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Investigation of Failure Mode and Fatigue Behavior of Flow Drill Screw Joints in Lap-Shear Specimens of Aluminum 6082-T6 Sheets

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ABSTRACT

Failure mode and fatigue behavior of flow drill screw (FDS) joints in lap-shear specimens of aluminum 6082-T6 sheets with and without clearance hole are investigated based on experiments and a structural stress fatigue life estimation model. Lap-shear specimens with FDS joints were tested under cyclic loading conditions. Optical micrographs show that the failure modes of the FDS joints in specimens with and without clearance hole are quite similar under cyclic loading conditions. The fatigue lives of the FDS joints in specimens with clearance hole are longer than those of the FDS joints in specimens without clearance hole for the given load ranges under cyclic loading conditions. A structural stress fatigue life estimation model is adopted to estimate the fatigue lives of the FDS joints in lap-shear specimens under high-cycle loading conditions. The closed-form structural stress solutions are based on the analytical solution for a plate with a rigid inclusion under a resultant shear load. The general trends of the fatigue life estimations are in agreement with those of the experimental results.

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INTRODUCTION

Mechanical joining methods such as self-piercing rivets, clinched joints and flow drill screw (FDS) joints have been used to join sheets in the automotive industry recently. FDS joints have the advantage of one-side access for manufacturing flexibility. The advantages of the FDS joining process have been discussed in Claus and Weitzel [1]. The processing parameters of FDS joints have been investigated by Skovron et al. [2, 3]. The mechanical behavior and the failure modes of FDSs have been investigated under combined shear and tension loading conditions by Szlosarek et al. [4]. The failure mode and fatigue behavior of FDS have not been examined in details.

In this paper, FDS joints in lap-shear specimens of aluminum 6082-T6 sheets with and without clearance hole are investigated based on experiments and a structural stress fatigue life estimation model. FDS joints in lap-shear specimens with and without clearance hole were tested under cyclic loading conditions. Optical micrographs were obtained to show the failure modes of the FDS joints in specimens with and without clearance hole. The fatigue lives of the FDS joints in specimens with and without clearance hole under cyclic loading conditions were also obtained. A structural stress fatigue life estimation model is adopted to estimate the fatigue lives of the FDS joints in lap-shear specimens. The closed-form structural stress solutions are based on the analytical solution for a plate with a rigid inclusion under a resultant shear load. The fatigue life estimations are then compared with those of the experimental results.

EXPERIMENTS

Lap-shear specimens were made by using 25 mm by 100 mm aluminum alloy 6082-T6 sheets with a thickness of 2 mm. The specimen has a 25 mm by 25 mm overlap area. Figures 1 and 2 show the top views of two lap-shear specimens with FDS joints with and without clearance hole, respectively. The type of the screws used is M5×25 EJOT External Torx Plus. Figures 3 and 4 show the micrographs of the cross sections along the symmetry planes of FDS joints in lap-shear specimens with and without clearance hole. As shown in the figures, the upper and lower sheets of the FDS joint with clearance hole has no gap when compared with that without clearance hole. The gap g for the FDS joint without clearance hole due to the extruded material from the FDS drilling process is marked in Figure 4.

Figure 1. A top view of a lap-shear specimen with a FDS joint with clearance hole.

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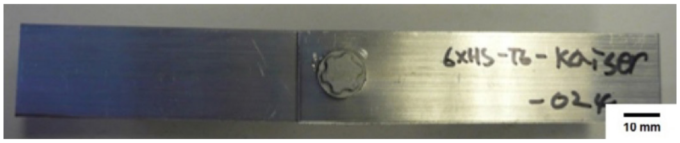

Figure 2. A top view of a lap-shear specimen with a FDS joint without clearance hole.

