

Fatigue Analysis of Swept Friction Stir Clinch Joints between Aluminum and Steel Sheets

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ABSTRACT

Fatigue analysis of swept friction stir clinch (Swept-FSC) joints between 6061-T6 aluminum (Al) and S45C steel (Fe) sheets was conducted through experimental approaches. Before fatigue tests, a parametric study for the probe geometry of FSC tools was conducted in order to eliminate the hook structure inside the joint and improve the mechanical performance of the joint. Then a series of quasi-static and fatigue tests for Al/Fe Swept-FSC joints in lap-shear (LP) and cross-tension (CT) specimens were conducted. The fatigue data were recorded. The fatigue behavior of Al/Fe Swept-FSC joints in LP and CT specimens were examined through optical and scanning electron microscopes. Experimental results indicated that LP specimens have two failure modes, while CT specimens have only one failure mode. The dominant fatigue crack of each failure mode was identified.

CITATION: Lin, P. and Chen, W., "Fatigue Analysis of Swept Friction Stir Clinch Joints between Aluminum and Steel Sheets," *SAE Int. J. Mater. Manf.* 10(2):2017, doi:10.4271/2017-01-0478.

INTRODUCTION

In order to improve the fuel efficiency and vehicle performance, the automotive industry continuously shifts from steels to aluminum alloys. Recently, the design concept of aluminum-steel hybrid car body, which optimizes the strength, mass, and cost of car body, has been widely used in the industry [1,2]. In order to join various components made of aluminum and steel sheets, many joining processes, such as friction stir spot welding (FSSW) [3, 4, 5], ultrasonic spot welding (USW) [6,7], clinching [8,9], friction bit joining (FBJ) [10], and self-piercing riveting (SPR) [11,12], were proposed. In contrast to the conventional welding processes, these joining processes make joints without melting the base metals, which can avoid the deficiency of the brittle intermetallic compound layer at the aluminum and steel interface [13].

Among the aforementioned processes, the FSSW process developed by Mazda Motor Corporation and Kawasaki Heavy Industry was originally used for joining similar and dissimilar aluminum sheets [14,15]. For FSSWs between aluminum and steel sheets (Al/Fe FSSWs), one of the challenges was the strength and melting point of steels, which were much higher than those of aluminum alloys. Recently, Mazda Motor Corporation modified the FSSW process to join aluminum sheets to zinc coated steel sheets [16,17]. In this study, the tool was not indented into the lower steel sheet. Only the upper aluminum sheet was stirred. It was interesting that the zinc layer

could interact with the aluminum sheet to form a discontinuous intermetallic layer, which provided good bonding strength for Al/Fe FSSWs. Note that nearly no mechanical interlock existed at the interface since the interface was nearly flat. Bozzi et al. [18] made Al/Fe FSSWs by using tungsten rhenium alloy (W25Re) tools, which could plunge through the upper aluminum layer and directly into the lower steel sheet. They showed that the strength of Al/Fe FSSWs strongly depends on the thickness of intermetallic compounds at the interface, not the size of the hook structure. This indicated that the mechanical interlock of their Al/Fe FSSWs appeared to be limited. Mechanical properties and failure modes of Al/Fe FSSWs under quasi-static loading conditions were studied by many researchers as well [3,4,19,20]. Their results showed that Al/Fe FSSWs could provide sufficient failure loads under shear dominant loading conditions, but poor failure loads under opening dominant loading conditions. This phenomenon was probably due to the characteristics of the intermetallic compound layer at the interface.

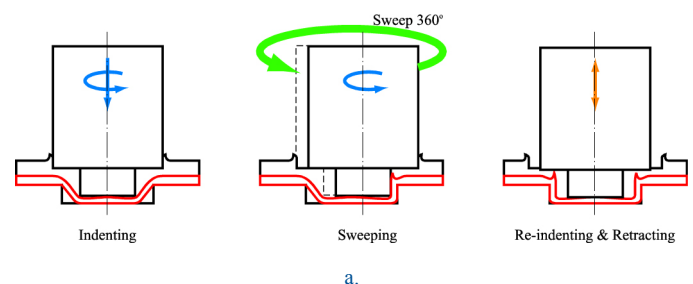


Figure 1. Schematics of the Swept-FSC process. [21]

