

Fatigue Behavior of Dissimilar Spot Friction Welds between Aluminum and Coated Steel Sheets in Lap-Shear and Cross-Tension Specimens

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ABSTRACT

Fatigue behavior of dissimilar Al/Fe spot friction welds between aluminum 6000 series alloy and coated steel sheets in lap-shear and cross-tension specimens is investigated based on experiments and three-dimensional finite element analyses. Micrographs of the welds after failure under quasi-static and cyclic loading conditions show that the Al/Fe welds in lap-shear and cross-tension specimens failed along the interfacial surface. Three-dimensional finite element analyses based on the micrographs of the welds before testing were conducted to obtain the J-integral solutions at the critical locations of the welds under lap-shear and cross-tension loading conditions. The numerical results suggest that the J-integral solutions at the critical locations of the welds can be used as a fracture mechanics parameter to correlate the experimental fatigue data of the Al/Fe spot friction welds in lap-shear and cross-tension specimens.

INTRODUCTION

Aluminum alloys are becoming to be widely used in the automotive industry. 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 [1,2]. Therefore, an efficient joining method is needed to join different components made of aluminum and steel sheets.

Recently, Mazda Motor Corporation [3] 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.

Note that the microstructures and failure modes of dissimilar spot friction welds between aluminum and coated steel sheets under lap-shear loading conditions have been studied based on experimental observations, for example, see Gendo et al. [4] and Tanaka et al. [5,6]. However, the fatigue behavior of dissimilar spot friction welds between aluminum and coated steel sheets under cyclic loading conditions has not been investigated.

In this paper, we investigate the fatigue behavior of dissimilar spot friction welds between aluminum and coated steel sheets in lap-shear and cross-tension specimens 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. The dissimilar spot friction weld between aluminum and coated steel sheets is therefore denoted as the Al/Fe weld in this paper. The Al/Fe welds in lap-shear and cross-tension specimens were tested under quasi-static and cyclic loading conditions. Micrographs of the welds after failure were examined to understand the fracture and failure mechanisms of the welds. Three-dimensional finite element analyses based on the micrographs of the welds before testing were conducted to obtain the J-integral solutions at the critical locations of the welds under lap-shear and cross-tension loading conditions. Finally, the J-integral 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 welds in lap-shear and cross-tension specimens.

MICROGRAPHS OF SPOT FRICTION WELD

The materials used in this investigation are aluminum 6000 series alloy and coated steel sheets with the thicknesses of 1.3 mm and 0.8 mm, respectively. The coating material is Zn-11%Al-3%Mg with a mass of 90 g/m² for one side [4]. Dissimilar Al/Fe spot friction welds were made by using a spot friction welding gun at Mazda Motor Corporation under displacement-controlled conditions. 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 mm and 2 mm, respectively. A tool rotational speed of 1500 rpm and a tool holding time of 5 sec were specified. The optimal plunge depth of 0.85 mm for the maximum failure strength of the Al/Fe welds in lap-shear specimens under this particular set of the welding processing parameters was identified by experiments. This optimal plunge depth and the welding processing parameters specified above were then used to make the Al/Fe 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 probe pin penetrated partially into the upper sheet. 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. Note that the concave tool shoulder squeezed out some upper sheet material but maintained some upper sheet material near the central hole. The tool shoulder indentation 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. The location of the crack tip, identified by the scanning electron micrograph of the crack tip region, is also marked in the figure.

SPECIMENS AND EXPERIMENTS

Lap-shear specimens were 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. Fig. 3(a) shows a lap-shear specimen with an Al/Fe spot friction weld. Note that one doubler made of the upper sheet and another doubler made of the lower sheet with a dimension of 30 mm × 30 mm are attached to the ends of the upper and lower sheets, respectively, of the lap-shear specimen during testing to align the applied load to avoid the initial realignment of the specimen during testing. Note that four steel pieces with a cross-sectional area of 30 mm × 30 mm are used to clamp the upper and lower sheets and the doublers to the lap-shear testing fixture. Therefore, the effective length of the upper and lower sheets is 70 mm. Fig. 3(b) shows a cross-tension specimen with an Al/Fe spot friction weld. Cross-tension specimens were 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 are 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.

The lap-shear and cross-tension specimens were first tested under quasi-static loading conditions by using an Instron testing machine at a monotonic displacement rate of 1.0 mm per minute. The average failure load, 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 kN and 0.4 kN, respectively. The failure loads were used as the reference loads to determine the loads applied for the fatigue tests. The lap-shear and cross-tension specimens were then tested under cyclic loading conditions by using an Instron servo-hydraulic fatigue testing machine with the load ratio R of 0.2. The test frequency was 10 Hz. The tests were terminated when specimens were separated, or nearly separated when the displacement of the two grips of specimens exceeded 10 mm. Fig. 4 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.

Micrographs taken from the lap-shear and cross-tension specimens after failure show that the Al/Fe welds in lap-shear and cross-tension specimens failed along the interfacial surface under quasi-static and cyclic loading conditions. Figs. 5(a) and 5(b) show close-up top views of the failed welds on the lower sheets of a lap-shear specimen and a cross-tension specimen, respectively.

testing, respectively. In these figures, the rough surface in the smaller marked ellipse outside the central smooth circular area represents the interfacial fracture surface.

