Observations of Exceptional Fatigue Crack Growth Behaviour in Friction Stir Welded Aluminium

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ABSTRACT. *This paper describes results from Fatigue Crack Growth (FCG) tests on Friction Stir (FS) welded aluminium alloys. Main focus is on the crack paths which, in some cases, is dramatically changed. The most extreme case is of a fatigue crack which rotates 90º upwards and continues to growth in that direction parallel to the applied load. To visualise the influence of the material behaviour in the FS Weld on the FCG properties, Digital Image Correlation (DIC) was used during the tests to visualise the strain field around the crack tip. From the strain fields, the size and geometry of the plastic zone is obtained, which can help to understand how the yield strength and the residual stresses in the FS weld influence the FCG behaviour.*

INTRODUCTION

Friction Stir (FS) welding is a relatively young joining technology with a high potential for the aerospace and other industries. Since FS welding is a solid-state process, it is possible to weld high strength aluminium alloys like AA2024 and AA7075. To use FS welding to manufacture an airworthy and damage tolerant structure, the fatigue behaviour must be fully understood. In previous Fatigue Initiation (FI) tests on FS welded AA2024-T3, remarkable Fatigue Crack Growth (FCG) behaviour was observed [1]. In the test configuration with the FS weld orientation under 45º with respect to the applied load, the FCG direction was changed dramatically when the crack enter the FS weld. However, the FI specimens were dedicated for initiation and not for FCG. Therefore, dedicated FCG centre crack specimens were subsequently tested to reproduce the unusual FCG behaviour.

Remarkable FCG behaviour was observed in various FS weld configurations in centre cracked fatigue specimens. This behaviour includes changes in crack growth direction whereby the mode I FCG changes into mode II FCG. Besides, the measured FCG rates are dependent on the crack tip location in the FS weld.

Numerous studies have tried to explain the FCG behaviour based on the local microstructure in the FS weld. In this paper the objective is to explain the FCG behaviour based on the macro mechanical behaviour of the FS weld. It is believed that the yield strength and the residual stresses in the FS weld influence the strain field in front of the crack tip. This means that the difference between the FCG behaviour in an

FS weld and in the base material is only a function of the yield strength and the residual stress. This implies that it is possible to use base material FCG properties to predict the FCG properties in an FS weld.

This theory does not account for the micro structure in the FS weld explicitly, but off course the micro structure is implicit taken into account through the yield strength.

This paper describes and discusses the results obtained from several FCG tests on different FS weld configurations, i.e. FS welds under an angle of 0º, 45º and 90º with respect to the applied load. To reveal the strain field, a new method was applied using Digital Image Correlation (DIC) during the fatigue test.

EXPERIMENTAL

Friction stir welds

Three aluminium alloys (AA2024-T3, AA7075-T6 and AA6013-T4) were used for this research, in both welded and un-welded (base material) condition. Welding was performed at EADS in Munich with an ESAB FS welding machine using respectively for AA2024-T3, AA7075-T6 and AA6013-T4, a welding speed of 350, 300 and 1000 rpm, a rotational speed of 550, 280 and 1500 rpm and a force of 19, 18 and 14 kN. A tool (Figure 1a) with a shoulder and pin diameter of respectively 13 and 5 mm was used for all three alloys with a tool angle of $\alpha = 2°$. Due to the rotation of the FSW tool, the process is a-symmetric with at one side a higher speed difference between the tool and the material, the Advancing Side (AS), than the other side, the Retreating Side (RS) (Figure 1a).

