Finite Element and Experimental Study of Crack Paths in 2198-T8 Offset Hole SE(T) Plates with FSW Jointed Pad-up under Fatigue Load

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ABSTRACT *Crack paths in friction stir welded SE(T) plates contain an offset hole were investigated. Fatigue tests were performed with and without friction stir weld in a range of samples, and then crack paths and fatigue crack growth rates were compared. In order to study the effect of offset hole on crack trajectory, crack paths were studied and compared after the offset hole made on a range of samples with and without weld. It is shown that crack grow rates are slower with weld than without weld. The position of hole has a big effect on crack path. Program was developed to input the residual stress distribution into finite element model by ABAQUS, crack paths were predicted to understand the test findings. These predictions were compared with experimental data gathered on crack deviation behaviour and used to assess the accuracy of the maximum tangential stress criterion for prediction of crack deviation behaviour.*
Keywords*: Friction stir weld; FEA; Crack path; Offset hole; Residual stress*

INTRODUCTION

Friction stir welding (FSW) is being explored as a potential method for aircraft construction where it can be used to replace mechanical fastening or riveting. In order to ensure damage tolerance of the aircraft it is necessary to understand how weld macrostructure and residual stress field contribute to determining the crack path and crack trajectory of propagating fatigue cracks within welded structures. In addition to parameters associated with the weld itself there are design related variables which may influence the trajectory adopted by the crack. These include changes in local section thickness (called pad-ups) at the site of the weld to reduce local stress to match the reduced strength of the welded region.

Residual stress is one important factor influencing crack growth in welded structures. In order to study the effect of residual stress on crack growth rate, Pouget [1] studied residual stress and microstructure effects on fatigue crack growth in 2050 friction stir welds. Bussu et al. [2] studied the role of residual stress and heat affected zone properties on fatigue crack propagation in friction stir welded 2024-T351 aluminium joints, and found the residual stress is responsible for differences in fatigue crack growth rate. Seongjin et al. [3] studied fatigue crack propagation behaviour of friction stir welded 6061-T6 C(T) samples. Anne-Laure et al. [4] investigated role of residual stress on FCP of FSW 6056-T78, also found that residual stress has an important impact on FCP. John et al. [5] studied the effects of residual stress on near threshold fatigue crack growth in friction stir welded 7050 T7451 for different sample geometries. Dalle Donne et al. [6, 7] also studied residual stress due to friction stir welding and its effect on fatigue crack growth. Dalle Donne's study included two different configurations: crack growth parallel and perpendicular to the weld. The work included both friction stir welded alloy 2024 and alloy 6013, and an apparent improvement of the fatigue properties in the welded material was observed. They showed that the variations observed in fatigue crack growth rates in the welded material can be linked to the presence of residual stresses.

About crack growing under mixed mode I/II loading, Rubinstein studied the mechanic of crack paths and the effect of the hole position on crack paths, and analyzed the possible perturbations of the crack paths [8]. D. Fersini used FRANC2D to calculate the mixed load crack growth of FSW lap joints [9]. Matthew approximate curved crack paths under mixed mode loading [10]. J. Qian and Fatemi made a literature review about mixed mode fatigue crack growth before 1996 [11].

In this research, four different pad-up geometries, contained within a single edge notched specimen (SE(T)) design in 2198-T8 aluminium, were studied to determine crack deviation behaviour. The effect of residual stress on crack paths was also studied. To explore the effect of geometry induced local stress gradients on crack trajectory, samples contained weld residual stress fields and also a stress concentration in the form of an open hole, which also provided a local stress gradient. Crack behaviour was studied both experimentally and via finite element simulations of the sample designs.

1. SAMPLE PREPARATION AND EXPERIMENT TECHNIQUES

12 ESE(T) samples were used to test 1.6 mm 2198-T8 aluminium sheet with and without offset hole. Crack was parallel to weld as shown in Fig.1. Dimensions of pad-up were as shown in Fig.1. Fatigue crack growth tests were performed on all samples according to procedures in ASTM E647, in laboratory air at $R = 0.1$, with a load frequency of 10Hz. Stress intensity factors for all specimens were calculated using the expressions recommended in ASTM E647. An automated optical video system was used to monitor crack paths for all samples. Crack lengths could be monitored to an accuracy of 0.1mm.

