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Fatigue behavior of dissimilar spot friction welds in lap-shear and cross-tension specimens of aluminum and steel sheets

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ABSTRACT

Fatigue behavior of dissimilar friction stir spot welds or spot friction welds in lap-shear and cross-tension specimens of aluminum 6000 series alloy and coated steel sheets is investigated based on experiments and three-dimensional finite element analyses. The Al/Fe spot friction welds in both types of specimens were tested under quasi-static and cyclic loading conditions. Optical micrographs of the welds after failure under quasi-static and cyclic loading conditions show that the Al/Fe welds in both types of specimens mainly fail along the interfacial surface between the aluminum and steel sheets. Three-dimensional finite element analyses based on the micrograph of the weld before testing were conducted to obtain stress intensity factor and J integral solutions for the crack fronts along the nugget circumferences of the welds in both types of specimens. The computational results suggest that the J integral and in-plane effective stress intensity factor solutions at the critical locations of the welds obtained from three-dimensional finite element analyses may be used as fracture mechanics parameters to correlate the experimental fatigue data for the Al/Fe spot friction welds in both types of specimens. Finally, the computational results are used to explain the experimental observations of the fatigue crack growth patterns of the welds.

1. Introduction

Aluminum alloys are widely used in the automotive industry. Recently, a friction stir spot welding or spot friction welding technology to join aluminum sheets was developed by Mazda Motor Corporation and Kawasaki Heavy Industry [1,2]. A comprehensive literature review of spot friction welding process can be found in Pan [3]. Spot friction welds between dissimilar aluminum sheets [4–7], between similar magnesium sheets [8–11] and between dissimilar magnesium and aluminum sheets [11] were investigated. Fatigue behavior of spot friction welds between similar and dissimilar sheet materials was investigated by experiments [12–20]. For fatigue life estimations, Lin et al. [15,16], Tran et al. [17,19] and Wang and Chen [18] adopted a kinked fatigue crack growth model of Newman and Dowling [21] and Lin et al. [22] to predict the fatigue lives of aluminum spot friction welds. Also, Tran et al. [17,19] developed a structural stress model and a through-nugget fatigue crack growth model to predict the fatigue lives of aluminum spot friction welds.

Material substitution from steels to aluminum alloys is one of the approaches to reduce vehicle weight. Recently, vehicles made of hybrid body structures which combine steel and aluminum parts have been produced in the automotive companies [23,24]. Therefore, an efficient joining method is needed to join different components made of aluminum and steel sheets. Recently, Mazda Motor Corporation [25] has modified the conventional spot friction welding technology to join aluminum to steel sheets. A schematic illustration of the spot friction welding process used to join an aluminum sheet to a coated steel sheet is shown in Fig. 1. As shown in the figure, a rotating tool with a probe pin is first plunged into the upper aluminum sheet until a pre-set plunge depth smaller than the thickness of the upper sheet is achieved. An anvil beneath the lower steel sheet is used to support the tool downward force induced by the tool penetration. The tool rotational speed is then maintained at the pre-set plunge depth for an appropriate time to generate frictional heat. Then, heated and softened material adjacent to the tool deforms plastically, and the interfacial oxide films on the surfaces of the aluminum and coated steel sheets are destroyed. The coating layer of the steel sheet is also removed at the same time due to the plastic flow of the aluminum sheet. As a result, the fresh surfaces of aluminum and steel sheets come in contact directly and a solid-state bond is made between the surfaces of the aluminum and steel sheets. Finally, the tool is drawn out of the upper aluminum sheet.

It should be noted that the microstructures and failure modes of dissimilar spot friction welds between aluminum and steel sheets under quasi-static loading conditions were studied by researchers

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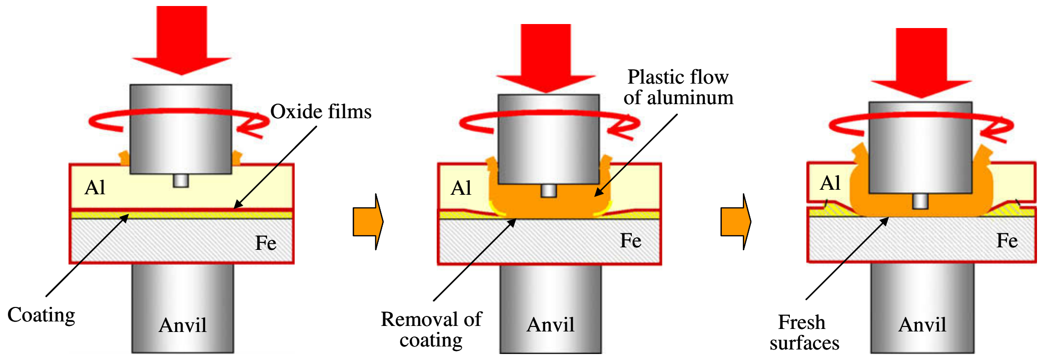