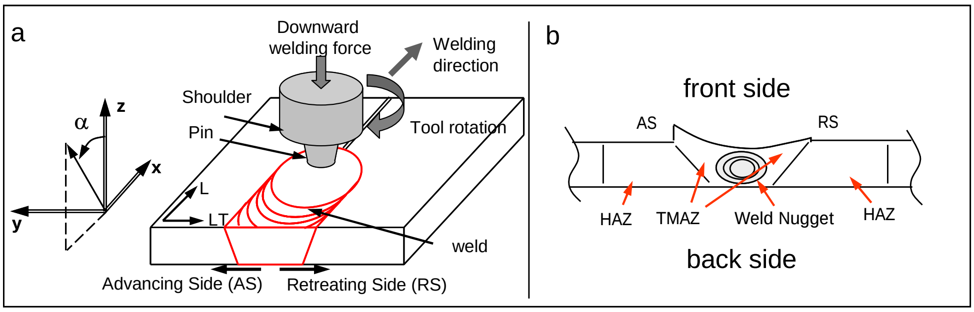

Figure 1, a: FS welding process, b: cross-section of resulting FS weld

As result of welding, the microstructure in and around the weld is changed resulting in three zones with a different thermodynamic and/or mechanical history (Figure 1b) [2-4] [5,6]. FS welding affects the yield strength, but this effect is highly dependent on the strengthening mechanism of the base material and the thermodynamic and mechanical processes during FS welding. The local yield strength for the FS welds used in this research were measured in a previous study [7] (Figure 2). Important to note is that the yield strength profiles of the three alloys are different due to the different strengthening mechanisms in the alloys and thus a varying influence of FS welding.

FS welding introduces residual stresses of significant magnitudes. For the FS welds used in this research, these stresses have been measured using X-ray diffraction technology [7]. The residual stresses have an anisotropic character, i.e. high residual stresses parallel to the weld (Figure 2), and low stresses perpendicular to the weld (not shown here).

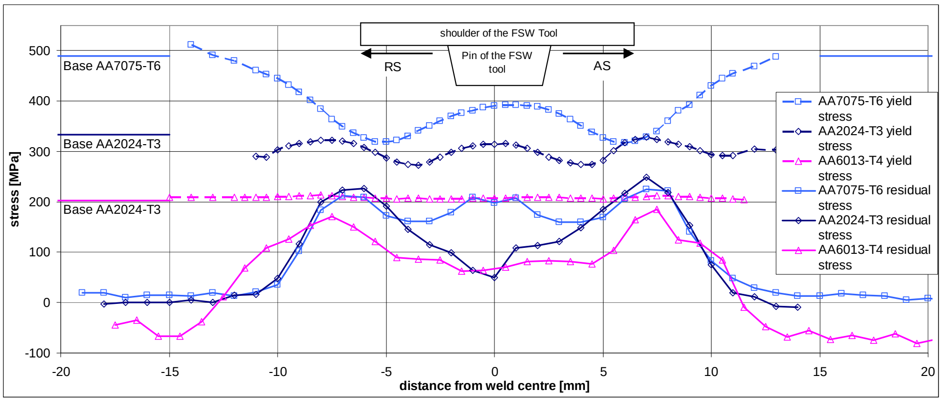

Figure 2, Yield strength profiles and residual stress profiles of FS welded materials

Fatigue crack growth specimens

For this research centre cracked fatigue specimens were used containing a hole (diameter 3 mm) with a manually made saw cut at one or two sides, depending on the test configuration (see Table 1). To evaluate the results, equivalent tests were performed on base material specimens. The material for those reference tests was obtained from the same sheets from which the welded specimens were taken.

The surfaces of the FS welds were machined and ground up to P1000, to remove the typical residual FS weld surface. This process reduced the thickness of the specimens 0.1 to 0.2 mm. All tests were performed in the 6 kN hydraulic fatigue test machine at the Delft Aerospace Structures & Materials Laboratory. The tests were conducted at 10 Hz with an applied stress amplitude of 60 MPa and a stress ratio R = 0.1.

Explanation of test configuration and expectations

The choice for the different FS weld configurations and the locations of the initial centre cracks in the specimens (Table 1), i.e. distance to the weld centre, is based upon the yield strength and residual stress profiles (Figure 2) and previous studies [1,11].

Because in some specimen the FS weld is at one side of the hole, the saw cut is only made at one side of the hole, resulting in asymmetric FCG. The configurations are chosen such that the fatigue properties in some specimens are only affected by the residual stress or the yield strength, and in other specimens are affected by both.