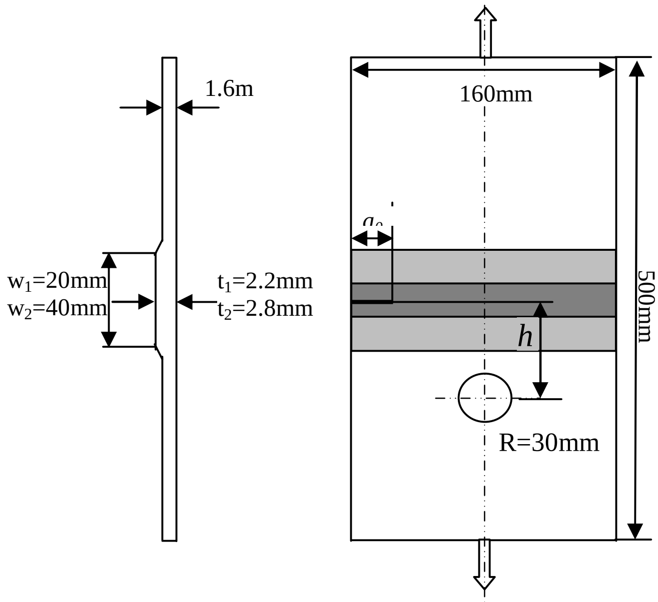

Fig.1 Geometry of the offset hole SE(T) specimen

2. EXPERIMENTAL RESULTS

In order to study the effect of weld and parameter weld on crack growth and crack paths, samples ware tested without and with the hole.

2.1 Samples Without The Hole

2.1.1 The Effect of Weld on Crack Growth Rate

Fig 2 shows fatigue crack growth rates da/dN as a function of $\Delta K_{applied}$ in the pad-up 20mmx2.2mm FSW samples, one without weld, and another one with weld. Both results are compared with parent material. With the weld, crack grows slower than without the weld and parent material.

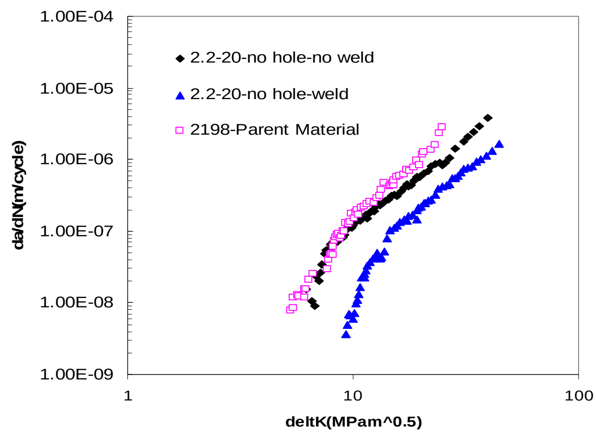

Fig 2 Crack growth rates versus ΔK for the same pad-up (20x2.2), R = 0.1

2.1.2 The Effect of Pad-up Thickness and Width on Crack Growth Rate

In Fig 3, crack growth rates measured in samples with different pad-up sizes are compared with parent material. For the samples with thickness 2.2mm, but different widths 40mm and 20mm, crack growth rates are similar, but for narrow one 20mm, crack grows a little faster than in the wider one 40mm. For the samples with the same width, different thickness (2.2mm and 2.8mm), fatigue crack grows faster in the thicker sample. This results show that thin and wide pad-up is better than thick and narrow one. In Fig 4, crack lengths versus cycles were shown for three different pad-up size samples. To grow the same crack length, wider and thinner samples need more cycles than narrow and thick samples.