The lap-shear specimens with doublers were first tested by using a MTS testing machine at a monotonic displacement rate of 7.62 mm/min. The tests were terminated when specimens were separated. The average failure loads were 7.2 kN and 7.3 kN for three lap-shear specimens with FDS joints without and with hole, respectively. The average failure loads were then used as the reference loads to determine the load ranges applied in the fatigue tests. The lap-shear specimens with doublers were then tested with the maximum loads, which are from 80% to 40% of the quasi-static failure loads, by using an Instron servo-hydraulic fatigue testing machine with a load ratio R of 0.1. The test frequency was 10 Hz. The tests were terminated when the specimens were separated or the displacement of two grips exceeded 5 mm.

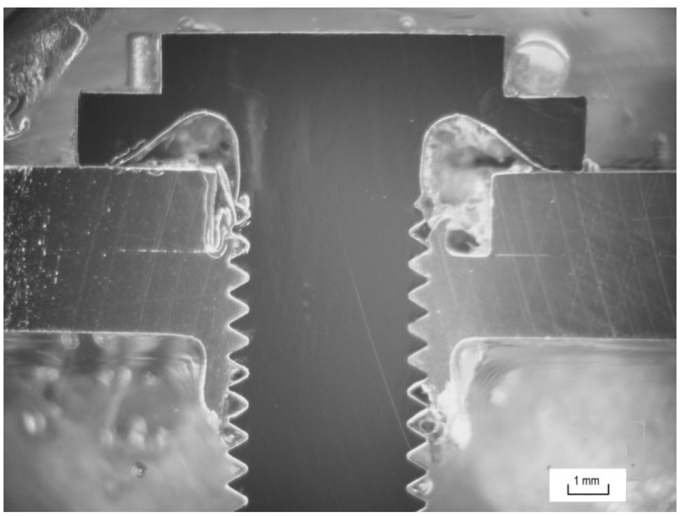

Figure 3. A micrograph of the cross section along the symmetry plane of a FDS joint in a lap-shear specimen with clearance hole.

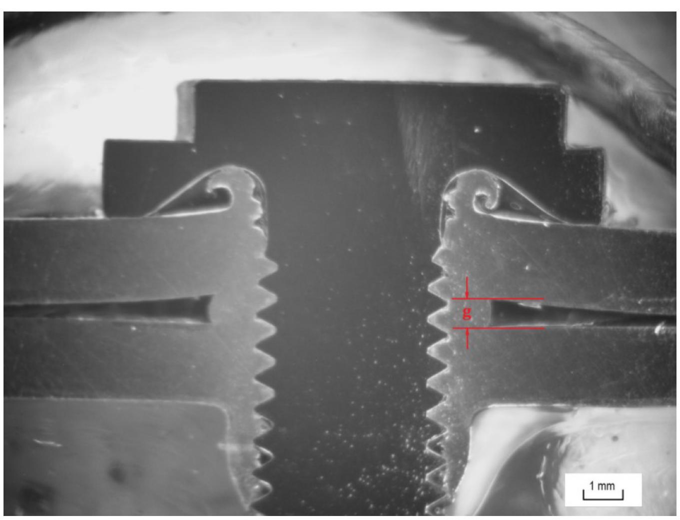

Figure 4. A micrograph of the cross section along the symmetry plane of a FDS joint in a lap-shear specimen without clearance hole.

Figure 5 shows the experimental results for FDS joints in lap-shear specimens with and without clearance hole under cyclic loading conditions. Based on experimental observations, the failure modes of FDS joints in lap-shear specimens under low-cycle and high-cycle loading conditions are different. The low-cycle and high-cycle definitions in this paper are based on the failure modes as discussed in the following.

