THE FATIGUE CHARACTERISTICS OF FRICTION STIR WELDED STIFFENED PANEL STRUCTURE

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In this paper, the FSW process is reviewed, and compared with other joining methods. In particular, the FSW process is considered as a manufacturing process for airframe structures. To this end a lap joint specimen was developed to represent the stiffened panel of an aircraft skin and its associated stiffener. The materials used in this test program were 2024-T3 as the skin and 7075-T6 as the stiffener. The skin and stiffener were joined using FSW.

In the test program the static strength of FSW stiffened panel structures fabricated from 2024-T3 and 7075-T6 were compared with values from the reference literature. In addition, 20 fatigue test specimens classified into 5 groups according to the existence of a tool pin hole and the welding sequence. The welding sequences considered were: Single Pass, Double Pass (Type I) and Double Pass (Type II). S-N curves, fatigue crack growth rate data and metallurgical analysis were investigated and presented for the five groups of FSW specimens.

1. Introduction

As a result of the high competition in the aerospace industry, many companies are trying to reduce manufacturing costs by making their parts simple and implementing sophisticated design for less labour costs. At the same time, major aircraft assembly companies want to improve structural efficiency and cost effectiveness for their airframe structures. Thus, many new technologies such as adapting advanced materials and improving manufacturing processes have been developed. In fact, some of new technologies are already implemented to get better cost effectiveness and structural performance. Friction stir welding (FSW) is a good example of a new manufacturing process because the welding speed is much higher than the conventional auto riveting machine and the costs per unit length are only a fraction of riveting costs.

In addition, FSW can weld some of 2xxx and 7xxx high strength aluminum series alloys, which were regarded as non-weldable materials, by other welding techniques such as fusion welding and laser welding. Since these high strength aluminum alloys are frequently used in airframe structures, FSW has high potential to replace riveting in many parts such as stiffened panel structures and thus contribute to the cost savings and structural efficiency dramatically. However, some doubt regarding the damage tolerance of welded components in airframes initiated the current study. To address the damage tolerance of welded aluminum components, this work will investigate how the structural performance of FSW components is influenced by defects and the tool entry and exit points.. This is part of a comprehensive program on the use of FSW in airframe structures including tensile tests, metallurgical studies, and fatigue tests.

Friction stir welding (FSW) is a solid state welding technique developed and patented by TWI Ltd., [1]. The process utilizes local friction heating to produce continuous weld seams by first plasticizing the material and then consolidating it along weld line. This is achieved by plunging a rotating, cylindrical, profiled tool with a shoulder and pin into the start of the joint line of the two workpieces and moving it slowly along the joint line, Figure 1, while maintaining downward pressure. The heat generated by friction causes the metal surrounding the rotating tool to plasticize and soften and as the tool moves forward this material is extruded/forged behind the tool where it cools and consolidates to form a solid bond. The quality of the weld seam is not symmetrical due to the rotation of the tool; where the tool translation and rotation have the same direction is called the advancing side and where the translation and rotation have opposite direction is called the retreating side of the weld. It has been observed that the advancing side of the weld is weaker than the retreating side due to the lack of material mixing which results in weld defects [2], [3]. In order to produce a full penetration butt weld joint the bottom of the tool need only penetrate close to the bottom of the workpiece. To make a lap-joint the tool must extend through to top sheet and part way into the lower sheet to produce the weld bond. The quality of the weld is a function of tool rotational speed, traverse speed and tool design.

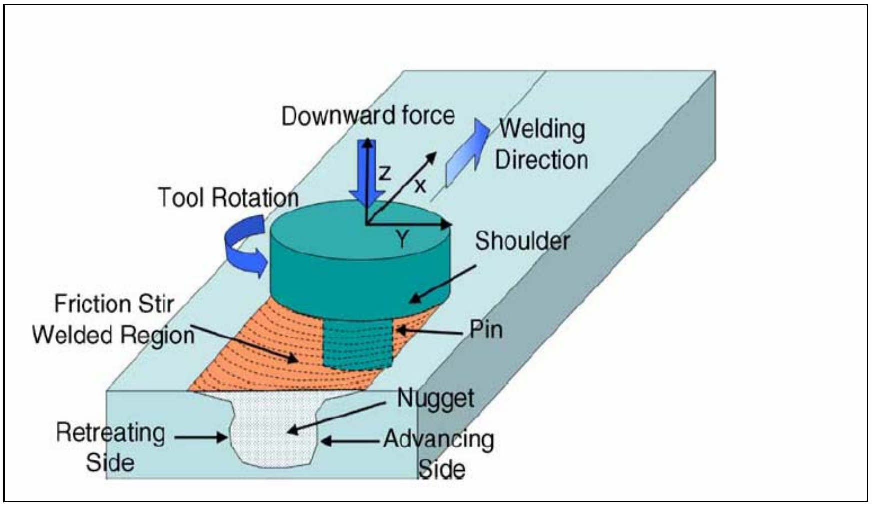


Figure 1. **Schematic drawing of friction stir welding [4]**

2. Materials and Test Specimens

In all the experiments performed a stiffened panel structure, representing a airframe structure, were manufactured from 2024-T3 aluminum with 2.311mm thickness representing the skin and 7075-T6 aluminum with 1.626mm thickness for the stiffener. FSW was used to join these two different aluminum materials. The chemical composition and mechanical properties of the materials are given in Table 1.