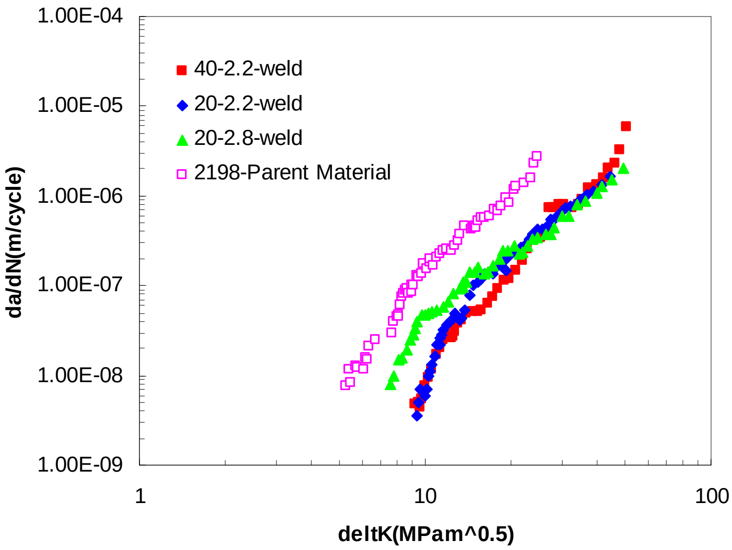

Fig 3 Crack growth rates versus ΔK for the different padup sizes

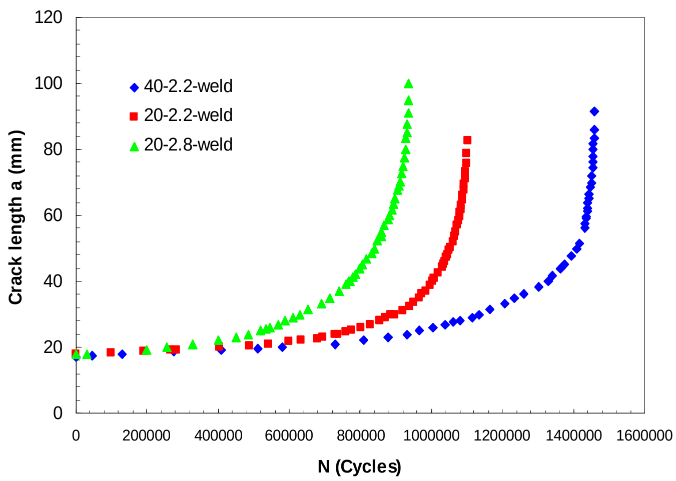

Fig 4 Crack length versus cycle for the different padup sizes

2.2 Samples With the Hole

In samples cutting a hole, the stress concentrates around the hole lead to crack deviation from the perpendicular to the hole side, so crack change from mode I into mixed mode of mode I and mode II. Then the crack length split into two (see Fig 5), a_{Ieff} and a_{IIeff}.

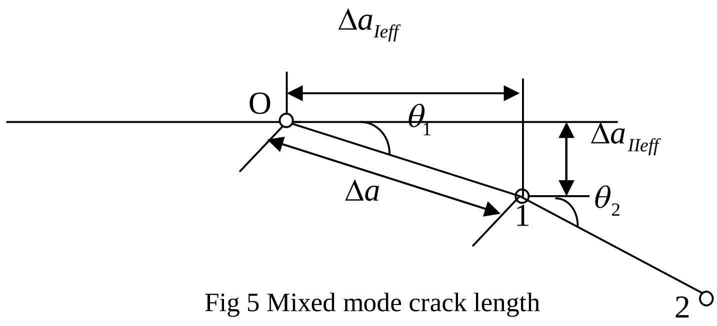

Fig 5 Mixed mode crack length

2.2.1 The Effect of Weld on Crack Growth Rate and Crack Path

Tests were performed at $h = 63mm$, crack didn't deviate at all, then the hole position change to $h = 51mm$. Fig 6 shows crack growth rates of effective a_I in pad-up size 2.8mmx40mm samples with the hole at $h = 51mm$. For the sample without weld, crack growth rate is bigger than parent material because the hole made on leads to local stress concentrating around it.

