

Failure Modes of Friction Stir Spot Welds in Lap-Shear Specimens of Dissimilar Advanced High Strength Steels under Quasi-Static and Cyclic Loading Conditions

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ABSTRACT

Failure modes of friction stir spot welds in lap-shear specimens of dissimilar high strength dual phase steel (DP780GA) and hot stamped boron steel (HSBS) sheets are investigated under quasi-static and cyclic loading conditions based on experimental observations. Optical micrographs of dissimilar DP780GA/HSBS friction stir spot welds made by a concave tool before and after failure are examined. The micrographs indicate that the failure modes of the welds under quasi-static and cyclic loading conditions are quite similar. The micrographs show that the DP780GA/HSBS welds mainly fail from cracks growing through the upper DP780GA sheets where the concave tool was plunged into during the welding process. Based on the observed failure modes, a kinked fatigue crack growth model is adopted to estimate fatigue lives. The fatigue life estimations are reasonably in agreement with the experimental results under low-cycle loading conditions but lower than the experimental results under high-cycle loading conditions.

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INTRODUCTION

Resistance spot welding is the most commonly used joining technique for body-in-white parts made of steel sheets. However, resistance spot welding of aluminum sheets is likely to produce poor welds as reported by Thornton et al. [1]. A friction stir spot welding technology for joining aluminum sheets has been developed by Mazda Motor Corporation and Kawasaki Heavy Industry [2, 3]. The most significant advantage of the friction stir spot welding process comparing to the conventional welding processes is that the joint can be made without melting the base metal. A schematic illustration of the friction stir spot welding process was presented, for example, in Lin et al. [4].

The mechanical behavior of aluminum friction stir spot welds under quasi-static loading conditions was studied, for example, see Lin et al. [4], Pan et al. [5], Fujimoto et al. [6, 7] and Hinrichs et al. [8]. The metallurgical aspects of aluminum 6111 friction stir spot welds were investigated by Mitlin et al. [9]. Tran et al. [10] investigated the failure loads of friction stir spot welds in aluminum 6111 lap-shear

specimens under quasi-static and dynamic loading conditions. Recently, Lin et al. [11,12] investigated the fatigue behavior of friction stir spot welds made by different tools in aluminum 6111 sheets based on experimental observations and fracture mechanics. A comprehensive literature review for friction stir spot welds can be found in Pan [13]. Note that most of the literature is for friction stir spot welds between similar aluminum sheets. However, dissimilar friction stir spot welds between aluminum 2017-T6 and 5052 sheets, between aluminum 5754 and 6111 sheets, and between aluminum 5754-O and 7075-T6 sheets were investigated by Tozaki et al. [14], Su et al. [15] and Tran et al. [16], respectively.

Most research on fatigue behavior of friction stir spot welds has been on aluminum alloys. Similar friction stir spot welds between high strength dual phase DP780 steel sheets and hot stamped boron steel (HSBS) sheets were recently made as reported in Santella et al. [17] and Hovanski et al. [18]. Fatigue behavior of similar and dissimilar friction stir spot welds between advanced high strength steel sheets needs to be thoroughly understood and design tools should be

developed for life prediction during product development. A comprehensive review of the fatigue research on similar and dissimilar friction stir spot welds can be found in Tran et al. [19] and Tran and Pan [20]. Tran et al. [19,21] adopted a kinked fatigue crack growth model and the structural stress model to correlate their fatigue data successfully based on the closed-form and computational stress intensity factor solutions for friction stir spot welds in lap-shear and cross-tension specimens.

In this paper, failure modes of friction stir spot welds in lap-shear specimens of dissimilar high strength dual phase steel (DP780GA) and hot stamped boron steel (HSBS) sheets are examined under quasi-static and cyclic loading conditions. Lap-shear specimens were made with DP780GA sheets used as the upper sheets where a concave tool was plunged into during the welding process. The lap-shear specimens were then tested under quasi-static and cyclic loading conditions. Optical micrographs of the welds after testing are used to examine the failure modes of the welds. Based on the observed failure modes, a kinked fatigue crack growth model is adopted to estimate fatigue lives. Finally, the estimated fatigue lives are compared with the experimental results.

