Effects of Residual Stresses on Fatigue Crack Propagation in Friction Stir Welded 2198-T8 and 2195-T8 Al-Li Alloy Joints

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ABSTRACT: Effects of weld residual stresses on fatigue crack growth (FCG), both parallel and perpendicular to aluminium friction stir welds, were investigated by experiments. A range of sample geometries were machined from identical welds; hence the hardness and microstructures were identical and the residual stress fields were different. Tests were conducted on M(T), C(T) and ESE(T) (eccentrically-loaded single edge crack tension) specimens with either longitudinal or transverse welds. Cracks growing into or growing away from the weld centre, as well as in the nugget zone were investigated. It is shown that residual stresses have significant effect on FCG rates and in the cases of M(T) with longer cracks and ESE(T) with crack growing into the weld compressive residual stresses caused extra crack closure and FCG rate reduction. For M(T) and C(T) samples with cracks parallel to the weld, the FCG rate was lower in the nugget than in parent material. Facture mechanics analysis is conducted to understand and explain the experimental findings.

Keywords: Friction stir weld; Residual stress; Fatigue crack growth

1. Introduction

In the last decades, new design concepts for aircraft structures have been developed in order to reduce the weight and costs. The integral metallic structure (IMS) with welding is one of the most promising. Friction Stir Welding (FSW) is now considered mature for simple applications. Weight savings of up to 15% and cost savings of 20% can be achieved by its application [1-2].

The role of residual stress on fatigue crack growth of FSW aluminium structures has been extensively studied [3-13]. Methods that have been developed to measure the residual stress distribution in friction stir weld plates include neutron diffraction; synchroton X-ray scanning; slitting methods; hole drilling; magnetizing stress indication, and the contour method. Altenkirch et al. [3] used synchrotron X-ray diffraction to measure residual stress distribution of a series of 7449-W51 aluminium friction stir welds, and study the effect of tensioning and sectioning on residual stresses distribution. Milan et al. [4] used slitting to measure residual stress distributions in AA2024-T3 friction stir welded joints. Staron [5], Sutton [6] used neutron diffraction to measure residual stress distribution in welded 2024-T3. All measurements showed a similar double-peak feature; residual stress achieves a double-peak tensile value in the heat affected zone (HAZ), smaller value in the nugget; tensile residual stresses are higher on the advancing side of the weld.

The effects of residual stress on fatigue crack propagation also have been studied. Pouget [7] studied residual stress and microstructure effects on fatigue crack growth in 2050 friction stir welds. Tests with CT samples were performed with the crack propagating perpendicular to the weld. Bussu et al. [8] 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 the differences in fatigue crack growth rate. Seongjin et al. [9] studied fatigue crack propagation behaviour of friction stir welded 6061-T6 C(T) samples. Anne-Laure et al. [10] 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. [11] studied the effects of residual stress on near threshold fatigue crack growth in friction stir welded 7050 T7451 for different sample geometries.

In all cases the notch was placed along the weld direction in the heat affected zone (HAZ). Crack growth rates measured in the HAZ were less than those in the parent metal. As the amount of crack growth reduction in the HAZ depended on the sample geometry, residual stresses were assumed to play a significant role. Dalle Donne et al. [12, 13] 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.

In this paper, the effects of residual stresses on fatigue crack growth in FSW 2198-T8 and 2195-T8 Al-Li alloy joints were investigated. The growth rates were compared with those measured in parent plate. Weld crack growth rates were predicted from measured weld residual stresses using the K_{resid} approach.

2. Sample preparation and experimental techniques

Friction stir welds were made in a series of sheets and plates of 2198 and 2195 aluminium lithium alloy. A range of sample geometries were machined from the plates and sheets. The samples all had identical welds and hence the hardness and microstructure were the same but samples had different residual stress distributions. Any measured differences in fatigue crack growth rates would arise from effects of residual stress.

M(T) samples were used to test 1.6 mm 2198-T8 aluminium sheet. There were two crack orientations, parallel and perpendicular to weld, as shown in Fig.1. C(T) and ESE(T) samples 8 mm thick were machined from 12.7 mm thick plates. In order to reduce distortion arising from residual stress relief during the skimming operation, 0.1 mm was removed alternately on the top and bottom surface. Samples were then cut from the 8 mm plates to the dimensions shown in Table 1.