(a) The chemical composition of 2024-T3 and 7075-T6 aluminum

	Cu (%)	Mn (%)	Mg (%)	Cr (%)	Zn (%)
2024-T3	4.4	0.6	1.5	0	0
7075-T6	1.6	0	2.5	0.23	5.6

(b) The mechanical properties of 2024-T3 and 7075-T6 aluminum

	UTS (MPa)	TYS (MPa)	Elongation (%)	ultimate shear (MPa)	Elastic modulus (GPa)
2024-T3	435	290	15	251	72
7075-T6	540	470	9	312	71

TABLE 1. The chemical and mechanical properties of 2024-T3 and 7075-T6 aluminum (Reference[5])

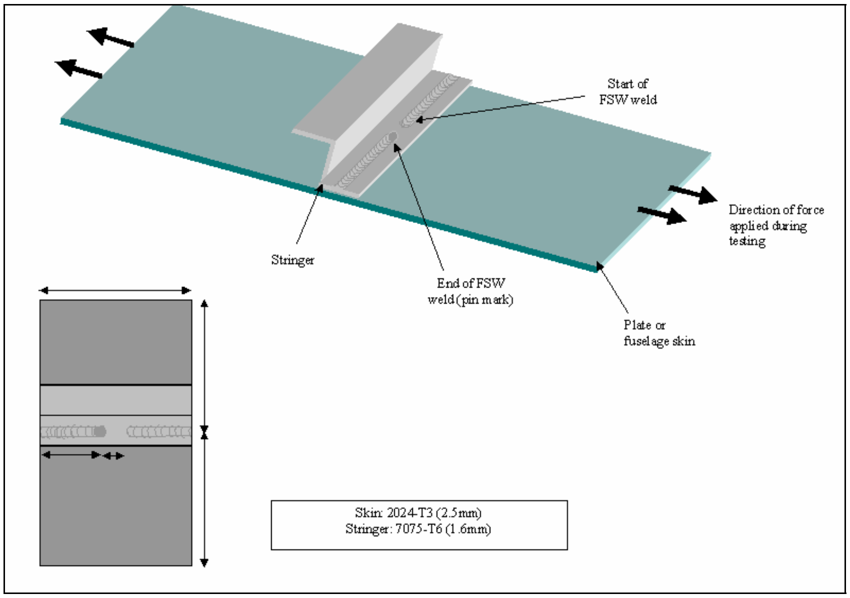


Figure 2. FSW test specimen configuration: (Courtesy NRC-IAR (Ottawa))

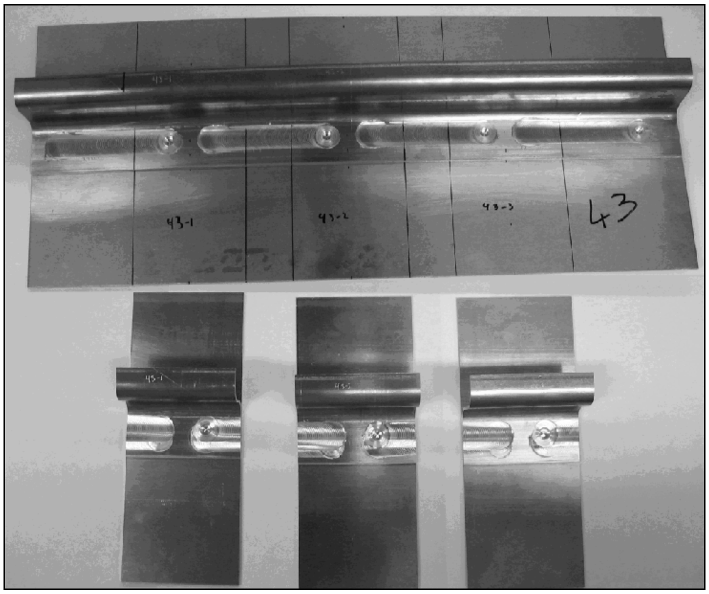


Figure 3. Specimens cut from original welded panel (Courtesy NRC-IAR (Ottawa))

The geometry of the test specimens are given in Figure 2, and were fabricated using a MTS ISTIR machine. The specimens were supplied by the National Research of Canada, Institute for Aerospace Research (NRC-IAR) and the welding parameters and process are described in [5] and [6]. A large stiffened panel was first friction stir welded and then the individual specimens were cut to a width of 76mm, Figure 3. In order to investigate the plunge-in of the pull-out of the FSW tool the weld was not continuous and the test specimens were cut so that there was a weld start and end point at the middle of each specimen. Also for comparison several specimens were produced with continuous welds, i.e. there was no weld start and stop point.