Fig. 1. A schematic illustration of the spot friction welding process used to join an aluminum sheet to a coated steel sheet.

based on experimental observations [26–28]. However, the fracture and failure mechanisms of dissimilar spot friction welds between aluminum and coated steel sheets under cyclic loading conditions have not been investigated. Note also that lap-shear and cross-tension specimens are commonly used to investigate the mechanical behavior of spot welds under shear and tensile dominant loading conditions, respectively. However, most of the literature for spot friction welds is for lap-shear specimens. Therefore, dissimilar spot friction welds in lap-shear and cross-tension specimens of aluminum and coated steel sheets were tested under quasi-static and cyclic loading conditions in this investigation.

In this paper, fatigue behavior of dissimilar spot friction welds in lap-shear and cross-tension specimens of aluminum and coated steel sheets is investigated based on experimental observations and three-dimensional finite element analyses. As schematically shown in Fig. 1, during the spot friction welding process, the tool contacts the upper aluminum sheet and penetrates the upper sheet to weld together the upper and lower sheets. In this paper, the notations of Gendo et al. [28] are followed to use Al and Fe to represent the aluminum and steel sheets, respectively. The dissimilar spot friction weld between aluminum and coated steel sheets is denoted as the Al/Fe weld. The Al/Fe welds in lap-shear and cross-tension specimens were tested under quasi-static and cyclic loading conditions. Optical micrographs of the welds after failure were examined to understand the fracture and failure mechanisms. Three-dimensional finite element analyses based on the micrograph of the weld before testing were conducted to obtain accurate stress intensity factor and *J* integral solutions for crack fronts along the nugget circumferences of the welds in lap-shear and cross-tension specimens. The *J* integral and in-plane effective stress intensity factor solutions at the critical locations of the welds obtained from three-dimensional finite element analyses are used to correlate the experimental fatigue data for the Al/Fe spot friction welds in both types of specimens. Finally, the computational results obtained from the finite element analyses are used to explain the experimental observations of the fatigue crack growth patterns of the welds.

2. Micrograph of Al/Fe spot friction weld

Aluminum 6000 series alloy and coated steel sheets with the thicknesses of 1.3 and 0.8 mm, respectively, are used in this investigation. The coated steel sheets were made by coating mild steel sheets with Zn-11%Al-3%Mg with a mass of 90 g/m^2 [28]. The Al/Fe spot friction welds were made by using a spot friction welding gun at Mazda Motor Corporation, Japan. For the spot friction welding process under displacement-controlled conditions, the important processing parameters are the tool geometry, tool rotational speed, tool plunge depth and processing time. In this investigation, a tool with a concave shoulder and a smooth probe pin was used to make the Al/Fe welds. The diameters of the tool shoulder and the tool probe pin are 10 and 2 mm, respectively. A tool rotational speed of 1500 rpm and a tool holding time of 5 s were specified. The optimal plunge depth of 0.85 mm for the maximum failure load of the Al/Fe welds in lap-shear specimens under this particular set of the processing parameters was identified by experiments. This optimal plunge depth and the processing parameters specified above were then used to make the Al/Fe spot friction welds in lap-shear and cross-tension specimens tested in this investigation.

Fig. 2 shows an optical micrograph of the cross section along the symmetry plane of an Al/Fe spot friction weld before testing. As shown in the figure, the indentation profile reflects the general shape of the smooth probe pin and the concave shoulder of the tool. Note that the tool plunged into the upper sheet material only and the lower sheet material was not deformed significantly under the tool. However, the bottom surface of the lower sheet appears to be slightly bent. Two notches, marked as N1 and N2, can be seen in the figure. The locations of the crack tips are also marked in the figure. Note that there is a flash on the top surface of the upper sheet near the tool shoulder indentation and there is a rise of the upper sheet material near the central hole due to the concave geometry of the tool shoulder. Note also that the microstructure of the interface layer between the aluminum and steel sheets in the Al/Fe spot friction weld was examined in Gendo et al. [28].

