Forced Crack Path Deviation

C. van Kranenburg(1), J. Zuidema(1) and F.A.Veer(2)

[1] Laboratory of Materials Science, Delft University of Technology,
Rotterdamseweg 137, 2628 AL, The Netherlands, C.vanKranenburg@tnw.tudelft.nl
[2] Faculty of Architecture, Delft University of Technology

ABSTRACT. *Earlier investigations have shown that the introduction of linear side grooves with a depth of 100 ìm over the full width of centre cracked tensile (CCT) specimen of AA5083 does not affect the crack growth rate. It was shown that the side grooves suppressed the formation of shear lips. The aim of the present study is to force the crack path in a certain direction by introducing deliberate defects, i.e. curved side grooves, to increase the crack path and thus the fatigue life. Constant amplitude fatigue crack growth tests at the same load ratios and a frequency of 1 Hz are performed on AA 2024 CCT specimens. Some test specimens have side grooved (curved and linear), other specimens are standard and serve as control. The loads on the side grooved and non-side grooved specimens is identical. The curved side groove causes two effects: Firstly the crack is forced at the surface from flat to slant while the crack in the middle of the specimen remains flat. This causes a small retardation in the crack growth rate. Secondly the crack is suddenly breaks away from the path it was forced into. This results in a morphological change in the crack surface from artificial into natural shear lip. This 'breaking out' process introduces a large amount of crack closure. The result of the combined effects is a significant retardation of the fatigue crack growth rate.*

INTRODUCTION

Recently it was shown that test frequency has a significant influence on the morphology of shear lips and the crack growth rate in AA2024. [1,2] This effect has not been seen in comparable studies on AA5083 [3]. In AA2024 shear lips are rough at higher frequencies and smooth at lower frequencies while in AA5083 only smooth shear lips are found. Earlier work [4] showed that suppressing shear lip development using linear side grooves in AA5083 has no effect on the crack growth rate-ΔK relationship. Aim of this paper is to investigate the influence of linear side grooves in the test frequency sensitive aluminium AA2024 alloy. The possibility of forcing the crack in a predetermined direction to increase the fatigue path using curved side grooves was also looked at. To investigate

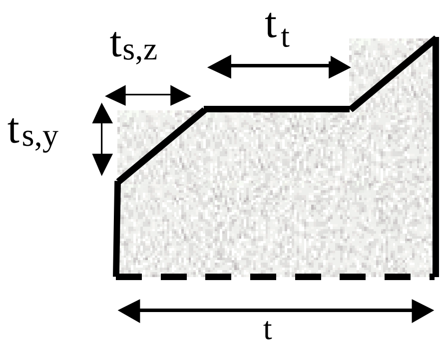


Figure 1. Cross section CCT in shear.

this last possibility a test series with curved side grooves was made and tested. The first curve, with a large radius, more or less follows the expected development of the natural shear lip. The second curve, with a small radius, forces the crack to grow at an angle higher than found in the natural shear lip. The shear lip width in the z direction, $t_{s,z}$, is defined in [1], see figure 1:

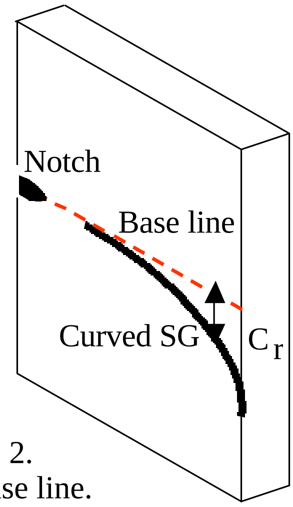


Figure 2.
C_r -Base line.

$$t_{s,z} = \frac{(t - t_t)}{2} \tag{1}$$

Since 45° is most ideal for shear lip formation:

$$t_{s,z} \approx t_{s,y} \tag{2}$$

The monotonic plastic zone size (Irwin) is defined as:

$$r_y = \frac{1}{2\pi}\left(\frac{K_I}{\sigma_{ys}}\right)^2 \tag{3}$$

It should be noted that is theoretical and for tensile cracks, the complex shape of the plastic zone in situations of partial or total shear is not clear. There are several methods to predict the development of shear lips [5]. A rough estimate, developed by Schijve [6], which is valid for constant amplitude testing, uses the following equation:

$$t_{s,z} = 2.85 * 10^{-3} \Delta K_{eff}^2 \tag{4}$$

The distance between base line and applied curve is defined as c_r, see figure 2.

EXPERIMENTAL SETUP

Constant amplitude tests have been conducted in normal laboratory air on AA5083 and AA2024CCT specimens. Specimen dimensions are W = 100 mm, *l* = 340 mm and *t* = 8 mm for AA5083 and 6 mm for AA2024. The chemical compositions are given in Table I.

Table I. Chemical compositions.

	Mg	Mn	Si	Fe	Cr	Cu	Zn	Ti
AA 5083	4.5	0.65	0.26	0.22	0.09	0.09	0.06	0.03
AA 2024	1.4	0.7	0.06	0.20	0.01	4.43	0.06	0.02

Four test series have been conducted. Test series 1 on AA5083, with and without side grooves. Test series 2,3 and 4 are done on AA2024 using different frequencies for each test series. Each series uses specimens with and without linear/curved side grooves. Tests series 1 was intended to show the effect of side grooves. Test series 2 was intended to determine the effect of test frequency on the fatigue crack growth rate in AA2024. Test series 3 was designed to investigate the effect of linear side grooves on frequency sensitive sheet. Finally test series 4 was done to investigate the possibility of forcing the crack path in a certain direction. The details of the loads used are given in Table II.

Table II. Load data.