EXPERIMENTS

High strength dual phase steel (DP780GA) sheets with a thickness of 1.5 mm were welded to hot stamped boron steel (HSBS) sheets with a thickness of 1.4 mm in the present work. A concave silicon nitride tool was used to make the DP780GA/HSBS welds under displacement controlled conditions. Figure 1(a) shows the concave tool tip with a pin that has three equally spaced flat features at its tip. The notation DP780GA/HSBS represents that the upper sheet is DP780GA where the tool was plunged into during the welding process. A tool rotational speed of 800 rpm, a plunge depth of 2.8 mm and a weld time of 4s were specified. Figure 1(b) shows a lap-shear specimen with a DP780GA/HSBS friction stir spot weld. The DP780GA/HSBS lap-shear specimens were made by using 30 mm×100 mm DP780GA and HSBS sheets. Figure 1(c) shows a schematic of a lap-shear specimen with a friction stir spot weld. The specimen has the width $2b$, the upper and lower sheet thicknesses t_l and t_u , the nugget radius r , the length L , the overlap length V and the applied force F (shown as the bold arrows). The weld is also schematically shown in the figure. Note that one doubler made of the upper sheet and another doubler made of the lower sheet were attached to the ends of the lower and upper sheets, respectively, of the lap-shear specimen to align the applied load to avoid the initial realignment of the specimen during testing under cyclic loading conditions.

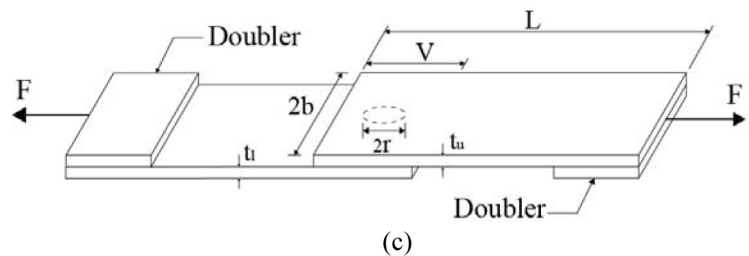
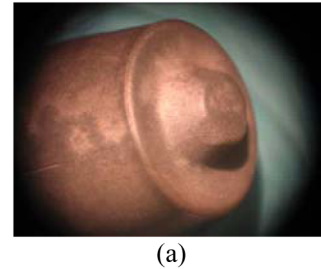


Figure 1. (a) A silicon nitride tool tip, (b) a top view of a DP780GA/HSBS lap-shear specimen and (c) a schematic of a lap-shear specimen with a friction stir spot weld.

Figure 2(a) shows an optical micrograph of the cross section along the symmetry plane of a DP780GA/HSBS friction stir spot weld before testing. As shown in the figure, the indentation profile reflects the shape of the pin and concave shoulder. Two notches, marked as N1 and N2, can be seen in the figure. Figure 2(b) shows a magnified view near the left crack tip in Figure 2(a). The location of the crack tip is marked in the figure. As shown in Figure 2(a), 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. As shown in Figure 2(a), the thickness of the weld nugget near the central hole is larger than that near the outer circumference of the shoulder indentation. The concave tool shoulder squeezed out some upper sheet material but maintained some upper sheet material near the central hole. The shoulder indentation resulted in a radial expansion of the upper sheet along the outer circumference of the shoulder indentation. However, due to the constraint of the neighboring material, the sheet was therefore bent along the outer circumference of the shoulder indentation. In Figure 2(a), the bends are marked as B1 and B2.

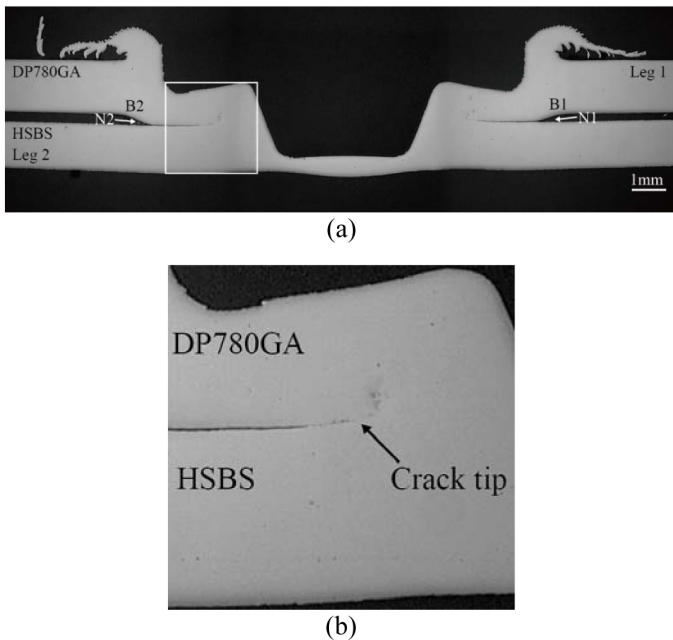


Figure 2. (a) An optical micrograph of the symmetry cross section of a DP780GA/HSBS weld and (b) a close-up optical micrograph near the left crack tip of the DP780GA/HSBS weld.