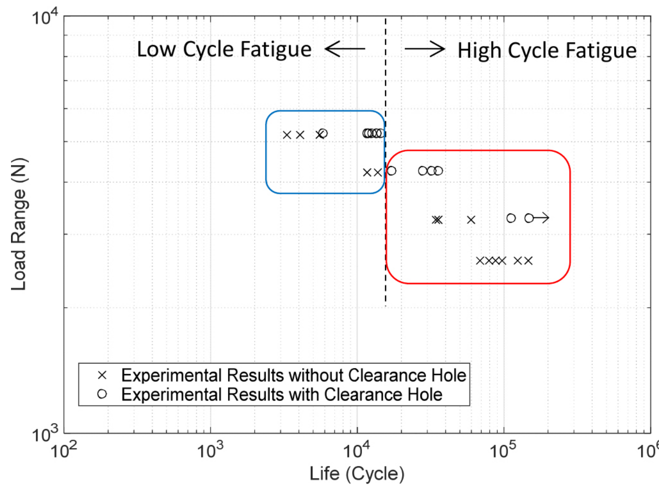

Figure 5. Experimental results for FDS joints in lap-shear specimens with and without clearance hole under cyclic loading conditions.

FATIGUE FAILURE MODES

Figure 6 shows a schematic of a lap-shear specimen with a FDS joint idealized as a rigid cylinder with a radius a under a resultant shear load F. In the figure, t_u and t_l represent the upper and lower sheet thicknesses, respectively, b represents the half specimen width, V represents the overlap length, and L represents the lengths of the upper and lower sheets. The critical locations of points A, B, C and D are 0º, 90º, 180º, and 270º with respect to the x axis, respectively. Two doublers are also shown schematically in the figure. Figure 7 shows a schematic of a top view of the FDS joint with the Cartesian $x - y$ and polar $r - \theta$ coordinate systems centered at the center of the FDS joint. The loading direction is in the x direction at $\theta = 0$.

Figures 8 and 9 show the failed FDS joints with clearance hole in lap-shear specimens under low-cycle and high-cycle loading conditions, respectively. It should be noted that the failures occurred in the lower sheets and Figures 8 and 9 are the bottom views of the failed specimens. The failure modes for the specimens with and without clearance hole are similar and, therefore, the images of the failed FDS joints without clearance hole will not be shown here. As shown in Figure 8 and suggested from the figure, the fatigue cracks grew from the screw at 90º and 270º into the lower sheet under low-cycle loading conditions. As shown in Figure 9 and suggested from the figure, the fatigue crack grew in the lower sheet at about 180º close to the screw and then to the sides of the specimen under high-cycle loading conditions.

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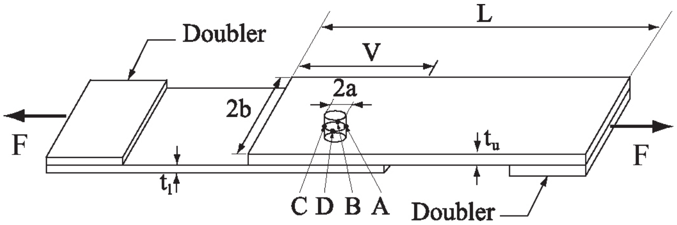

Figure 6. A schematic of a lap-shear specimen with a FDS joint idealized as a rigid cylinder under the applied resultant forces shown as the bold arrows.

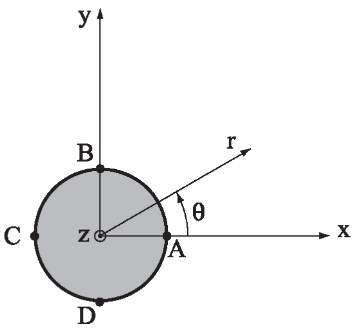

Figure 7. A schematic of a top view of the joint (modeled as a rigid inclusion) in the lower sheet of the specimen with the cylindrical and Cartesian coordinate systems centered at the center of the joint on the mid plane of the lower sheet.

Figure 8. A bottom view of a failed FDS joint in a lap-shear specimen under low-cycle loading conditions.

Figure 9. A bottom view of a failed FDS joint in a lap-shear specimen under high-cycle loading conditions.