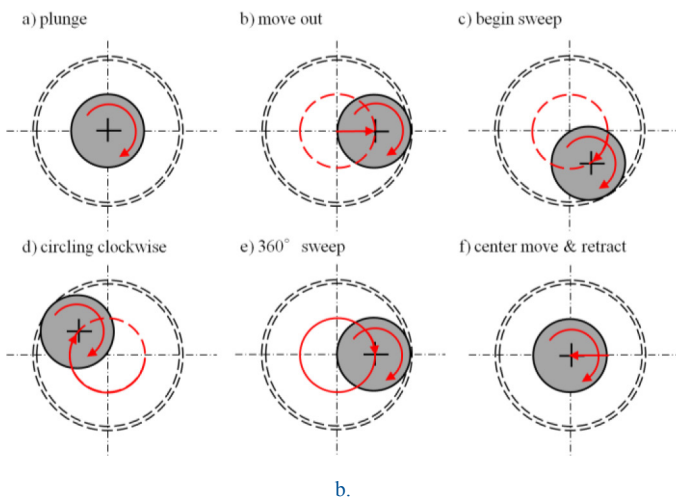


Figure 1. (cont.) Schematics of the Swept-FSC process. [21]

In recent days, a new joining process, swept friction stir clinching (Swept-FSC), was proposed to join aluminum sheets to steel sheets [21]. This process in fact was a combination of the swept-friction stir spot welding (Swept-FSSW) and clinching processes. Note that the Swept-FSSW process was a variation of the FSSW process developed by Buffa et al. [22] and Tweedy et al. [23]. The key point of this process was the tool sweeping motion, which could enlarge the stir zone and provide good mechanical properties for Swept-FSSWs. On the other hand, the clinching process was a traditional mechanical fastening process. Sheet metals were punched by a tool into a die and deformed as two button structures, which could provide good mechanical interlock between them [24].

A schematic illustration of the Swept-FSC process used to join an aluminum sheet (Al) to a steel sheet (Fe) is shown in Fig. 1. In this figure, a rotating tool with a probe is first indented into the upper aluminum sheet until the initial indentation depth is achieved. An anvil with a circular cavity beneath the lower steel sheet is taken as a die. The tool rotational speed is maintained for the whole joining process to generate frictional heat. The heated and softened sheets are then punched into the die to form two shallow button structures. Next, the rotating tool is moved outward for a distance and then swept counterclockwise along a circular path to form two deep button structures. Note that the tool sweeping motion here is used for expanding the size of the outer button (Fe). Consequently, the inner and outer button structures can provide a strong mechanical interlock between two sheets. Finally, the tool is moved backward to the initial location, punched a little more to fill the remaining cavities or holes in the inner button (Al), and then retracted from the surface. A dissimilar Al/Fe Swept-FSC joint is made. Note that unlike the aforementioned FSSW process, the zinc coated steel sheet is not necessary in this process.

In this paper, a parametric study for the probe geometry of FSC tools is first conducted. Five FSC tools with various step-probe designs are used to make Al/Fe Swept-FSC joints with less hook structure and larger joint strength. Lap-shear (LP) and cross-tension (CT) specimens

are then used to evaluate the fatigue performance of Al/Fe Swept-FSC joints. Fatigue data and failure modes of Al/Fe Swept-FSC joints in LP and CT specimens are recorded. Pictures and optical micrographs of the Al/Fe Swept-FSC joints before and after failure are examined. Dominant fatigue crack of each failure mode is identified. Fatigue behavior of Swept-FSC joints are investigated and discussed.

EXPERIMENTS

Aluminum 6061-T4 sheets with a thickness of 1.6 mm and bare steel S45C sheets with a thickness of 1.0 mm were used. Five FSC tools, T1 to T5 tools, with flat shoulders and step-probes were used to make Swept-FSC joints, as shown in Fig. 2. In Fig. 2, the shoulder diameter D_s was 12 mm. The step-probes had two steps. The detailed dimensions of the probes were listed in Table 1. The diameter and length of the 1st step are denoted as D_1 and L_1 , respectively. Those of the 2nd step are denoted as D_2 and L_2 , respectively. A die with a circular cavity at the center was used to make the button structure of Swept-FSC joints, as shown in Fig. 3. The depth and diameter of the cavity were 2 mm and 10 mm, respectively. The joints were made by a CNC milling machine from MAZAK Corporation.