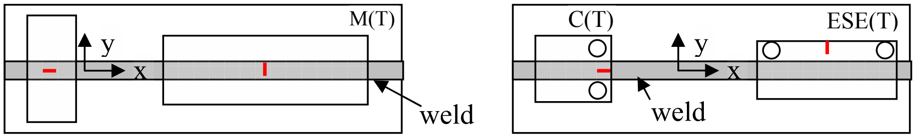

Fig.1 Schematic drawing showing type of M(T), C(T) and ESE(T)

Table 1 Sample type and size

Relationship with weld	Type	Sample size (mm): length x width (W)	Sample amount
Crack perpendicular to weld	M(T)	350x100; 550x200	2 for each size
Crack parallel to weld	M(T)	300x100; 300x200; 300x334	
Crack parallel to weld	C(T)	84x87.5(70); 120x125(100); 240x250(200)	
Crack perpendicular to weld	ESE(T)	148x40; 185x50; 370x100	

Fatigue crack growth tests were performed on all samples to procedures in ASTM E647, in laboratory air at $R = 0.1$, with a load frequency of 10Hz. Fatigue crack growth tests were conducted as well on unwelded plate at R ratios of 0.1, 0.35 and 0.6. Stress intensity factors for all specimens were calculated using the expressions recommended in ASTM E647. The electric potential method [14] was used to monitor crack growth for C(T) and ESE(T) samples, while an automated optical video system was used to monitor crack growth for M(T) samples. Crack lengths could be monitored to an accuracy of 0.1mm.

3. Experimental results

3.1 Parent metal fatigue properties

Fig.2 shows the parent metal fatigue crack growth rates da/dN as a function of $\Delta K_{applied}$ for R values of 0.1, 0.3 and 0.6 in 1.6 mm 2198 sheet. Crack growth rates at $R = 0.1$ are smaller than at $R = 0.35$ and $R = 0.6$ For 2195-T8 C(T) samples 8 mm thick, the effects of R ratio are more pronounced.

3.2 M(T) Samples 1.6 mm sheet, cracks perpendicular to the weld

In Fig.3 crack growth rates measured in two sample sizes are compared with rates measured in unwelded sheet. Crack growth rates are similar to those measured in parent sheet and are insensitive to sample size. This suggests residual stresses are small. There are two reasons for small residual stress: one is that sample is very thin; the other is the 6 mm notch made in the middle of weld to start the crack, which will relax longitudinal weld residual stresses.

3.3 Fatigue crack growth rates in welded 8.0 mm ESE(T) samples

It was not possible to initiate fatigue cracks at the notches of the largest (370 X 100 mm and 185 X 50 mm) variants of these samples, even after prolonged cycling at applied loads equivalent to K_{max} values approaching K_{IC} for static