In the 90º specimen configuration the fatigue properties are only affected by the yield strength because the residual stresses are oriented parallel to the crack. Regions with high yield strength lead to small plastic zones and thus limited crack closure, which should result in higher FCG rates compared to the base material, visa versa low yield strength should lead to lower FCG rates. Typical locations in the yield profiles (Figure 2) were chosen for the hole in FS welded AA2024-T3 and AA7075-T6 (Table 1).

For the 0º configuration no significant change of crack path is expected, because the residual stresses are parallel to the applied load and do not lead to a rotation of the principle stress at the crack tip. Nevertheless, a change in FCG rate is expected because the residual stress adds up to the applied load. Interesting for this configuration is the comparison between the FCG rates in AA7075-T6 and AA6013-T4, because the latter material has no change in yield strength in the FS weld, but only a residual stress field.

The 45º configuration was expected to show changes in the crack path because the residual stress should result in a rotation of the principle stress and thus the orientation of the crack path. Moreover, the yield strength profiles of the FS welds will change the orientation of the plastic zones and thus influence the crack path orientation.

Table 1, configurations of specimens

Material:	Configuration:	Distance hole to weld centre [mm]:	Saw cut:
AA2024-T3	45º FS weld	8.3 (for all)	1-side
	90º FS weld	0.0; 3.0; 6.5; 6.5	2-side
AA7075-T6	0º FS weld	21.6; 16.6	1-side
	45º FS weld	8.3 (for all)	1-side
	90º FS weld	7.0; 10.0	2-side
AA6013-T4	0º FS weld	19.0; 10.9	1-side

Digital image correlation

To obtain the strain field around the crack tip, (DIC) was used [8,9]. The software to process the images was developed by the author [10]. The images of 1600 by 1200 pixels were captured at certain fatigue life intervals, using a CCD camera which was positioned in front of the specimen and aligned perpendicular to the specimen’s surface. To obtain a high accuracy (large amount of pixels/mm^2) but also a large measurement area, a grid of images were taken with a small overlap using an x-y-z controlled rack. The reference image was taken at a load of 1 kN, while all the subsequent images were taken at the maximum fatigue load. The measured strains were corrected afterwards for the applied load in the reference image.

From the deformation measured in the images, the strains in two directions were obtained, i.e. x- and y-strain. For this research only the y-strain is of interest, because it is oriented in the direction of the applied load. To obtain the strain in the images a grid was used with an initial distance between the grid points of 60 pixels (L_0). The strains are calculated for each image individually after which the images and the strain data are fitted together to obtain the full measurement area.

RESULTS

The most interesting observations made during this study are presented in this chapter.

90º configuration specimens

In the 90º configuration the FCG rates are higher in the regions where the yield strength is small and lower in the regions with a higher yield strength. The magnitude of the yield strength is in most cases confirmed with the size of the plastic zone. Only at 6.5 mm where the plastic zone is larger than the base material while the FCG rates are increased. However, the geometry of the plastic zone observed in this specimen was highly asymmetric with one butterfly wing much larger than the other. Furthermore, most specimens did not show a significant change of path towards a nearby region with higher or lower yield strength.

0º configuration specimens

In the 0º configuration the FCG rate is changed in the FS welded AA7075-T6 when the crack enters the residual stress field and the area with reduced yields strength. The crack path is mostly unchanged except in one of the two specimens where the crack followed a circular path which has the same geometry as the circular onion ring structure in the nugget. This behaviour was only found at the front side of the FS weld.

AA6013-T4 did show a much lower change in FCG rates than AA7075-T6 and no change in crack paths.

45º configuration specimens

Figure 3 and Figure 4 show the crack paths found in two specimens in which the FS weld was oriented 45º with respect to the load. At certain crack lengths along the crack path, two contours are plotted corresponding to these crack lengths. Each contour represent a constant strain level, in this case the engineering yield strain of AA7075-T6. One contour is obtained from the strain data from the test for which the crack path is plotted. The other contour at each crack length is obtained from reference test on base material (AA7075-T6) at equivalent crack length.

The circles plotted at the different crack lengths, represent the theoretical plastic zone size, belonging to that crack length, calculated with the theory from Irwin and Dugdale.