As shown in Fig. 2, the thickness of the weld nugget near the central hole is larger than that near the outer circumference of the tool shoulder indentation due to the concave geometry of the tool shoulder. The concave tool shoulder squeezed out some upper sheet material but maintained some upper sheet material near the central hole. It should be noted that there are sharp changes of the upper sheet thickness near the locations of the two crack tips. As suggested in Fig. 2, the material under the tool shoulder indentation flowed outward and resulted in a radial expansion of the upper sheet material along the outer circumference of the tool shoulder indentation. However, due to the constraint of the neighboring material, the sheet was therefore bent along the outer circumference of the tool shoulder indentation. The bends are marked as B1 and B2 as shown in Fig. 2. Note that a small gap between the upper and lower sheets is observed for the Al/Fe weld shown in Fig. 2.

3. Specimens and experiments

Fig. 3a shows a lap-shear specimen with an Al/Fe spot friction weld. The lap-shear specimen was made by using a 30 mm × 100 mm aluminum sheet and a 30 mm × 100 mm coated steel sheet with a 30 mm × 30 mm overlap area. Note that one doubler made of the upper sheet and another doubler made of the lower

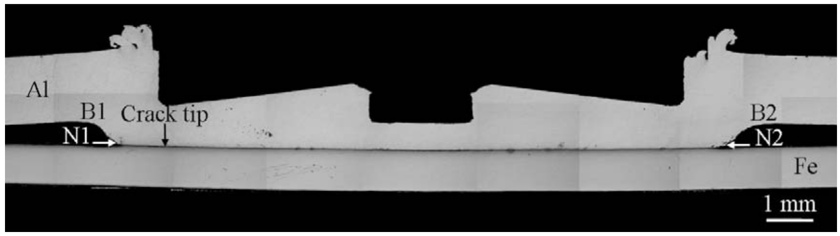


Fig. 2. An optical micrograph of the cross section along the symmetry plane of an Al/Fe spot friction weld before testing.

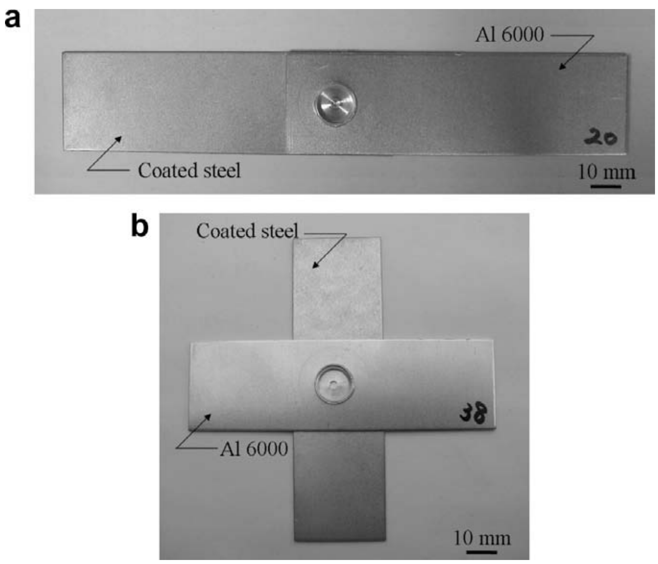


Fig. 3. (a) A lap-shear specimen with an Al/Fe spot friction weld, (b) a cross-tension specimen with an Al/Fe spot friction weld.

sheet with a dimension of 30 mm × 30 mm were attached to the ends of the upper and lower sheets, respectively, of the lap-shear specimen during testing to align the applied load to minimize the initial realignment of the specimen during testing. Fig. 3b shows a cross-tension specimen with an Al/Fe spot friction weld. The cross-tension specimen was made by using a 30 mm × 100 mm aluminum sheet and a 30 mm × 100 mm coated steel sheet with a 30 mm × 30 mm overlap area. Note that four steel pieces with a cross-sectional area of 33 mm × 30 mm were used to clamp the upper and lower sheets, except the overlap area, to the cross-tension testing fixture. Therefore, the tolerance width between the overlap area and the clamped area is 2 mm. Due to the finite compliance of the welding machine and welding fixture, the actual plunge depths of the tool penetration and weld geometries were not precisely the same under the same processing parameters. In order to minimize the effects of the weld geometry on the experimental results, we selected the lap-shear and cross-tension specimens with the Al/Fe spot friction welds that have nearly the same actual plunge depths of the tool penetration for quasi-static and fatigue tests.

Lap-shear and cross-tension specimens with Al/Fe spot friction welds were tested first under quasi-static loading conditions and then under cyclic loading conditions. The descriptions of the experimental procedures can be found in Tran et al. [17,19] and are not reported here. Fig. 4a shows typical load–displacement curves for the Al/Fe spot friction welds in lap-shear and cross-tension specimens under quasi-static loading conditions. The average failure loads, defined as the maximum load of the load–displacement curve, obtained from five tested lap-shear specimens and five tested cross-tension specimens are 3.1 and 0.44 kN, respectively.