The series of specimens produced were categorized as follows:

(i) SP series - with a single pass weld and tool entry and exit points, Figure 4
(ii) SP-C series – with continuous weld
(iii) DP-C series – double pass with continuous weld
(iv) DP I and DP II series – double pass weld with tool entry and exit points, Figure 5.

Fig. 4. Single Pass (SP) specimen

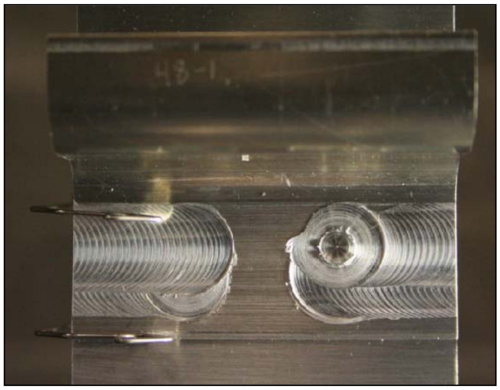


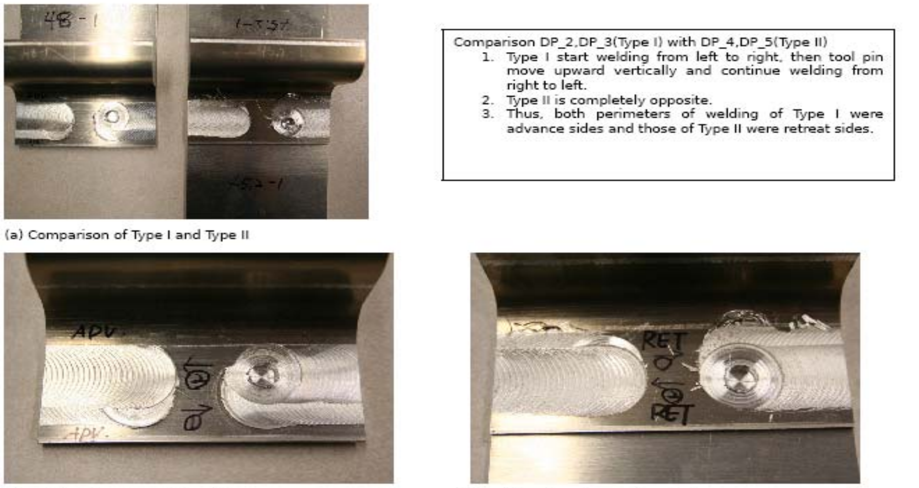
Fig. 5. Double Pass (DP) specimen (Type I)

The double pass (DP) specimens were designated as Type I and Type II as defined by the welding procedure, as shown in Figure 6. For the DP specimens Type I the welding traversed from left to right at the first welding pass and on the second pass the welding tool moved to the retreating side of the weld and traversed from right to left. For Type II DP specimens the second pass was completed from right to left after the tool had moved to the advancing side of the weld. In both cases the rotation of the tool pin is counterclockwise. Therefore, Type I specimens have advancing welds on both sides of the joint and Type II specimens have retreating welds at each side. The Type II specimens are considered to be relatively stronger than the Type I due to the increased mixing of material in the overlapped area and the wider weld area [2],[3].

3. Experimental Testing

All testing was carried out using an MTS hydraulic testing machine with a FlexTest SE Plus controller and Multipurpose Testware software. Prior to carrying out the fatigue tests, the static tensile strength of several FSW specimens were measured. The loads were applied to the 2024-T3 skin material, with the 7075-T6 stiffener carrying no load, and the tests were carried out using strain control up to failure of the specimens.

The results of these tests for a SP and DP Type I specimens both with tool pin hole are given in Table 2 and plotted in Figure 7. The FSW specimens are compared with 2024-T3 base material. From the tests it can be seen that the maximum tensile stress of FSW SP and DP specimens are about 100 MPa lower than that of 2024-T3 base material which is a result of the tool pin-hole and the existence of weld defects. Also the welding efficiency, defined as the ratio of the ultimate tensile strength of the FSW joint to that of the base (parent) material, (i.e. the tensile stress for 2024-T3 base material) is 77% and 80% for the SP for DP specimens respectively. It should also be noted that the overall maximum elongations for a SP and a DP weld specimens are greatly reduced as compared to 2024-T3 base material as a result of the low elongation of the welding nugget.