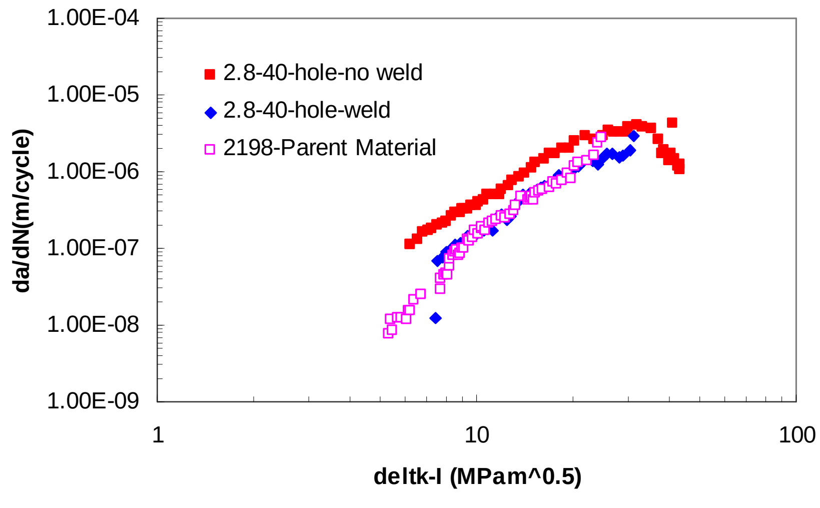

Fig 6 Crack growth rates versus ΔK for pad-up 2.8x40

In Fig.7, both cracks went into the hole and crack paths were compared. Effective crack length a_I was decreased in the welded sample, so crack went into the hole earlier. For the friction stir welded samples, it is well known that residual stress distribution feature is: the double peak residual stress along the weld direction is bigger, while residual stress perpendicular weld is smaller. The reason is when crack deviate from mode I into mixed mode crack, the double peak residual stress aggregates crack growth in mode II.

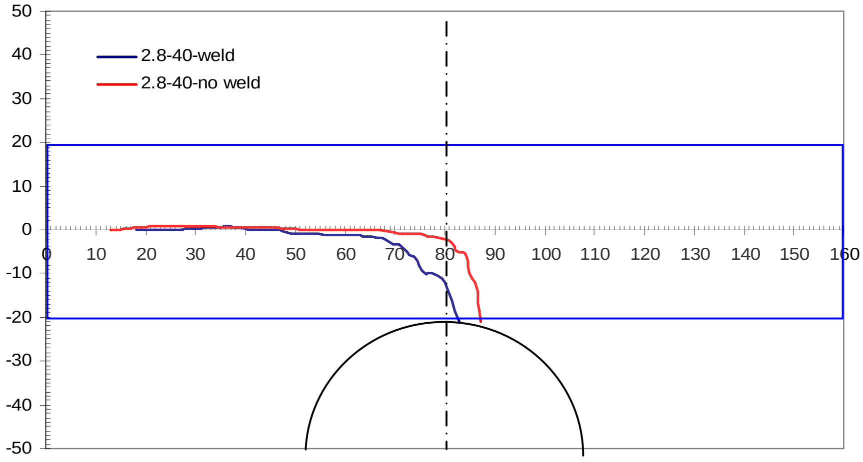

Fig 7 The effect of weld on crack path with the hole

2.2.2 The Effect of Pad-up Parameter on Crack Growth Rate and Crack Path

For different pad-up size welded samples, crack growth rates of effective a_I were compared with each other and parent material in Fig. 8. Compared with crack growth rates shown in Fig3, crack growth rates increase for all samples and the effect of pad-up sizes become smaller. Even this, the effect of pad-up thickness still can be pointed out: crack grows slower with thin pad-up (2.2mmx40mm) than thick pad-up (2.8mmx40mm), similar to the results without the hole on. Crack paths of different pad-up size were distributed in Fig. 9.