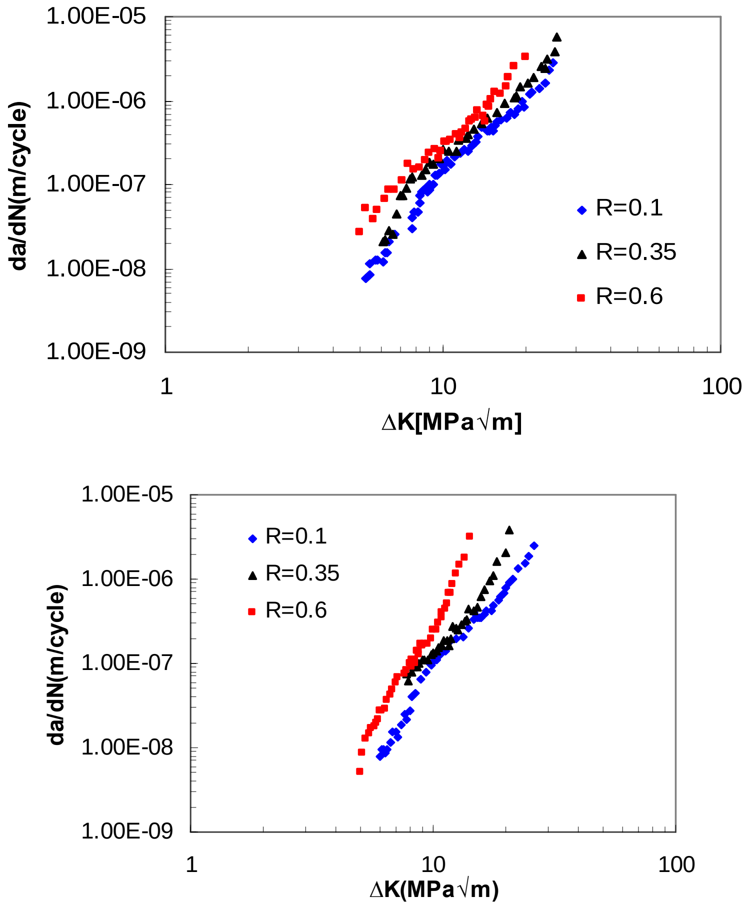

Fig 2 Fatigue crack growth rates parent material; top 2198 1.6 mm and bottom 8 mm 2195-T8 for R=0.1, 0.35, 0.6

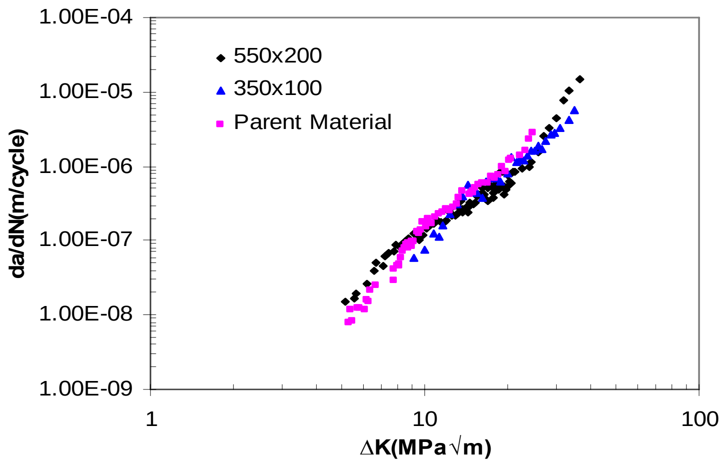

Fig.3 Crack growth rates versus ΔK for different M(T) sample sizes, 2198, 1.6 mm; R = 0.1

fracture. Fatigue cracks were initiated in the smallest sample 148x40 mm at R = 0.1 and these data are shown in Fig.4, compared with growth rates from parent material. Fig.4 shows weld crack growth rates reduced by a factor approaching 10 at $\Delta K_{applied}$ =8 MPa $m^{1/2}$, with the parent & weld curves converging rapidly at longer crack lengths.

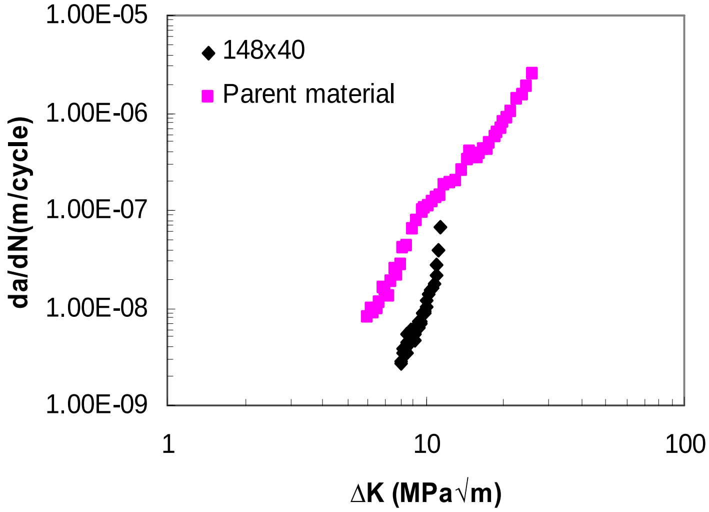

Fig.4 2195 alloy, da/dN Vs ΔK, 8 mm thick, ESE(T) samples, R = 0.1

3.4 Cracks parallel to the weld- 1.6 mm M(T) samples 2198-T8

For cracks parallel to weld, the fatigue cracks grew along the weld centreline in the weld nugget, In this orientation cracks will be influenced by residual stresses perpendicular to the weld. Fig.5 shows da/dN versus ΔK for 1.6 mm 2198 sheet. Crack growth rates of different sample sizes are similar and are all slower than da/dN in the parent sheet. Pouget [7] also observed this effect.