Figures 10 and 11 show the micrographs of the FDS joints in lap-shear specimens along the symmetry planes with and without clearance hole under low-cycle loading conditions, respectively. The gap *g* for the FDS joint without clearance hole is marked in Figure 11. As shown in Figure 8 and suggested from the figure, the fatigue cracks grew in the aluminum sheets from the screw in the directions of 90° and 270° and then the specimen separated from the screws from the left side. Therefore, the aluminum material is clearly separated from the steel screw threads on the left sides of the figures.

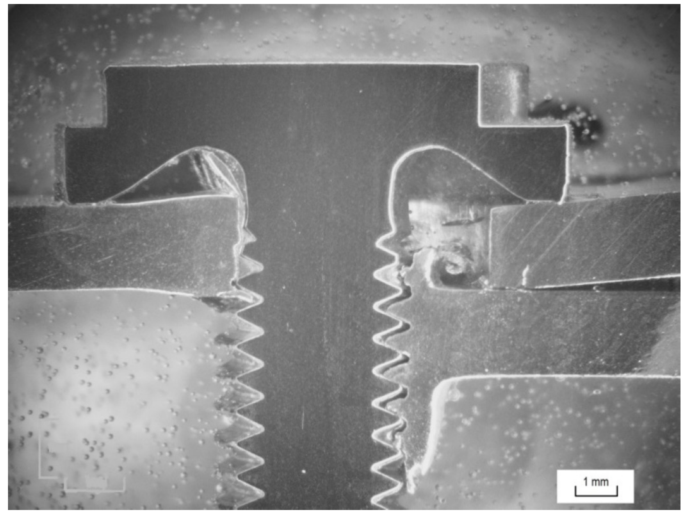

Figure 10. A micrograph of a failed FDS joint in a lap-shear specimen along the symmetry plane with clearance hole at the fatigue life of 14,570 cycles under a load range of 5,247 N (low-cycle loading conditions).

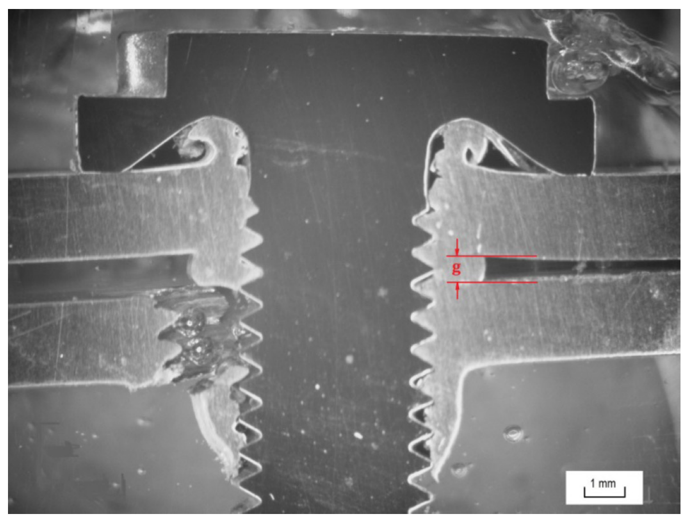

Figure 11. A micrograph of a failed FDS joint in a lap-shear specimen along the symmetry plane without clearance hole at the fatigue life of 11,687 cycles under a load range of 4,218 N (low-cycle loading conditions).

Figures 12 and 13 show the micrographs of the FDS joints in lap-shear specimens along the symmetry planes with and without clearance hole under high-cycle loading conditions, respectively. The gap *g* for the FDS joint without clearance hole is marked in Figure 13. As shown in Figure 9 and suggested form the figure, the fatigue crack grew in the lower sheet at about $\theta = 180°$ close to the screw and then into the lower sheet to the sides of the specimen.

Therefore, the aluminum material near the screw threads is still attached to the steel screw threads on the left sides of the figures.