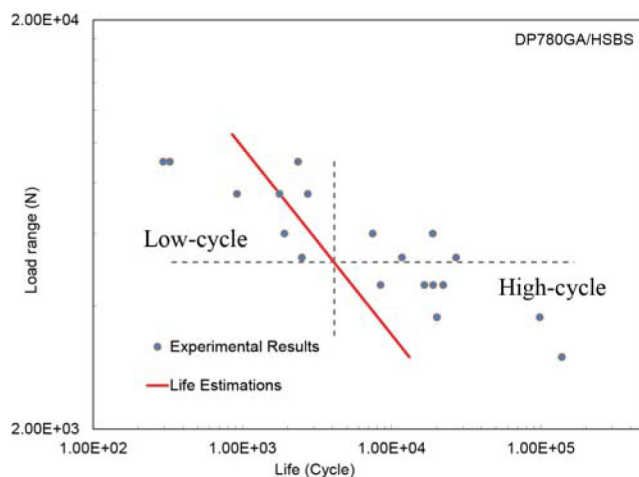


Figure 3. Experimental results and fatigue life estimations for DP780GA/HSBS welds.

The lap-shear specimens were first tested without using doublers under quasi-static loading conditions by using an Instron servo-hydraulic testing machine at a displacement rate of 10 mm per minute. The average failure load, defined as the average of the maximum loads of the load-displacement curves obtained from four lap-shear specimens, was 11.75 kN. The failure load was used as the reference load to determine the applied loads for the fatigue tests. The lap-shear specimens were then tested with doublers under cyclic loading conditions by using an Instron servo-hydraulic fatigue testing machine with the load ratio of 0.1 and test

frequency of 10 Hz. The tests were terminated when specimens were separated. Figure 3 shows the experimental results for DP780GA/HSBS welds in lap-shear specimens. The fatigue life estimations based on a kinked fatigue crack growth model are also shown in the figure. The fatigue life estimations based on the kinked fatigue crack growth model will be discussed later.

FAILURE MODES

FAILURE MODE UNDER QUASI-STATIC LOADING CONDITIONS

Figure 4(a) shows an optical micrograph of the cross section along the symmetry plane of a failed DP780GA/HSBS weld in a lap-shear specimen under quasi-static loading conditions. The bold arrows in Figure 4(a) schematically show the direction of the applied load. The applied load stretches the upper right sheet (marked as Leg 1) and the lower left sheet (marked as Leg 2). As shown in Figure 4(a), two cracks, marked as crack 1 and crack 2, appear to emanate from the original crack tips of the weld. Crack 1 propagates through the upper sheet thickness and the shear failure surface is marked by S1 in the figure. The failure then propagates around the nugget circumference. Without the support of the upper sheet, crack 2 propagates a bit along the original interface between the upper and lower sheets and then into the stir zone. The weld is then separated through the left portion of the nugget by a fracture surface marked as S2 in the figure. The upper sheet is finally torn off. Figure 4(b) shows a top view of the failed weld on the lower HSBS sheet before sectioning. As shown in the figure, the weld failed along the nugget circumference on the right side and in the nugget on the left side. As suggested in Figure 4(a), crack 1 appears to be the dominant crack that causes the failure of the DP780GA/HSBS weld under quasi-static loading conditions. In summary, the DP780GA/HSBS welds mainly fail from the crack growing through the upper sheet thickness and the fracture surface through the nugget under quasi-static loading conditions.

FAILURE MODE UNDER LOW-CYCLE LOADING CONDITIONS

Figures 5(a) and 5(c) show optical micrographs of the cross sections along the symmetry planes of failed DP780GA/HSBS welds at the fatigue lives of 326 and 1,904 cycles under load ranges of 9 and 6 kN, respectively. Figure 5(a) shows the first failure mode and Figure 5(c) shows the second failure mode under low-cycle loading conditions. The bold arrows in Figures 5(a) and 5(c) schematically show the direction of the applied load. The failure mode under quasi-static loading conditions and the first failure mode under low-cycle loading conditions are quite similar, whereas the second failure mode under low-cycle loading conditions is slightly different from the first failure mode under low-cycle loading conditions.