3.5 Cracks parallel to weld- C(T) samples 8 mm 2195-T8

Three sizes of C(T) samples were tested, all with the crack growing in the weld centre line. Crack growth rates versus ΔK for all samples sizes are shown in Fig.6. As in the M(T) 2198 samples, cracks growing on the weld centreline grow slower than those of the parent plate. Growth rates in the largest sample are slowest and growth rates in the smallest sample are most similar to parent plate growth rates.

4. Discussion

4.1 weld residual stresses and K_{resid}

For the M(T) samples 500 x 200 mm, a previously published residual stress distribution for FSW in thin sheet is available (Fratini [15]). The residual stress

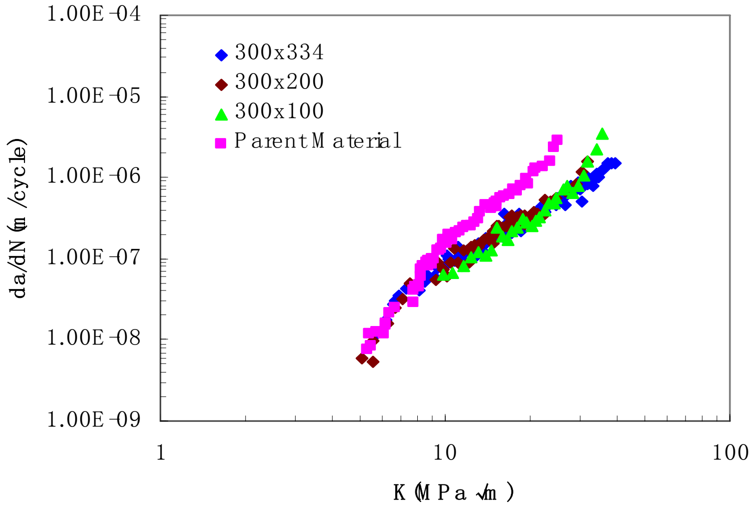

Fig.5 Crack growth rate parallel to the weld in1.6 mm M(T) samples of 2198

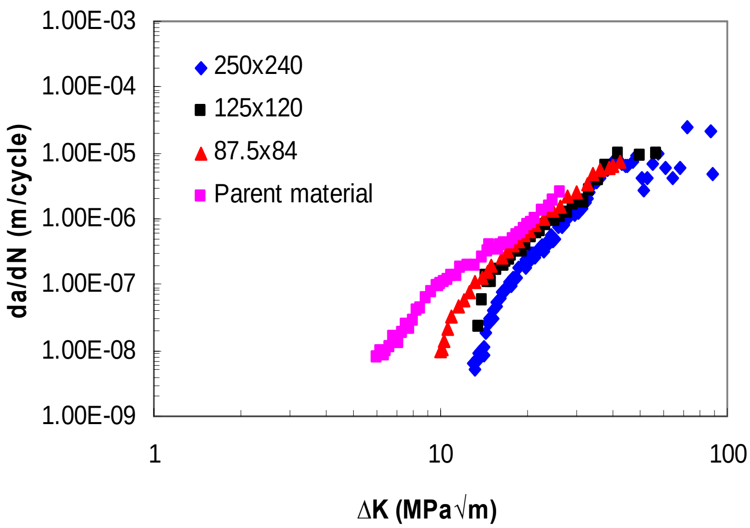

Fig.6 Crack growth rate in 8 mm C(T) samples parallel to the weld 2195 alloy R=0.1

distributions in the 8 mm ESE(T) samples tested in this work were measured using neutron diffraction. Details are in given in [16]. Examples of the stress distributions obtained are shown in Fig. 7 for the 1.6 mm M(T) 2198, and in figure 8 for 8 mm 2195 ESE(T) sample geometries. Also shown in these figures is the calculated distribution of $K_{residual}$ the calculated stress intensity arising at a crack tip from the measured residual stress field. Finite element analysis (FEA) was used to calculate K_{resid}. Residual stress distributions were put in the FE model by a subroutine. The virtual crack closure technique (VCCT) method was

