

Failure Mode and Fatigue Behavior of Friction Stir Spot Welds in Lap-Shear Specimens of Dissimilar Advanced High Strength Steels

Seung Hoon Hong, Katherine Avery and Jwo Pan
Univ of Michigan-Ann Arbor

Michael Santella, Zhili Feng and Tsung-Yu Pan
Oak Ridge National Laboratory

ABSTRACT

Failure mode and fatigue behavior of friction stir spot welds made with convex and concave tools in lap-shear specimens of dissimilar high strength dual phase steel (DP780GA) and hot stamped boron steel (HSBS) sheets are investigated based on experiments and a kinked fatigue crack growth model. Lap-shear specimens with the welds were tested under both quasistatic and cyclic loading conditions. Optical micrographs indicate that under both quasi-static and cyclic loading conditions, the welds mainly fail from cracks growing through the upper DP780GA sheets where the tools were plunged in during the welding processes. Based on the observed failure mode, a kinked fatigue crack growth model is adopted to estimate fatigue lives of the welds. In the kinked crack fatigue crack growth model, the stress intensity factor solutions for fatigue life estimations are based on the closed-form solutions for idealized spot welds in lap-shear specimens. 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

Many materials are used for automotive body structures and, among them, advanced high strength steel (AHSS) is experiencing the most rapid growth. AHSS allows for stronger, thinner components that reduce total vehicle weight to improve fuel economy and increase passenger safety without significant cost penalties. Resistance spot welding is the traditional joining technique for body-in-white parts made of steel sheets. However, Shi et al. [1] reported that the softening of the Heat Affected Zone (HAZ) may improve the ductility but may possibly limit the strength of the resistance spot welds in AHSS. Since resistance spot welding of aluminum sheets is likely to produce poor welds as reported by Thornton et al. [2], a friction stir spot welding (FSSW) technology for joining aluminum sheets has been developed by Mazda Motor Corporation and Kawasaki Heavy Industry [3, 4]. Recently, friction stir spot welding has been shown to be successful in joining advanced high strength steel (AHSS) sheets in Feng et al. [5], Santella et al. [6] and Hovanski et al.

[7]. The solid state bonding that occurs during FSSW provides a significant advantage over the conventional fusion welding processes. A schematic illustration of the friction stir spot welding process used to join metal sheets was shown, for example, in Lin et al. [8]. A comprehensive literature review for friction stir spot welding can be found in Pan [9].

It should be noted that most research on failure mode and fatigue behavior of friction stir spot welds has focused on similar sheets of aluminum alloys. Mitlin et al. [10] investigated the metallurgical aspects of aluminum 6111 friction stir spot welds. The mechanical behavior of aluminum friction stir spot welds under quasi-static loading conditions was studied in Lin et al. [8], Pan et al. [11], Fujimoto et al. [12, 13] and Hinrichs et al. [14]. Tran et al. [15] investigated the failure loads of friction stir spot welds in aluminum 6111 lap-shear specimens under quasi-static and dynamic loading conditions. 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. [16], Su et al. [17] and Tran et al. [18], respectively. Lin et al. [19, 20] investigated the fatigue behavior of friction stir spot welds made with concave and flat tools in aluminum 6111 sheets based on experimental observations and fracture mechanics. A comprehensive review of the fatigue research on similar and dissimilar friction stir spot welds can be found in Tran et al. [21] and Tran and Pan [22].

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. [6] and Hovanski et al. [7]. Failure modes of friction stir spot welds of dissimilar advanced high strength steels were investigated by Hong et al. [23]. Fatigue behavior of similar and dissimilar friction stir spot welds between AHSS sheets needs to be thoroughly understood and design tools should be developed for life prediction during product development.

The kinked fatigue crack growth model of Newman and Dowling [24] and Lin et al. [25] has been adopted by Lin et al. [19, 20], Tran et al. [26] and Wang and Chen [27] to predict the fatigue lives of friction stir spot welds. Tran et al. [26] developed a structural stress model to successfully correlate fatigue data to closed-form and computational stress intensity factor solutions for friction stir spot welds in lap-shear and cross-tension specimens.

In this paper, the failure modes and fatigue behaviors of friction stir spot welds made with concave and convex tools in lap-shear specimens of dissimilar galvanized DP780GA and 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 the concave or convex 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 before and 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.

