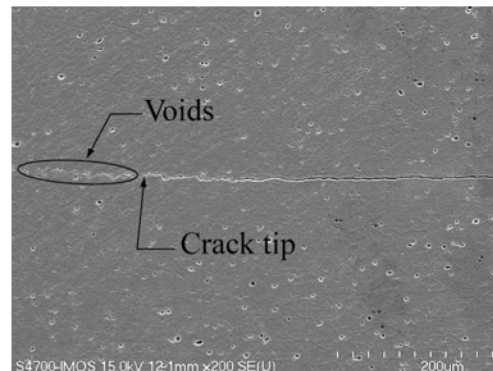
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(a)



(b)



(c)

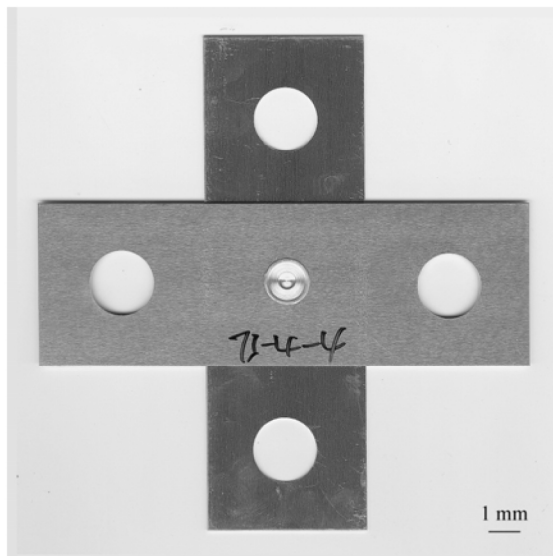
Figure 1. (a) An optical micrograph of the cross section along the symmetry plane of a spot friction weld, (b) a close-up optical micrograph of region I, (c) a close-up scanning electron micrograph of region II.

different loading conditions are identified. Based on the paths of the dominant kinked fatigue cracks, a fatigue crack growth model of Newman and Dowling [11] and Lin et al. [12] is adopted to estimate the fatigue lives of the spot friction welds. The global and local stress intensity factor solutions for finite kinked cracks determined based on three-dimensional finite element computations and the Paris law for fatigue crack propagation are used in the fatigue crack growth model. Finally, the life estimations based on the fatigue crack growth model with the experimentally determined kink angles are compared with the experimental results.

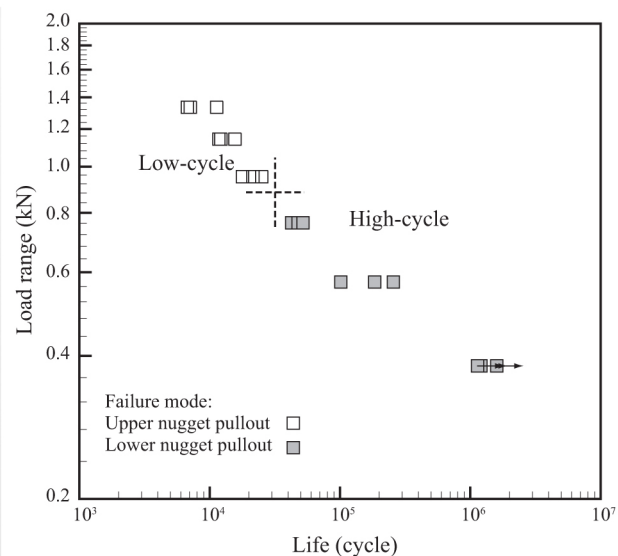
SPOT FRICTION WELDS OF ALUMINUM 6061-T6 SHEETS

Aluminum 6061-T6 sheets with a thickness of 1 mm were used for spot friction welding. A tool with a flat shoulder and a M5 threaded probe pin was used. The diameter of the tool shoulder is 12 mm. The diameter and length of the probe pin are 5 mm and 1.5 mm, respectively. A tool rotational speed of 800 rpm, a tool indentation depth of 1.5 mm, a tool dwelling time of 1 sec., and a tool indentation rate of 12 mm/min were applied for spot friction welding. Notably, these processing parameters were determined by the design of experiments (DOE) for the maximum failure strengths of welds in cross-tension specimens.