LP specimens were made by using two 25.4 mm by 101.6 mm sheets with a 25.4 mm by 25.4 mm overlap area. Two doublers were adopted in the tests for LP specimens to align the applied load at the initial realignment stage. CT 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. Note that the aluminum 6061-T4 and steel S45C sheets were taken as the upper and lower sheets of both specimens, respectively.

In quasi-static tests, LP and CT specimens were tested by using a MTS servo-hydraulic testing machine at a monotonic displacement rate of 5.0 mm/min. The loads and displacements were simultaneously recorded during the tests. The average failure load obtained from three tested specimens was then used as the reference load to determine the load ranges applied in the fatigue test. In fatigue tests, the specimens were tested with a load ratio R of 0.1. The test frequency for LP specimens was 10 Hz and that for CT specimens was 5 Hz.

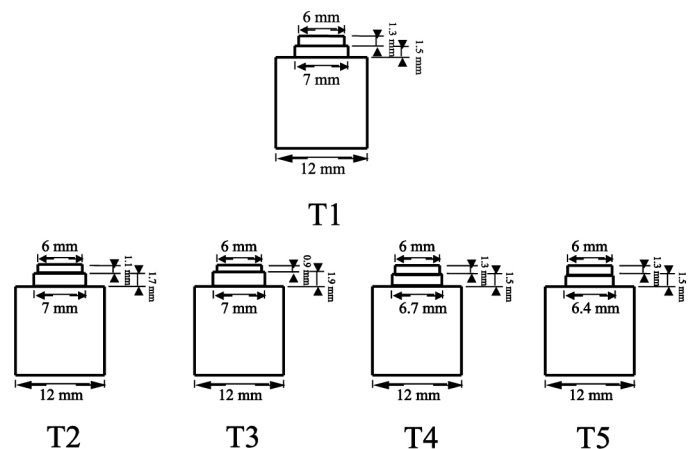


Figure 2. Schematics of five FSC tools with flat shoulders and various step-probes.

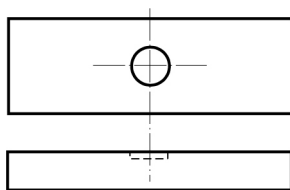


Figure 3. Schematics of a FSC die with a circular cavity at the center.

Table 1. The detailed dimensions of five FSC tools, T1 to T5. The diameter and length of the 1st step are denoted as D_1 and L_1 , respectively. Those of the 2nd step are denoted as D_2 and L_2 , respectively.

	T1	T2	T3	T4	T5
D_1	6	6	6	6	6
D_2	7	7	7	6.7	6.4
L_1	1.3	1.1	0.9	1.3	1.3
L_2	1.5	1.7	1.9	1.5	1.5

Unit: mm

SWEPT-FSC JOINTS

In this paper, a preliminary study for the effects of step-probes on the hook structure of Swept-FSC joints was conducted. Fig. 4(a) shows a micrograph of the cross section of a Swept-FSC made by an original FSC tool. The original FSC tool developed by Lin et al. [21] has a flat shoulder and a cylindrical probe. The shoulder diameter is 12 mm. The probe diameter is 7 mm and the probe length is 2.8 mm. As shown in Fig. 4(a), the Swept-FSC joint made by the original tool has large hook structure and deep groove along the circumference of the outer button. Note that the hook may cause significant stress concentration near the tip. The groove can provide strong mechanical interlock between the inner and outer buttons.

Fig. 4(b) shows a micrograph of the cross section of a Swept-FSC made by T1 tool. As shown in Fig. 2, the probe of T1 tool has a step structure. It should be noted that in order to remove the hook structure in Fig. 4(a), the length L_1 and the diameter D_2 of T1 tool are determined based on the location and width of the hook root, respectively. As shown in Fig. 4(b), although the general shape of this joint is similar to that made by the original tool, the hook of this joint becomes very small. This indicates that during the sweeping motion, the step probe trims the hook tip away and bends the remaining hook outwards simultaneously. Consequently, the stress concentration caused by the hooks, which is important to the fatigue performance, can be significantly decreased. On the other hand, the step structure of the probe slightly decreases the groove width or inner button thickness due to the small diameter of the 1st step probe. This fact may slightly decrease the shear strength of the joint. However, the opening strength of the joint may significantly increase since the minimum thickness of the inner button shoulder increases.