SPECIMENS

DP780GA sheets with a nominal thickness of 1.5 mm were friction stir spot welded to HSBS sheets with a nominal thickness of 1.4 mm in a lap-shear configuration. The notation DP780GA/HSBS represents that the upper sheet is DP780GA where the tool was plunged into during the welding process. The DP780GA/HSBS friction stir spot welds were made by using a MTS-ISTR system in a displacement-control mode. For the friction stir spot 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, two different tool shoulder geometries, concave with smooth surface and convex with spiral pattern, were used to make the DP780GA/HSBS welds. Figures 1(a) and 1(b) show close-up views of the concave and convex tool

tips, respectively, with pins that have three equally spaced flat features. The rotational speed was specified as 800 rpm for the concave and convex tools. A plunge depth of 2.8 mm and a weld time of 4 s were specified.

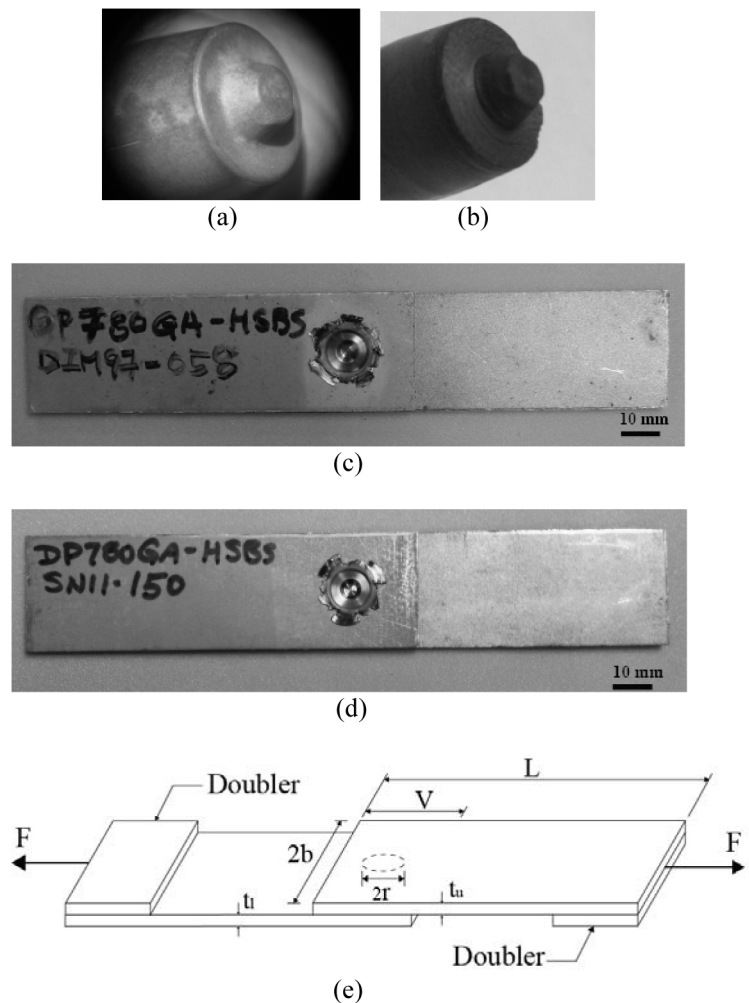


Figure 1. Close-up views of silicon nitride (a) concave and (b) convex tool tips. Top views of DP780GA/HSBS lap-shear specimens made with the (c) concave and (d) convex tools. (e) A schematic of a lap-shear specimen with a friction stir spot weld.

Figures 1(c) and 1(d) show lap-shear specimens with DP780GA/HSBS friction stir spot welds made with the concave and convex tools, respectively. The DP780GA/HSBS lap-shear specimens were made by using 30 mm × 100 mm DP780GA and HSBS sheets. Figure 1(e) shows a schematic of a lap-shear specimen. The specimen has the width $2b$, the nominal lower and upper sheet thicknesses t_l and t_u , respectively, the nugget radius r , the length L , and the overlap length V . The applied force F is shown as the bold arrows. The weld is schematically shown in the figure with the diameter $2r$. Doublers were used during testing of the lap-shear specimens to align the applied load and minimize the initial realignment of the specimen during testing under

quasi-static and cyclic loading conditions. One doubler, made of the upper sheet, was placed adjacent to the upper sheet, and the other, made of the lower sheet, was placed adjacent to the lower sheet. The maximum plunge loads were different for different specimens. Specimens made with similar maximum plunge loads were selected for quasi-static and fatigue tests.