Figure 1(a) shows an optical micrograph of the cross section along the symmetry plane of a spot friction weld before testing. As shown in the figure, the indentation profile reflects the general shape of the tool shoulder and probe pin. The tool shoulder and probe pin squeeze out a portion of the upper sheet material and consequently, the squeezed out material forms a ring on the top surface of the upper sheet along the outer circumference of the shoulder indentation. Near the central hole, the two gray areas near the central hole of welds are denoted as the thermal-mechanical affected zones (TMAZ's) where the materials are severely plastically deformed and recrystallized. Two notches, marked as N1 and N2, can be seen in the figure. Figure 1(b) shows a close-up optical micrograph of region I where the notch N2 extends and becomes a crack. As shown in the figure, the interfacial surface becomes vague and gradually disappears into the thermal-mechanical affected zone. The interfacial surface between two deformed sheet materials slightly rises up outside the stir zone. The location of the crack tip is marked in this figure. Note that the location of the crack tip can be identified by a scanning electron micrograph of region II as shown in Figure 1(c). As shown in Figure 1(c), some part of the crack surface beyond the tip becomes voids which appear to be bonded by the welding process.



(a)



(b)

Figure 2. (a) A cross-tension specimen with a spot friction weld, (b) experimental results of the spot friction welds in cross-tension specimens under cyclic loading conditions.

EXPERIMENTS

Cross-tension specimens were made by using two 50.8 mm by 152.4 mm sheets with a 50.8 mm by 50.8 mm overlap area. Figure 2(a) shows a cross-tension specimen with a spot friction weld. Cross-tension specimens were first tested by using a SHIMADZU AG-I universal testing machine at a monotonic displacement rate of 1.0 mm per minute. Four steel plates with 50.8 mm by 50.8 mm areas were applied for clamping the ends of the upper and lower sheets of cross-tension specimens during testing. The tests were terminated when specimens separated. The average failure load obtained from ten tested specimens is 2.12 kN. The cross-tension specimens were then tested by using a MTS servo-hydraulic fatigue testing machine with the load ratio R of 0.1. The test frequency was 5 Hz. The tests were terminated when specimens separated. Some tests were terminated before the final failures in order to observe the fatigue crack growth behaviors of welds.

Figure 2(b) shows the experimental results for spot friction welds in cross-tension specimens under cyclic loading conditions. Three specimens were tested for each load range. Due to the limited operation time of our testing machine, some tests were terminated manually as their cycles were beyond 1.0×10^6 . These results are marked by small arrows as shown in Figure 2(b). Based on the experimental observation, the failure modes of spot friction welds in cross-tension specimens under cyclic loading conditions are quite complex. Two different failure modes can be found, marked by blank and solid square symbols in Figure 2(b). In the following section, the details of the failure modes of spot friction welds

in cross-tension specimens under different loading conditions will be presented and discussed.

FAILURE MODES UNDER QUASI-STATIC AND CYCLIC LOADING CONDITIONS

A TWO-DIMENSIONAL GENERAL OVERVIEW OF FAILURE MODES

The experiments were conducted under quasi-static and cyclic loading conditions. According to the experimental results, the failed spot friction welds under quasi-static loading conditions show one failure mode. The failed spot friction welds under cyclic loading conditions with fatigue life below 2×10^4 cycles show a similar failure mode. The failed spot friction welds under cyclic loading conditions with fatigue life from 2×10^4 to 10^6 cycles show a different failure mode. Since the failure modes of spot friction welds in cross-tension specimens are quite complex, a two-dimensional general overview of the failure modes under quasi-static, low-cycle fatigue (lives of 10^3 to 2×10^4) and high-cycle fatigue (lives of 2×10^4 to 10^6) loading conditions is first presented.

Figure 3(a) shows a schematic of the top view of a cross-tension specimen under applied loads. The “dot” and “cross” symbols represent the upward and downward directions of the applied loads, respectively. In fact, the ends of the lower sheet are rigidly fixed and only those of the upper sheet are moved cyclically during testing. The gray square areas at the