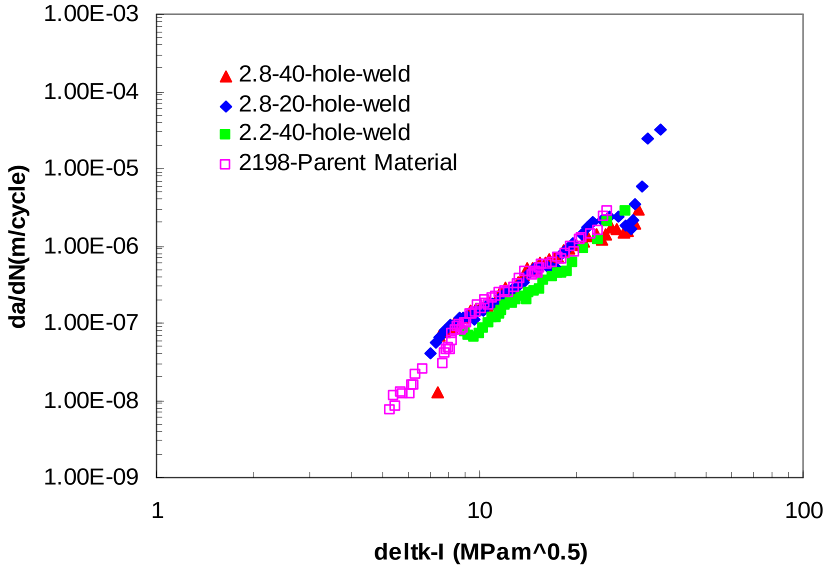

Fig 8 Crack growth rates versus ΔK for the different pad-up sizes

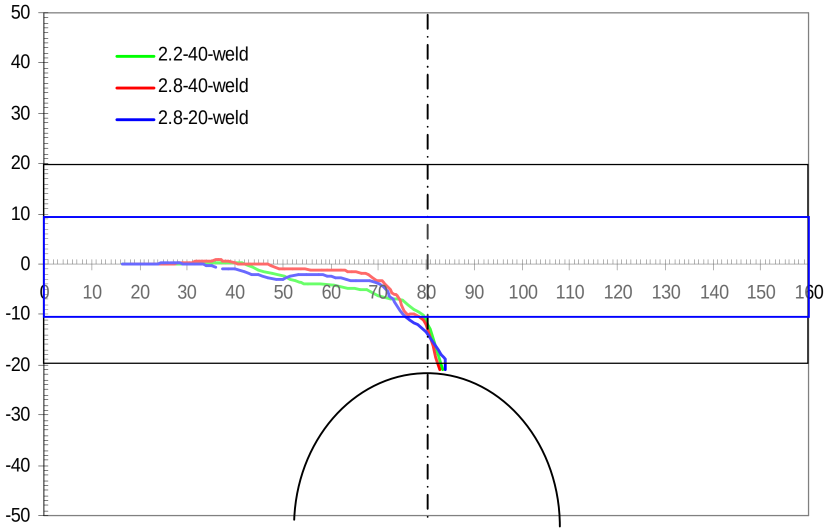

Fig. 9 The effect of pad-up parameter on crack path with the hole

3. PREDICTIONS OF FINITIE ELEMENT ANALYSIS

A 2D Finite element model of the sample was built then meshed with 4-node quadrilateral elements in ABAQUS. The maximum tangential stress criterion was used to predict the crack path. The SIGINI code was used to build a subroutine to input example residual stress profiles into the models. The effect of hole position and residual stress on crack paths was investigated (see Fig.10) with the same pad-up size at 2.8mmx40mm. For $h = 63mm$, crack just get a little deviation from centre line, doesn't go into the hole, while $h = 51mm$, crack goes into the hole.

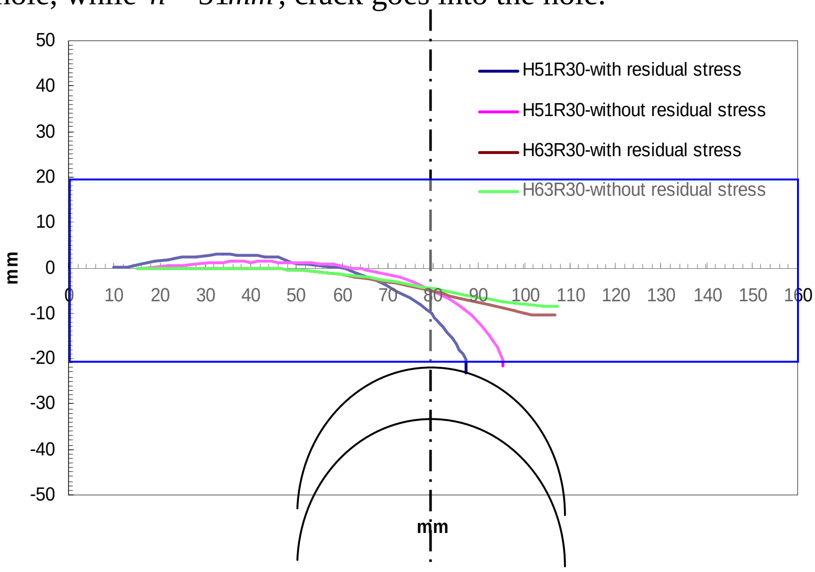

Fig.10 Predicted crack paths by FEA

The numerical calculation results so far show the distance between hole and specimen centre influences crack path significantly, and determines whether a crack grows into the hole or not. Weld residual stresses do not change crack trajectory appreciably, only the effective crack length at deviation is modified slightly.

4. CONCLUSIONS

The experiment results so far show that thick, narrow pad-up geometries increase the tendency to crack deviation; weld residual stresses change the effective crack length at deviation into the hole, and do not change crack trajectory appreciably. The FEA results agree well with the experiment results.

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