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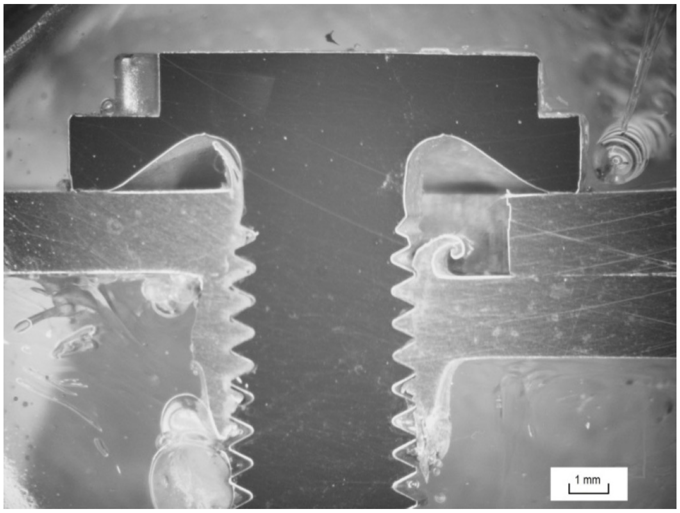

Figure 12. A micrograph of a failed FDS joint in a lap-shear specimen along the symmetry plane with clearance hole at the fatigue life of 27,814 cycles under a load range of 4,263 N (high-cycle loading conditions).

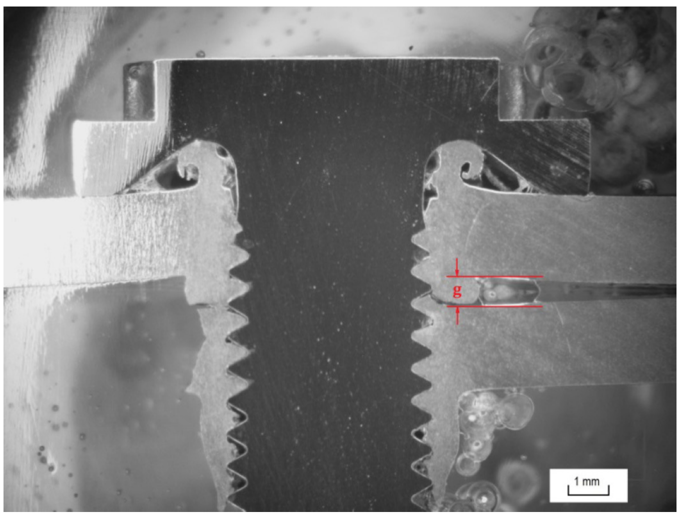

Figure 13. A micrograph of a failed FDS joint in a lap-shear specimen along the symmetry plane without clearance hole at the fatigue life of 59,413 cycles under a load range of 3,245 N (high-cycle loading conditions).

LIFE ESTIMATIONS FOR HIGH-CYCLE FATIGUE

The failure mode for FDS joints under high-cycle loading conditions are quite similar to those of self-piercing rivets and clinched joints in lap-shear specimens in Su et al. [5] where the structural stress solutions near a rigid inclusion in a lap-shear specimen were used to correlate the fatigue lives of the joints . The structural stress solutions were listed in Su et al. [5] and will not be repeated here. For the FDS joints with clearance hole, the structural stress solutions just follow the equations in Su et al. [5] with t_u replaced by t_l since the failure occurred in the lower sheet. For the FDS joints without clearance hole but with a gap g as marked in Figure 4, the structural stress solutions also follow the equations in Su et al. [5] with t_u replaced by t_l and $\widetilde{M}(=F(t_l+g/2)/(8b))$ for $(\sigma_{rr})_{COB}$ and $M(=F(t_l+g/2)/2)$ for $(\sigma_{rr})_{CEB}$. Here, the gap g is due to the extruded material from the FDS drilling process.