WELD MICROGRAPHS

Figures 2(a) and 2(b) show optical micrographs of the cross sections along the symmetry planes of DP780GA/HSBS FSSWs made with the concave and convex tools before testing, respectively. As shown in the figures, the indentation profiles reflect the respective shapes of the pins and tool shoulders. Two notches, marked as N1 and N2, can be seen in the figures. The notches extend and become cracks. Figures 2(c) and 2(d) show magnified views near the left crack tip in Figures 2(a) and 2(b). The locations of the crack tips are marked in each figure. The effective sheet thicknesses $t'_u = 1.03$ mm and $t'_l = 1.38$ mm are measured at the crack tips of the DP780GA/HSBS weld made with a concave tool as shown in Figure 2(a). The effective sheet thicknesses $t'_u = 1.23$ mm and $t'_l = 1.38$ mm are measured at the crack tips of the DP780GA/HSBS weld made with a convex tool as shown in Figure 2(b). It should be noted that the change of the upper sheet thickness near the locations of the two crack tips in Figure 2(a) is larger than the change of the upper sheet thickness near the locations of the two crack tips in Figure 2(b) due to the different geometries of the concave and convex tool shoulders. The weld diameter, $2r$, is 7.36 mm for the weld made with the concave tool and 6.17 mm for the weld made with the convex tool. As shown in Figures 2(a) and 2(b), there are flashes present on the top surfaces of the upper sheets near the tool shoulder indentations. Figure 2(a) shows that there is a rise of the upper sheet material near the central hole due to the geometry of the concave tool shoulder. Such a rise is not seen in Figure 2(b) due to the different geometry of the convex tool shoulder.

As shown in Figures 2(a) and 2(b), 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 Figures 2(a) and 2(b), the bends are marked as B1 and B2. Small gaps were formed between the upper and lower sheets of the DP780GA/HSBS welds as shown in Figures 2(a) and 2(b). The concave tool resulted in a greater degree of bend and gap than the convex tool.

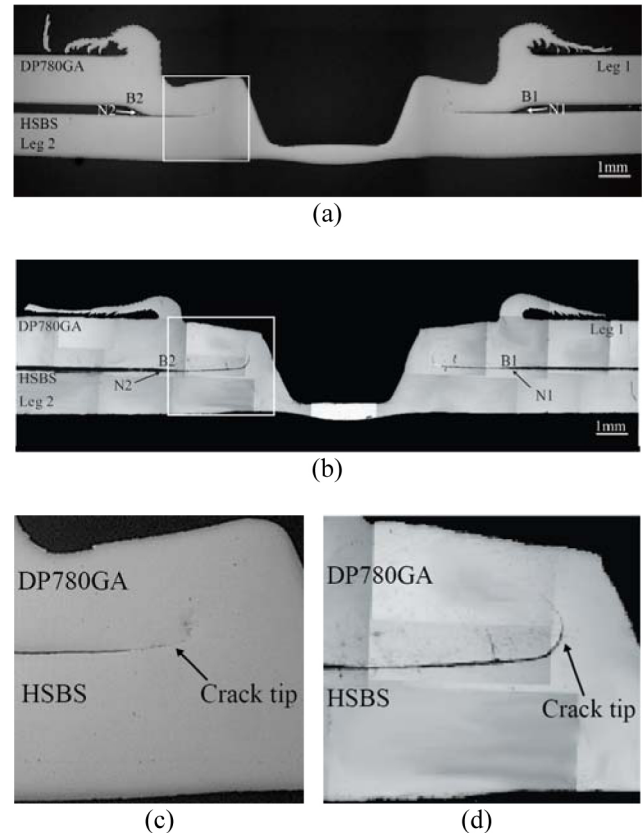


Figure 2. Optical micrographs of the symmetry cross sections of DP780GA/HSBS welds made with the (a) concave and (b) convex tools. Close-up optical micrographs near the left crack tips of the DP780GA/HSBS welds made with the (c) concave and (d) convex tools.

EXPERIMENTS

The lap-shear specimens were first tested with 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, was found to be 11.6 kN for the concave tool and 12.4 kN for the convex tool. Fatigue tests were conducted on the lap-shear specimens to determine if the welds made by the convex tool with the higher average failure load have longer fatigue lives under cyclic loading conditions. The failure loads were used 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 or survived 10^5 cycles.