THREE-DIMENSIONAL FINITE ELEMENT ANALYSES

In the finite element analyses, the weld nugget and base metals are assumed to be linear elastic isotropic materials. The Young's moduli of the aluminum and coated steel sheets are taken as 68.9 GPa and 207 GPa, respectively. The Poisson's ratios for the aluminum and coated steel sheets are taken as 0.33 and 0.30, respectively. The commercial finite element program ABAQUS [7] is employed to perform the computations. Second-order quarter point crack-tip elements with collapsed nodes are used to model the $1/\sqrt{r}$ singularity near the crack tip. Here r represents the radial distance to the crack tip.

A schematic plot of a lap-shear specimen with a spot weld plotted as a circular cylinder with a size of $2a$ is shown in Fig. 6(a). In Fig. 6(a), the shaded parts represent the parts where the specimen is clamped to the testing fixture, and the large bold arrows schematically show the loads applied to the specimen. In the figure, the length L ($= 100$ mm), the effective length L' ($= 70$ mm), the overlap length V ($= 30$ mm), the half width b ($= 15$ mm), and the upper and lower sheet thicknesses t_u ($= 1.3$ mm) and t_l ($= 0.8$ mm) are based on the dimensions of the specimen and testing fixture. Note that $2a$ ($= 10.8$ mm) represents the diameter of the spot weld. The critical locations of the weld are marked as A, B, C and D in the figure.

In the finite element analysis, the shaded parts of the lap-shear specimen in Fig. 6(a) were not modeled. The finite element analysis was based on the equivalent specimen geometry without the clamped parts shown in Fig. 6(b). Fig. 6(b) also shows the equivalent boundary conditions applied to the three-dimensional finite element model for the lap-shear specimen. As shown in Fig. 6(b), a uniform displacement in the $+x$ direction is applied to the right edge surface of the upper sheet, and the displacements in the y and z directions for the right edge surface of the upper sheet are constrained. Also, the displacements in the x , y and z directions for the left edge surface of the lower sheet are fixed.

Due to symmetry, a half of the equivalent lap-shear specimen shown in Fig. 6(b) is modeled. The three-dimensional finite element model and a close-up view of the mesh near the weld for a half of an equivalent lap-shear specimen are shown in Figs. 6(c) and 6(d), respectively. The three-dimensional finite element mesh near the weld shown in Fig. 6(d) is based on the optical micrograph shown in Fig. 2. As shown in Fig. 6(d), the mesh near the crack front along the circumference of the weld is refined to assure reasonable aspect ratios of the

three-dimensional solid elements. The three-dimensional finite element model for the half equivalent lap-shear specimen has 18,077 second-order solid elements. Two original crack tips, marked as A and B in Fig. 6(d), are also shown in the figure. Based on the finite element analysis, the J-integral solution is maximum at the crack tip marked as B in Fig. 6(d).

A schematic plot of a cross-tension specimen with a spot weld plotted as a circular cylinder with a size of $2a$ is shown in Fig. 7(a). In Fig. 7(a), the shaded parts represent the parts where the specimen is clamped to the testing fixture, and the large bold arrows schematically show the loads applied to the specimen. In the figure, the half width b ($= 15$ mm), the tolerance width e ($= 2.0$ mm) between the overlap area and the clamped area, and the upper and lower sheet thicknesses t_u ($= 1.3$ mm) and t_l ($= 0.8$ mm) are based on the dimensions of the specimen and testing fixture. Note that $2a$ ($= 10.8$ mm) represents the diameter of the spot weld. The critical locations of the weld are marked as A, B, C and D in the figure.

In the finite element analysis, the shaded parts of the cross-tension specimen in Fig. 7(a) were not modeled. The finite element analysis was based on the equivalent specimen geometry without the clamped parts shown in Fig. 7(b). Fig. 7(b) also shows the equivalent boundary conditions applied to the three-dimensional finite element model for the cross-tension specimen. As shown in Fig. 7(b), a uniform displacement in the $+z$ direction is applied to the outer edge surfaces of the tolerance areas of the upper sheet and the displacements in the x and y directions for the outer edge surfaces of the tolerance areas of the upper sheet are constrained. Also, the displacements in the x , y and z directions for the outer edge surfaces of the tolerance areas of the lower sheet are fixed.

Due to symmetry, a quarter of the equivalent cross-tension specimen shown in Fig. 7(b) is modeled. The three-dimensional finite element model and a close-up view of the mesh near the weld for a quarter of an equivalent cross-tension specimen are shown in Figs. 7(c) and 7(d), respectively. The three-dimensional finite element mesh near the weld shown in Fig. 7(d) is based on the optical micrograph shown in Fig. 2. As shown in Fig. 7(d), the mesh near the crack front along the circumference of the weld is refined to assure reasonable aspect ratios of the three-dimensional solid elements. The three-dimensional finite element model for the quarter equivalent cross-tension specimen has 8,469 second-order solid elements. Two original crack tips, marked as A and C in Fig. 7(d), are also shown in the figure. Based on the finite element analysis, the J-integral solution is maximum at the crack tip marked as C in Fig. 7(d).