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used to perform the analysis. Strain energy release rate for unit thickness can be then evaluated with the formulation:

$$G = \frac{F_j u_i}{2t\Delta c} \quad (1)$$

where F_j is the reaction force on j node; u_i is the total displacement from i node; t is thickness of samples and Δc is element size. For plane stress, the relation between the strain energy release rate and SIF is the following:

$$G = \frac{K^2}{E} \quad (2)$$

If residual stress was input to the model, K_{res} can be obtained from equation (1) and (2). The effective R ratio at the crack tip can then be calculated by the following equation:

$$R_{eff} = \frac{K_{\min} + K_{res}}{K_{\max} + K_{res}} \quad (3)$$

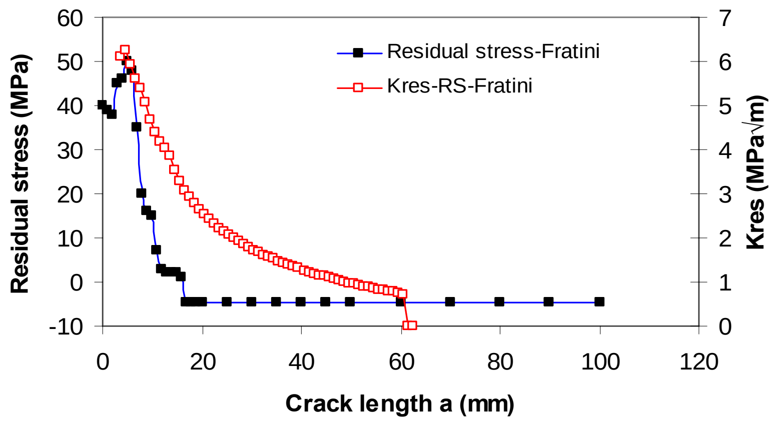

Fig 7 Residual stress distribution and K_{res} of M(T) samples. Sample centre and weld centre line at point zero; crack perpendicular to weld line

Fig 7 shows the tensile stresses longitudinal to the weld in thin sheet are relatively small and decrease rapidly from the weld centreline to zero at less than 20 mm from the weld line. K_{resid} values follow the same trend, remaining tensile- decreasing from 5 MPa $m^{1/2}$ to 1 MPa $m^{1/2}$. This is opposite to ESE(T) samples (e.g. in Fig 8) , where residual stresses are compressive near the notch tip, becoming tensile 10 mm from the notch tip, and increasing to a peak value of over 100 MPa in the first of the two weld maxima in the HAZ.

4.2 Residual stress effects on crack growth perpendicular to the weld line

The two sample geometries thus have very different residual stress fields arising from the same weld process applied to different thickness. In 1.6 mm 2198,

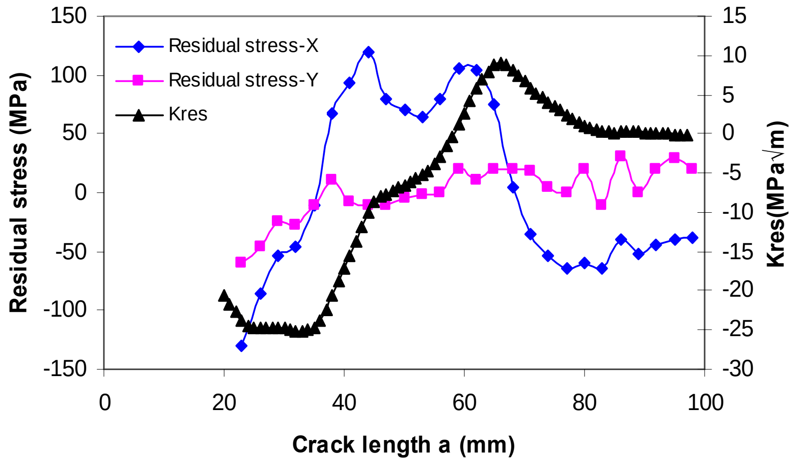

Fig 8 Residual stress distribution and K_{res} for ESE(T) 370 mm x100 mm sample; sample edges located at crack length = 0 and 100 mm; notch 20mm long. X direction parallel to weld line Y direction perpendicular to weld