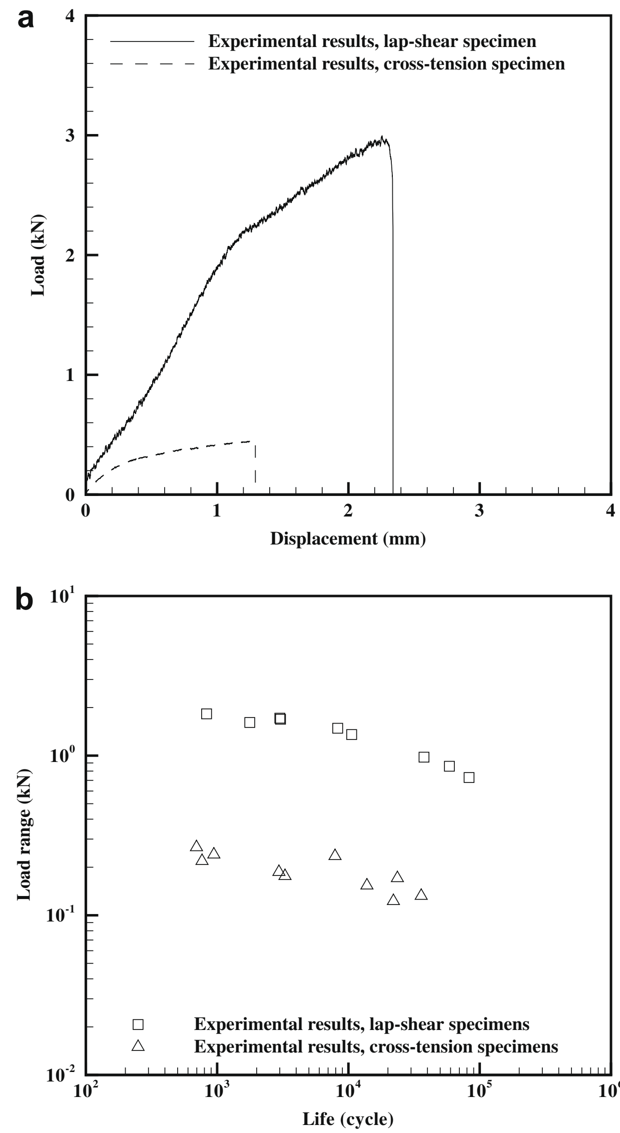


Fig. 4. (a) Typical load–displacement curves for the Al/Fe welds in lap-shear and cross-tension specimens under quasi-static loading conditions, (b) the load range as a function of the fatigue life for the Al/Fe welds in lap-shear and cross-tension specimens under cyclic loading conditions.

Fig. 4b shows the load range as a function of the fatigue life for the Al/Fe spot friction welds in lap-shear and cross-tension specimens under cyclic loading conditions. As shown in Fig. 4b, the number of available specimens for fatigue testing is limited. After visual examinations, at least two failed lap-shear specimens, two partially failed lap-shear specimens, two partially failed cross-tension specimens and two failed cross-tension specimens with the representative failure modes were cross-sectioned to examine the failure modes. In the following, typical micrographs to show the failure modes of the Al/Fe spot friction welds in lap-shear and cross-tension specimens under cyclic loading conditions are presented.

4. Failure modes of Al/Fe spot friction welds under cyclic loading conditions

4.1. Failure modes of Al/Fe welds in lap-shear specimens

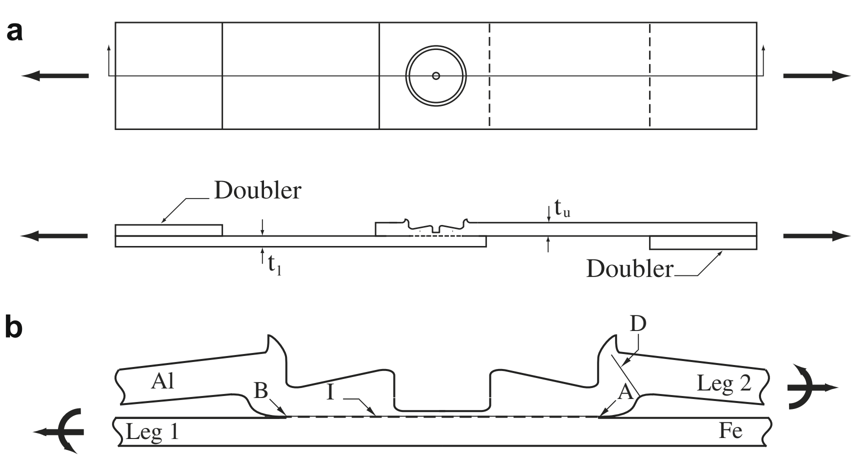
Based on the experimental observations, the failed Al/Fe welds in lap-shear specimens under quasi-static loading conditions show the interfacial failure mode. The failed Al/Fe welds in lap-shear specimens under cyclic loading conditions also show the interfacial failure mode but with a fatigue crack growth near the bend. Fig. 5a shows schematic plots of a spot friction weld in a lap-shear specimen under applied resultant loads (shown as the bold arrows). Fig. 5b shows a schematic plot of the cross section along the symmetry plane of an Al/Fe spot friction weld in a lap-shear specimen. In this figure (and in Fig. 7b as shown later), the thick dashed line represents the interfacial surface between the aluminum and steel sheets and the thin solid lines represent either the fracture surfaces or cracks. It should be noted that the interfacial surface was well bonded as discussed in Gendo et al. [28]. Fig. 5c summarizes the failure modes of the Al/Fe spot friction welds in lap-shear specimens under quasi-static and cyclic loading conditions.