Comparison DP_2,DP_3(Type I) with DP_4,DP_5(Type II)

1. Type I start welding from left to right, then tool pin move upward vertically and continue welding from right to left.
2. Type II is completely opposite.
3. Thus, both perimeters of welding of Type I were advance sides and those of Type II were retreat sides.

(a) Comparison of Type I and Type II

(b)Welding directions and vertical movement sequence for Type I

(c) Welding directions and vertical movement sequence for Type II

Figure 6. Double Pass Type I and Type II Welding Procedure

	SP with tool pin hole	**DP(Type I) with tool pin hole**	**2024-T3 Material**
Yield stress	325 MPa	325 MPa	330 MPa
Tensile Strength	370.5 MPa	383.3 MPa	480 MPa
Max.Elongation	1.5 %	1.8 %	19 %

TABLE 2. The mechanical properties between SP and DP(Type I) FSW specimens and 2024-T3 specimen

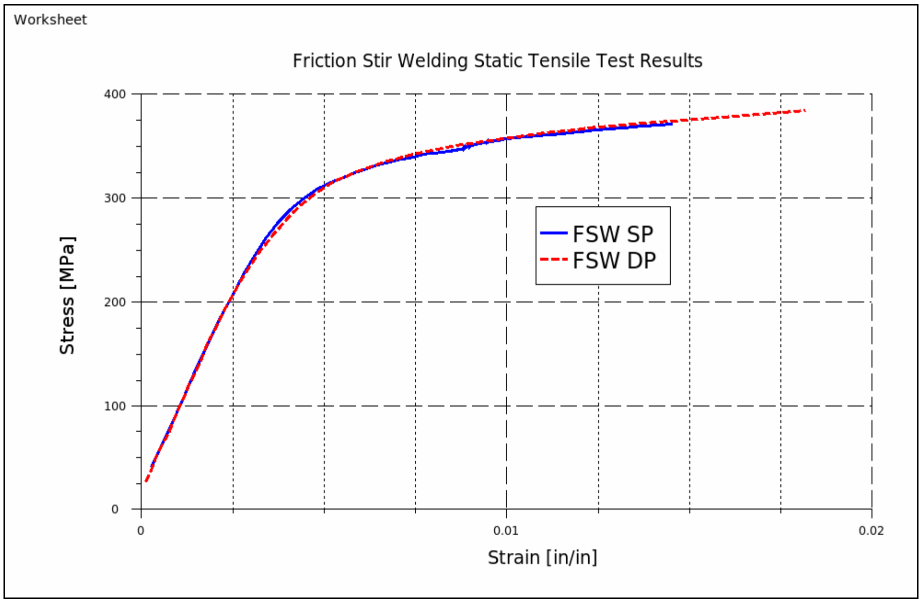


Figure 7. Static Tensile Test Results for FSW SP and DP Specimens

The fatigue tests were carried out at a stress ratio of R = 0.1, a frequency of 5 Hz and load levels of 10, 12, 15 and 20 ksi (69, 82, 103 and 107 MPa). Prior to test the weld area and the reverse side of the specimen were cleaned and slightly polished so that the crack initiation and propagation could be observed using a microscope and digital meter. The tests were stopped periodically to examine the weld area for crack initiation and thereafter for measurement of the propagating cracks. The SN results for all the specimen series are given in Figures 8 to 10. In addition, the failed specimens were examined by scanning electron microscopy (SEM) to view the crack development at the tool plunge-in and pull-out region.