In order to estimate the fatigue lives, the geometric parameters for the rigid inclusion and for the specimen need to be specified. It should be mentioned that the micrographs shown in this paper are not exactly taken along the symmetry planes, although the effort has been made to be as close as possible to the symmetry plane. Figure 13 has the largest measurement of the mean radii of the screws in these micrographs. This indicates that the micrograph may be closest to the symmetry plane. The gap g is estimated to be 0.8 mm from the micrograph in Figure 13. The rigid inclusion radius a is taken as the mean radius of screw and is measured as 2.3 mm from Figure 13.

The fatigue crack appears to be initiated near the edge of the extruded material for the FDS joint without clearance hole as shown in Figure 13. Therefore, the location for the structural stress based on the rigid inclusion model for estimation of fatigue lives is selected at this location. The radial distance r for calculation of the structural stress is estimated as 3.5 mm from the micrograph in Figure 13. The fatigue crack for the FDS joint with clearance hole appears also to be initiated at some distance from the screw as shown in Figure 12. For simplicity, the radial distance r for calculation of the structural stress for estimation of fatigue lives is also taken as 3.5 mm. It should be mentioned that the lower sheet thickness t_l is 2 mm and the half specimen width b is 12.5 mm.

Based on the stress-life curve for AA6082-T6 [6], the fatigue life estimations based on the structural stress solutions under high-cycle loading conditions are shown in Figure 14. The details of the fatigue life estimations for the FDS joints will be presented in the future. The fatigue life estimations for the FDS joints with and without clearance hole (without and with gap) are reasonably in agreement with the corresponding experimental results for the given load ranges. As indicated from the structural stress solutions, the gap for the FDS joints without clearance hole gives larger structural stresses and therefore results in shorter fatigue lives. This general trend for the FDS joints with and without clearance hole (without and with gap) is in agreement with that of the experimental results.

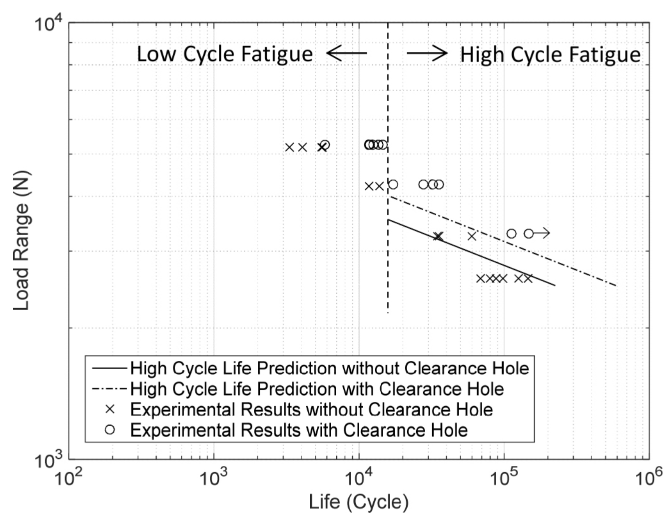

Figure 14. Experimental results and the fatigue estimations based on the structural stress under high-cycle loading conditions.

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CONCLUSIONS

The failure mode and fatigue behavior of flow drill screw (FDS) joints in lap-shear specimens of aluminum 6082-T6 sheets with and without clearance hole are investigated based on experiments and a structural stress fatigue life estimation model. Lap-shear specimens with FDS joints were tested under cyclic loading conditions. Optical micrographs show that the failure modes of the FDS joints in specimens with and without clearance hole are quite similar under cyclic loading conditions. The fatigue lives of the FDS joints in specimens with clearance hole are longer than those of the FDS joints in specimens without clearance hole for the given load ranges under cyclic loading conditions. A structural stress fatigue life estimation model is adopted to estimate the fatigue lives of the FDS joints in lap-shear specimens under high-cycle loading conditions. The closed-form structural stress solutions are based on the analytical solution for a plate with a rigid inclusion under a resultant shear load. The general trends of the fatigue life estimations are in agreement with those of the experimental results.

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