As shown in Fig. 5b and as summarized in Fig. 5c, under quasi-static loading conditions, cracks A and B emanate from the original crack tips of the weld and propagate a bit along the interfacial surface. Crack B then becomes crack I that continues to grow along the interfacial surface. When the load continues to increase, the upper and lower sheets are eventually separated by a fracture surface along the interfacial surface. Under cyclic loading conditions, cracks A and B emanate from the original crack tips of the weld and propagate a bit along the interfacial surface. Crack B then becomes crack I that continues to grow along the interfacial surface. Another fatigue crack, marked as D, emanates from the bend surface outside the nugget on the right portion of the upper aluminum sheet and propagates into the upper sheet thickness. Finally, the upper and lower sheets are eventually separated by a fracture surface along the interfacial surface. Since we focus on the fatigue behavior of the Al/Fe spot friction weld, only the micrographs to show the failure mode of the welds under cyclic loading conditions are reported here.

Fig. 6a shows an optical micrograph of the cross section along the symmetry plane of a *partially failed* Al/Fe spot friction weld in a lap-shear specimen at the fatigue life of 6.5×10^3 cycles under a load range of 2.08 kN. Note that interrupted tests were conducted to examine the fatigue crack growth patterns in *partially failed* welds in this investigation. Each interrupted test was stopped at about 75% of the fatigue life of the corresponding failed weld under the given load range. The bold arrows in the figure schematically show the direction of the applied load. Due to the large deformation in the final stage of the specimen failure, the weld nugget rotated clockwise slightly. Therefore, the sheets near the nugget are slightly bent. The applied loads stretch the upper right aluminum sheet and the lower left steel sheet as shown. The location of the crack tip due to the propagation of crack I2b along the interfacial surface at the fatigue life of 6.5×10^3 cycles is also marked in Fig. 6a.

As shown in Fig. 6a, two fatigue cracks, marked as I2a and I2b, emanate from the original crack tips of the weld and propagate a bit along the interfacial surface. Note that the locations of the crack tips are approximately determined from the optical micrographs of the welds due to small crack opening angles. Crack I2b then continues to grow along the interfacial surface. Another fatigue crack, marked as crack U2, emanates from the bend surface outside the nugget on the right portion of the upper aluminum sheet. As shown in Fig. 6a, fatigue crack U2 propagates partially into the upper sheet thickness at the fatigue life of 6.5×10^3 cycles. Near the final stage of the specimen failure, after fatigue crack U2 propagates almost through the upper sheet thickness, without enough support of the upper sheet near the stretching side of the nugget, the nugget is rotated clockwise and the sheets near the nugget are therefore bent. The upper and lower sheets are eventually separated through a fracture surface along the interfacial surface. Based on the micrograph shown in Fig. 6a, fatigue crack I2b appears to be the dominant fatigue crack that causes the final failure of the lap-shear specimen.

Fig. 6b shows a close-up top view of the spot friction weld on the lower sheet and a close-up bottom view of the spot friction weld on the upper sheet of a failed lap-shear specimen under cyclic



c

	Failure mode
Quasi-static	A, B → I → Interfacial crack
Cyclic	A, B, D → I → Interfacial crack

Fig. 5. (a) Schematic plots of a spot friction weld in a lap-shear specimen under applied resultant loads, (b) a schematic plot of the cross section along the symmetry plane of an Al/Fe weld in a lap-shear specimen, (c) failure modes of the Al/Fe welds in lap-shear specimens under quasi-static and cyclic loading conditions.