The grid points used in the DIC to calculate the strain are positioned at a certain distance around the crack path. If the plastic zone size is smaller than the distance between these points (approximately 0.5 mm) then the shape of the plastic zone cannot be measured. The main difference between the two specimens in Figure 3 and Figure 4 is the direction of welding. Therefore the orientation of the circular structure (material flows) in the nugget is different.

As can be seen in Figure 3 and Figure 4 the crack path changes initially to a direction perpendicular to the FS weld orientation. Once the nugget of the FS weld is crossed (see tool edge and Figure 1), the crack path changes back in the first specimen to an orientation perpendicular to the applied load. This behaviour was also observed for the FCG through an FS weld in AA2024-T3 in the same 45º configuration (not shown in this paper).

The plastic zone size (Figure 3) are larger in the FS weld compared to the base material, and the geometry changes from the well known "butterfly" shape (a = 5 mm) towards an elliptical shape perpendicular to the FS weld (a = 10 mm). Outside the nugget, the contour shows again a butterfly shape with a strong orientation parallel to the FS weld.

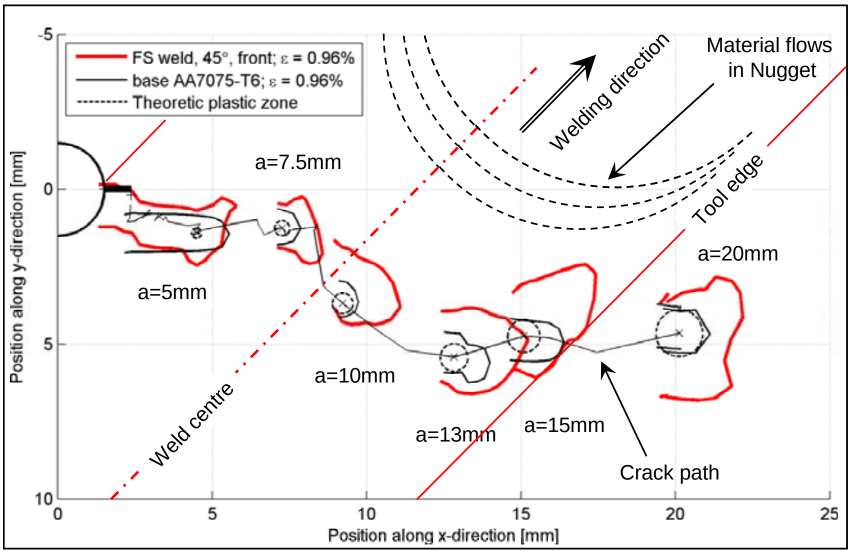

Figure 3, Contour plots FS welded AA7075-T6; 45° configuration, front side FS weld