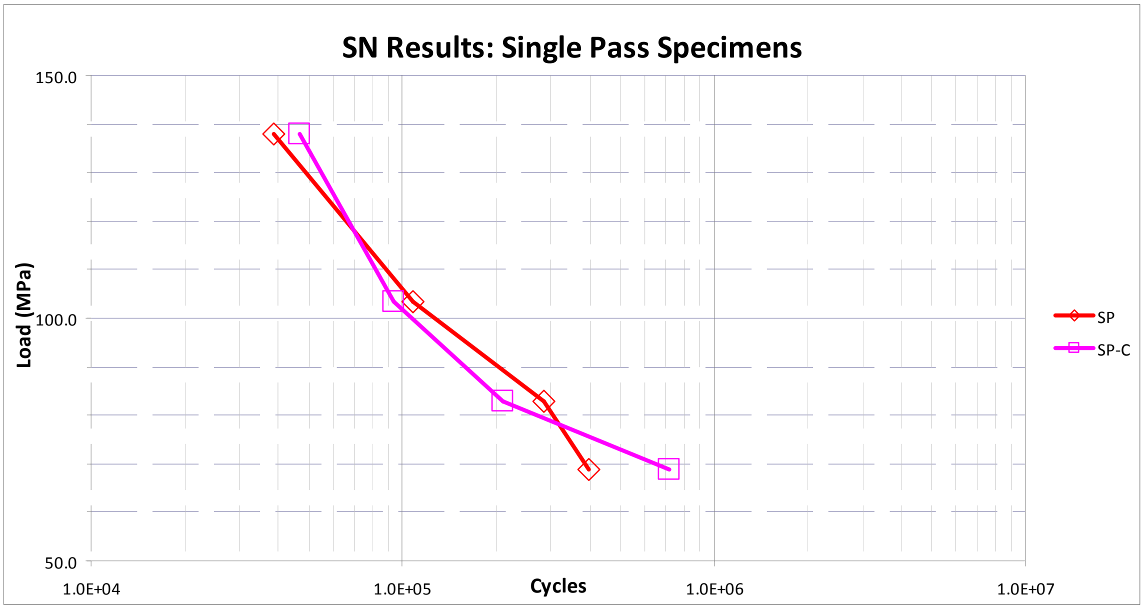


Figure 8. S-N results for Single Pass FSW Specimens

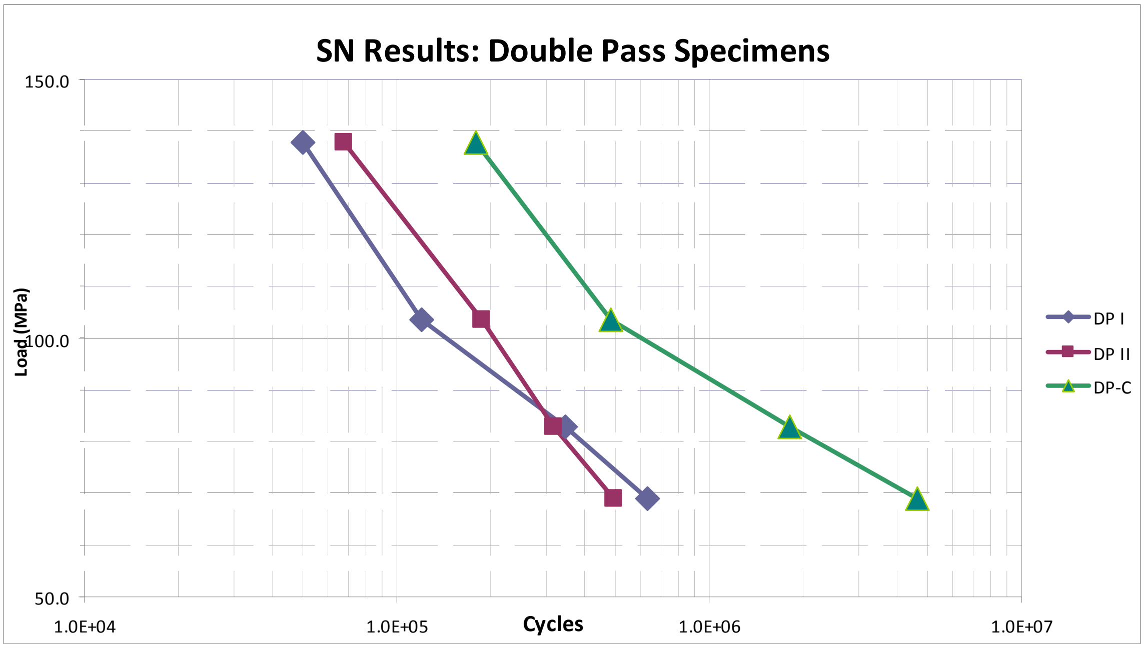


Figure 9. S-N results for Double Pass FSW Specimens

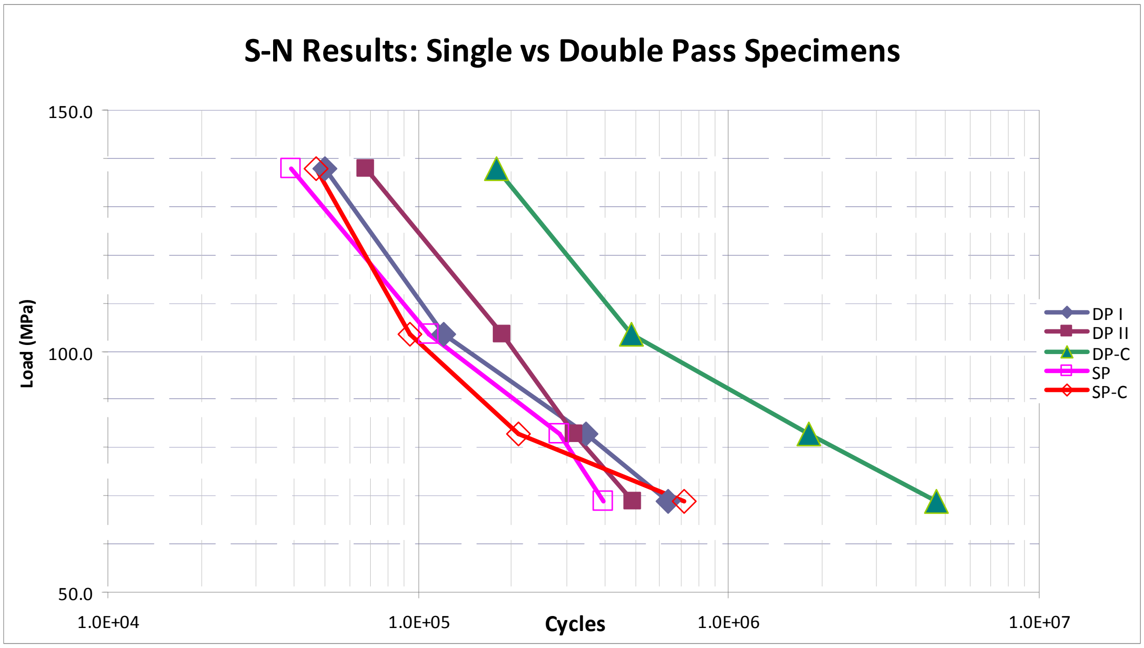
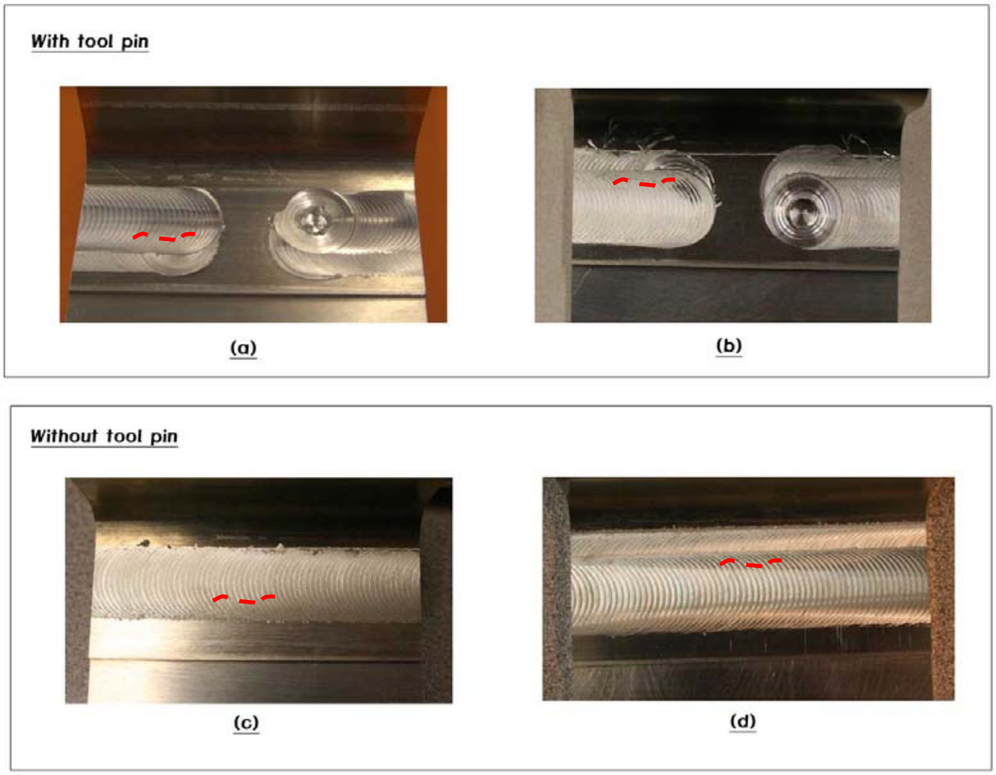


Figure 10. Comparison of Single and Double Pass FSW Specimens

4. Discussion of Results

With reference to Figures 8-10 it can be seen that the different FSW configurations had an effect on the fatigue lives. The DP Type II specimens had superior fatigue lives as compared to other groups of specimens. In fact the DP Type II specimen tested at 10 ksi (69 MPa) was a run-out. Also, in general continuous weld specimens had better lives than the respective specimens with tool pin holes. The average fatigue life from best to worst was DP-C, DP-II, DP-I, SP-C and SP. An indication of the position of crack initiation on several representative continuous and non-continuous weld specimens are shown in Figure 11, as observed from the backside of the specimens. In general, for the specimens with tool pin holes the cracks initiated at the exit hole or at the pin hole which was filled by the second weld pass. In continuous weld specimens, cracks initiated at defects at the interface between the 2024-T3 and 7075-T6 materials. An SEM photograph of the fracture surface of a DP Type I specimen with tool pin hole tested at 20 ksi (138 MPa) is shown in Figure 12 and illustrates that both the 1st tool pin pullout position and the 2nd tool pin pullout position were crack initiators. However, the surface crack of the 1st tool pin pullout position on the 2024-T3 the bottom of the weld was detected and propagated to the fracture, while the 2nd tool pin pullout position did not fully develop as a surface crack. Also, the cracks in this specimen propagated as several independent surface cracks at first and then coalesced into one large surface crack. However, SEM photographs of fracture surfaces also showed that DP specimens had much less welding defects than SP specimens.