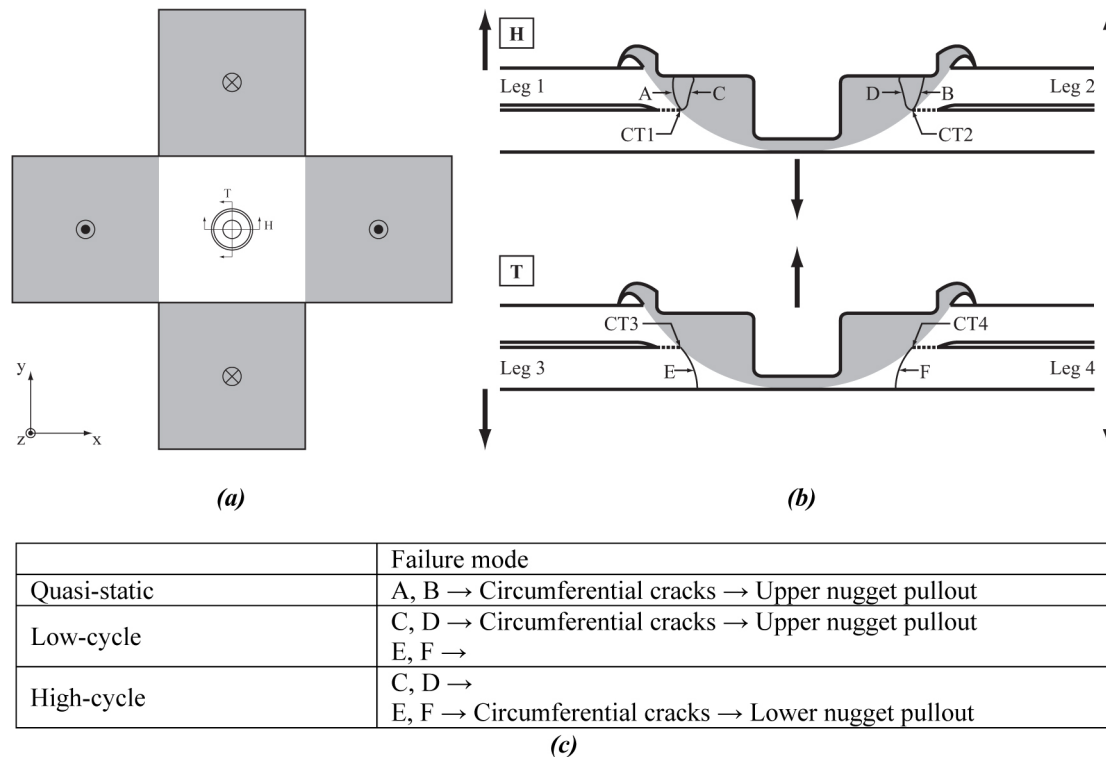


Figure 3. (a) A schematic of the top view of a cross-tension specimen with sheet thickness $t = 1$ mm under a cross-tension load (marked by “dot” and “cross” symbols), (b) schematics of the cross sections along the horizontal (marked by H) and transverse (marked by T) symmetry planes of the spot friction weld under a cross-tension load (marked by bold arrows), respectively, (c) the failure modes of spot friction welds under quasi-static, low-cycle and high-cycle loading conditions.

ends of the upper and lower sheets are fully clamped by fixtures during testing. In order to clearly explain the fatigue behavior of welds, the cross sections along the horizontal (marked by H) and transverse (marked by T) symmetry planes of the weld are presented in [Figure 3\(b\)](#). The arrows in [Figure 3\(b\)](#) represent the applied loads at the ends of the sheets. Due to overlap, the applied loads of the lower sheet are only marked by one upward arrow in the horizontal cross section. Those of the upper sheet are also marked by one downward arrow in the transverse cross section. In [Figure 3\(b\)](#), the gray area represents the thermal-mechanical affected zone, the short dash lines near the two notches represent the unwelded interfacial surface, and the thin solid lines represent either fracture surface or fatigue crack. [Figure 3\(c\)](#) shows a table which summarizes the failure modes of spot friction welds under different loading conditions.

As shown in [Figure 3\(b\)](#) and as summarized in [Figure 3\(c\)](#), two necking/shear failures are initiated at locations A and B under quasi-static loading conditions. Then, the failures propagate along the nugget circumference. Finally, the upper sheet is pulled out. Under low-cycle loading conditions, two fatigue cracks (marked by C and D) appear to emanate from the original crack tips (marked by points CT1 and CT2, respectively) and grow into the upper sheet. Another two fatigue cracks (marked by E and F) appear to emanate from

the original crack tips (marked by points CT3 and CT4, respectively) and grow into the lower sheet. The two fatigue cracks (marked by C and D) appear to be the dominant cracks to propagate through the upper sheet thickness based on the experimental observations. Then, the failures propagate along the nugget circumference. Finally, the upper sheet is pulled out.

Under high-cycle loading conditions, the fatigue crack growth behaviors at the initial stage are similar to those under low-cycle loading conditions. Four fatigue cracks (marked by C, D, E and F) appear to emanate from their original crack tips (marked by points CT1, CT2, CT3 and CT4), respectively. However, the two fatigue cracks (marked by E and F) appear to be the dominant cracks to propagate through the lower sheet thickness based on the experimental observations. Then, the failures propagate along the nugget circumference. Finally, the lower sheet is pulled out. In the following, the details of the failure modes of spot friction welds in cross-tension specimens under different loading conditions will be presented by pictures and micrographs.