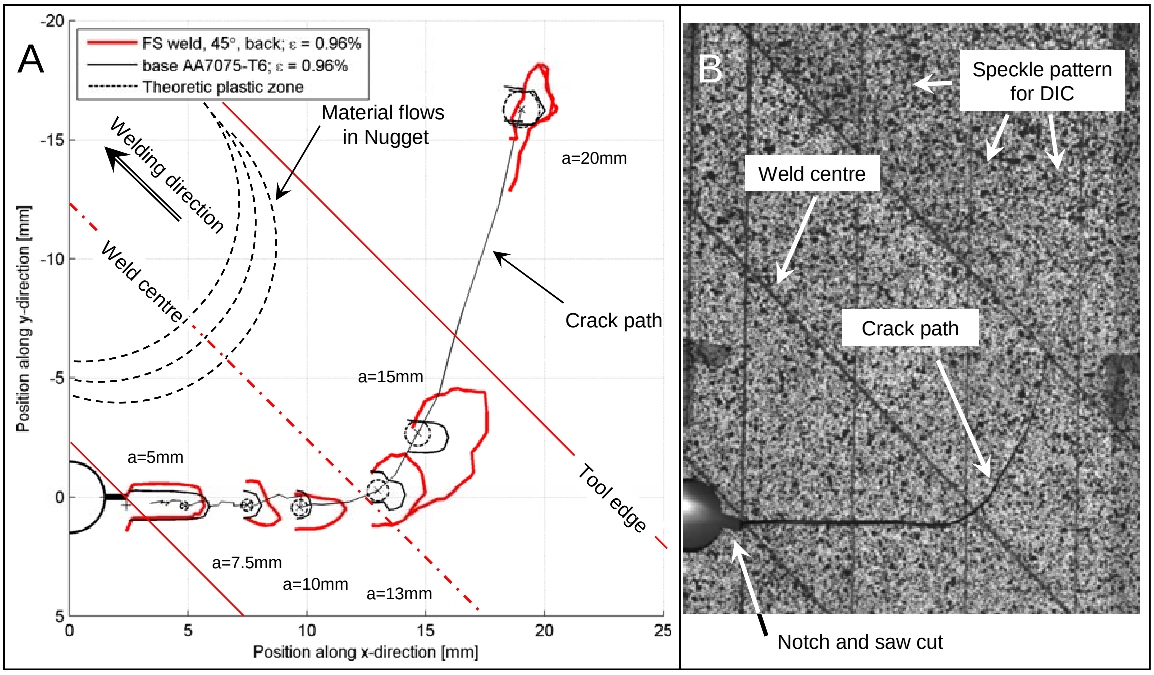

Figure 4, A: Contour plots FS welded AA7075-T6; 45° configuration; back side FS weld, B: image of specimen with crack path

The specimen in Figure 4 shows initially similar behaviour as the specimen in Figure 3, but once it crossed the nugget it does not rotate back perpendicular to the applied load, but continues to growth upwards parallel to the applied load. The crack continues to growth upwards until the crack at the other side of the hole reached the edge of the specimen and the whole specimen fails statically.

DISCUSSION

90º configuration specimens

The measured FCG rates are as expected, high at the location with high yield strength and low at the location of low yield strength for both FS welded AA2024-T3 and AA7075-T6. The size of the plastic zones in these specimens, confirm the influence of yield strength and thus the influence on the amount of crack closure. The opposite was seen however for specimen with a crack at 6.5 mm from the centre of the FS weld in AA2024-T3. Probably the asymmetric geometry of the plastic zone is less effective for crack closure because the plastic zone is below and not at the crack path; therefore the largest part of the compressive zone does not result in crack closure.

0º configuration specimens

The large difference between the effect of AA7075-T6 and AA6013-T4 on the FCG rate in the 0º FS weld configuration can mostly be contributed to the yield strength. The yield strength of AA6013-T4 is low resulting in large amount of plasticity around the crack tip, which leads to a re-distribution of the residual stresses and thus a lower stress peak at the crack tip. Whereas for AA7075-T6 the residual stresses are not redistributed at all because of the high yield strength with a very small plastic zone.

The crack path observed in AA7075-T6 is an indication that the circular structure in the nugget is prone to FCG, this has also been observed in a previous study [11].

45º configuration specimens

The initial change of FCG direction to an orientation perpendicular to the FS weld, close to the weld centre, seems to be related to the strain field and thus the orientation of the principle stress. Just before the point of rotation, one wing of the plastic zone becomes significant larger than the other (see contour of the plastic zone at 7.5 mm in Figure 3). This behaviour is shown in both FS welded AA2024-T3 and AA7075-T6 specimens in 45º configuration, no matter from which side the crack is coming. However, how the crack grows out of the FS weld, seems to be related to the orientation of the circular micro structure in the nugget. This can explain the different behaviour observed between the results in Figure 3 and Figure 4. In Figure 3 the circular structure is horizontally oriented whereas in Figure 4 they are vertically upward oriented. If this is indeed the explanation, this would indicate that the microstructure in the nugget has a large impact on the crack path. This is contradicting with the statement in the introduction that the FCG direction is solely a function of the yield strength and residual stress.

CONCLUSIONS

- The FCG rate and direction are influenced by the presence of an FS weld. The orientation of the FS weld with respect to the orientation of the load and thus the fatigue crack plays an important role in what the FCG behaviour will be.
- Using DIC, a strain field is revealed which shows the relationship between the FCG behaviour and the macro mechanical properties, in this case the local yield strength and the residual stress.
- The micro structure of the FS weld still has an influence on the FCG rate, but the macro FCG behaviour, shown in the tests is not explained by the local micro structure.

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