(a) DP (Type I) with tool pin hole
(b) DP (Type II) with tool pin hole
(c) SP without tool pin hole
(d) DP (Type II) without tool pin hole

Figure 11. Crack initiation positions in specimens with and without tool pin holes

The surface crack growth for all specimens was measured by an optical microscope with a digital meter which has an accuracy of 0.01 mm. All measurements were recorded when the maximum load was applied to the specimen because the crack could be clearly seen at the maximum crack opening. Half of the total crack length was used for the calculation of the surface crack propagation rate. Also, the primary crack, which was normally the initial crack, was used to calculate the surface crack propagation rate in case of multiple surface cracks in DP (both Type I and II) with tool pin hole.

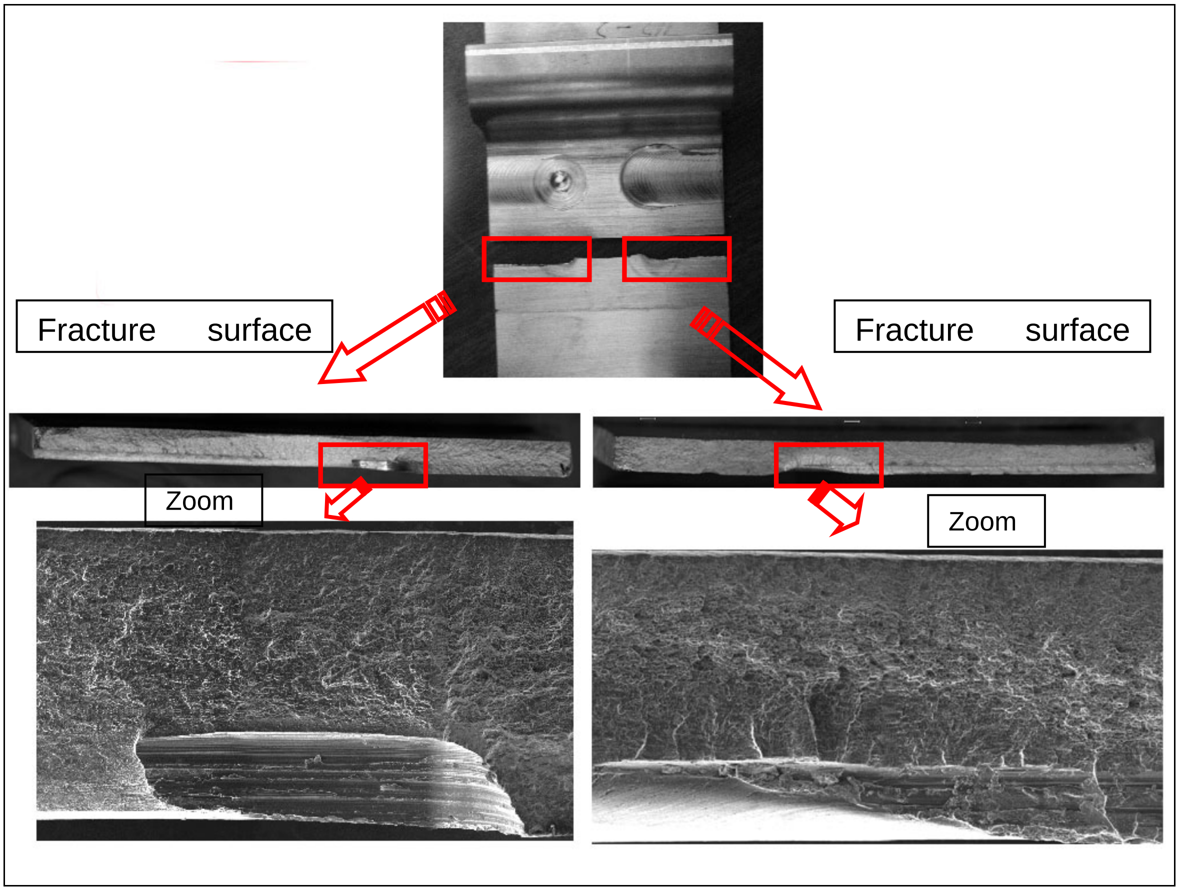


Figure 12. **The SEM pictures of a DP (Type I) specimen with tool pin hole tested at 20 ksi.**

The crack propagation of 17 specimens was measured and that of two SP-C specimens could not be measured since the crack propagation was too fast to be measured while one DP-C specimen was a run-out condition . Typical plots of crack growth for several FSW configurations are shown in Figure 13 for tests carried out at 12 ksi (82 MPa). Additional plot are given in [7].