Figs. 4(c) and 4(d) show close-up top and back views of a Swept-FSC joint. As shown in the top view, the top surface of the joint looks like a button with a central hole. The flash squeezed from the upper sheet (Al) is accumulated along the outer circumference of the joint. As shown in the back view, a circular bulge of the lower sheet (Fe) caused by the tool and die can be seen.

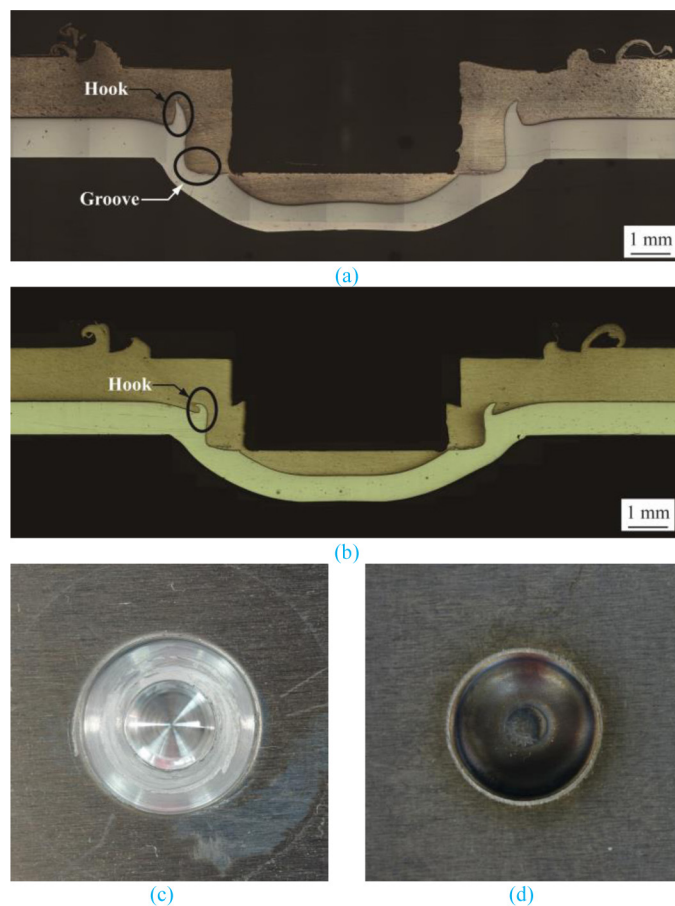


Figure 4. Micrographs of Swept-FSC joints made by (a) original FSC tool [21], and (b) T1 tool. The close-up (c) top view and (d) back view of a Swept-FSC joint.

SWEPT-FSC TOOL MODIFICATION

In the previous section, the preliminary study has confirmed the design concept of step-probes for hook elimination. However, the correlations between the geometry of step-probes and the mechanical performance of FSC joints have not been validated. In the following, the effects of the step-probe length and step-probe diameter on the failure loads and fatigue lives of FSC joints in LP specimens will be investigated.

Step-Probe Length

In order to investigate the effects of step-probe lengths on the mechanical performance of Swept-FSC joints, three FSC tools, T1, T2 and T3, with various probe length combinations are used here. Fig. 5(a) shows the failure load vs. the step-probe length for Swept-FSC joints in LP specimens. For the Swept-FSC joints used here, a rotational speed of 700 rpm, an initial indentation depth of 2.9 mm, and an indentation rate of 120 mm/min were applied for initial indenting. Next, a feed rate of 30 mm/min and a path radius of 1.5 mm were applied for sweeping. Finally, a final depth of 3.1 mm was applied for filling.

As shown in Fig. 5(a), the average failure load decreases and then increases as the step-probe length L_1 decreases (or L_2 increases). Note that the Swept-FSC joints made by T2 tool have the lowest failure load and highest standard deviation. The possible reason is that the