stresses are tensile around the crack initiation notch location, are relatively small and result in small positive K_{resid} , which will enhance the local R_{eff} ratio from 0.1 to 0.5- 0.15, depending on crack length. Fig.2 shows that tensile R ratio effects in this material are small, and little influence of weld residual stress fields can be expected. This is demonstrated experimentally in Fig 3, and can be predicted by using the Walker equation [17] to interpolate da/dN data from the curves in Fig.2, and calculate crack growth rates for each increment of growth across the welded sample under the influence of the local $R_{effective}$. The results of this prediction for M(T) samples is shown in Fig. 9, where excellent agreement between predicted and experimental data is found.

For ESE(T) samples the residual stresses around the notch tip are compressive for stresses perpendicular to the weld. K_{res} is negative becoming positive at longer crack lengths as residual stresses become tensile. When the crack length is small, R_{eff} will be either negative or large and positive, implying ΔK completely or partially in compression. The crack will be completely or partially closed for much of the load cycle. Fatigue cracks will either not initiate or will initiate and grow slowly, depending on the size of $\Delta K_{effective}$. As K_{resid} increases rapidly with increasing crack growth, R_{eff} ratios will become large and positive, causing rapid acceleration of the crack as observed in Fig. 4.

4.3 Crack growth on weld centrelines

In 1.6 mm M(T) samples, Fig 5 shows that crack growth rates were consistently slower than in parent sheet, but there was no difference in da/dN in different size samples, strongly suggesting that residual stresses were not the cause of the

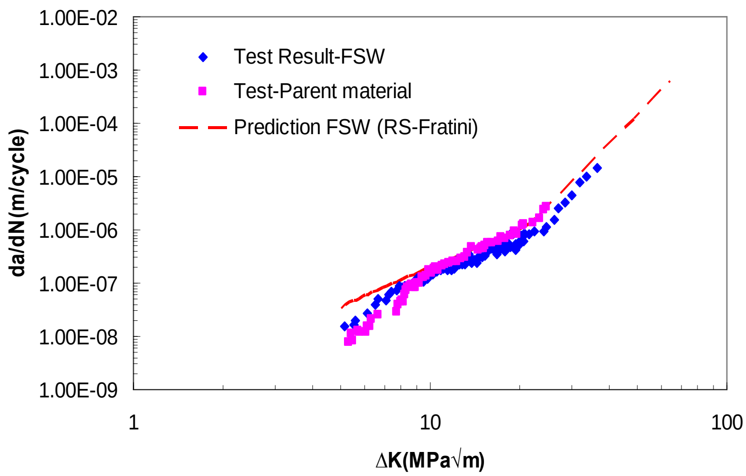

Fig.9 Comparison between prediction and test of FCG of M(T) samples

reduction. The fine equi-axed recrystallised microstructure at the FSW weld line has been shown to have [18] local ductilities up to 20%, significantly greater than the parent material, and this may be the reason for the reduced growth rate.

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8 mm thick CT samples all had greatly reduced growth rates compared with the parent plate, but in this case growth rates in the largest samples were the slowest and were fastest in small samples, strongly suggesting that compressive residual stresses were contributing in addition to local ductility influences. Investigations to obtain more complete residual stress data in all the samples and to develop fatigue crack growth rate models for compressive residual stress fields are continuing and will be reported in later papers.

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5 Conclusions

(1) In 1.6 mm thick 2198 M (T) samples, residual stresses are small and tensile; crack growth rates are similar to parent material, and sample size has little effect on crack growth rate.
(2) In 8 mm thick ESE(T) samples, residual stresses are large, are in compression around the initiating notch, changing rapidly to tension away from the notch. Crack growth rates are significantly retarded in the notch region.
(3) For crack growth along the weld line, rates are slower than in the parent material; sample size has little effect on crack growth rate in 1.6 mm sheet, but a significant effect in 8 mm plate.
(4) Prediction FCG results using LEFM analysis are strongly dependent on the material microstructure changes due to friction stir weld, geometry and other FSW parameters.

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