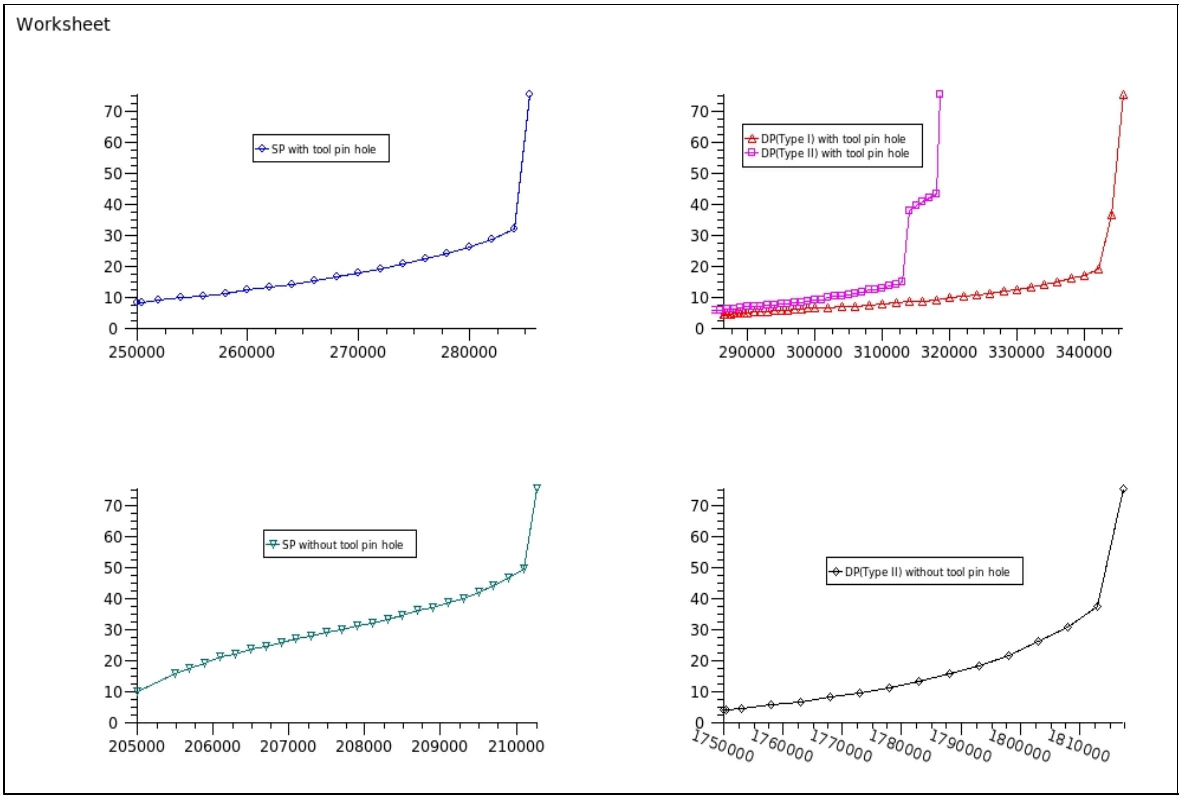


Figure. 13 . **The plot of crack length (mm) vs cycles for fatigue tests at 82 MPa (12 ksi)**

5. Conclusions

In this study, the fatigue tests of the 5 series of FSW stiffened panel specimens were carried out. Fatigue life and crack initiation positions and propagation mechanisms were studied using SEM pictures.

The SP specimens with and without tool pin hole showed a high occurrance of initial defects which developed during the FSW process. These defects acted as crack initiations and thus reduced the fatigue lives of SP specimens. Though the tensile strength of SP specimens in the static strength test was similar to that of DP (Type I) specimen, the fatigue life of SP specimens was shorter than that of DP specimens since the welding area of these specimens is smaller than that of DP specimens and the material mixing in the weld area is less resulting in more weld defects.

The two different types of DP (Type I, II) specimens with tool pin hole showed a similar result regarding the fatigue life since the crack initiation developed first in the 1st tool pin pullout. Also, a crack developed much later at the 2nd tool pin pullout position or in some cases was not detected. However, the tensile strength of DP(Type II) specimen is better than that of DP(Type I) specimen since the micro structural constitution of DP(Type I) specimen is weaker than that of DP(Type II) specimen due to the weak end points of both advancing sides in DP(Type I) specimen.

The DP (Type II) specimens with continuous weld showed outstanding fatigue lives since they did not include the tool pin hole which was a major factor in initiating a crack. In addition, the increased welding area of DP (double pass) welding improved the physical fatigue resistance and the second weld pass in the DP specimen appeared to reduce the microstructure defects which resulted in crack initiation and eventual failure of the specimen.

6. Acknowledgement

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7. References

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