	Pmax [kN]	**R**	**Frequency** [Hz]	**Side grooves**
TEST SERIES 1 **AA5083, with and without linear side grooves**	40	0.5	10	None
	95	0.1	10	None
	40	0.5	10	Linear
	95	0.1	10	Linear
TEST SERIES 2 **AA2024, without side grooves, different frequency**	30	0.1	1	None
	29	0.1	10	None
	30	0.1	25	None
TEST SERIES 3 **AA2024, with linear side grooves, different frequencies**	30	0.1	1,10,25*	None
	30	0.1	1,10,25	Linear
TEST SERIES 4 **AA 2024, curved side grooves fixed frequency**	30	0.1	1	curved radius=68.9
	30	0.1	1	curved radius=162.5

* for frequency = 25 Hz: Pmax=72 kN

There are two types of specimens with side grooves: linear and curved. The linear side groove is a straight line over the full width of the specimen. The curved side grooves have a radius of 68.9 or 162.5 mm and start from an initial crack length of 10mm. Between the starter notch and the crack length of 10mm a linear side groove was applied. All side grooves had a depth of 0.1 mm and were created by putting a scratch on the surface using the edge of a chisel. A curved side groove with radius 162.5 mm follows the development of the natural shear lip. The curve with the smaller radius (68.9 mm) causes an initial slant growth that has an angle greater than 45°. The crack length was measured using the pulsed direct current potential drop technique. The side-grooved specimens were calibrated using this technique. Data is analysed using the procedures given in ASTM 647 [6]

RESULTS

Test Series 1: AA5083, with and without Linear Side Grooves

Results of research into the effects of different types of side grooves on fatigue crack growth in AA5083 were presented earlier [4], but the effect linear side grooves will be summarized here. In AA5083 there are no statistically significant differences between the crack growth rates in specimens with and without side grooves. This suggests that introducing side grooves in this material does influence the fatigue life. However a difference in crack front shape is observed. The crack front in side-grooved specimens is flat while in normal specimens it is convex.

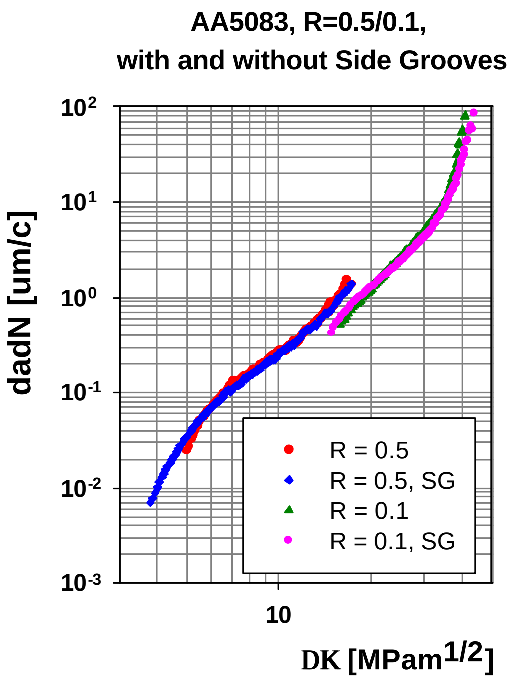


Figure 3. Results test series 1: AA5083, with and without linear side grooves.

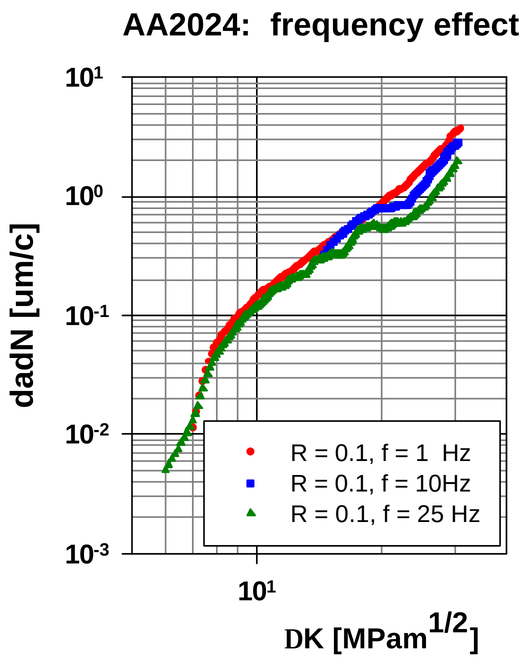


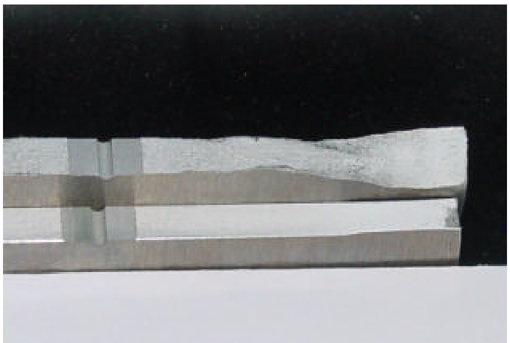
Figure 4. Results test series 2: AA2024, different frequencies.

Test Series 2: AA2024, Different Frequencies

In AA2024 different behaviour is observed. The results of tests at 3 different frequencies are shown in figure 4. Plots of da/dN versus ΔK using a load ratio of 0.1 are shown. Shear lips are rough at higher frequencies and smooth at frequencies of 5 Hz or less. The difference in shear lip roughness is considered to be responsible for the difference in the crack growth rate.

Test Series 3: AA2024, Linear Side Groove

The results for tests using linear side grooves are the same at all frequencies as for specimens tested without side grooves at 1 Hz, which have smooth shear lips. This situation is similar to that found in AA5083 under all conditions. The side groove causes the crack to remain flat and eliminates the frequency effect by suppressing the rough shear lip at the higher frequencies.



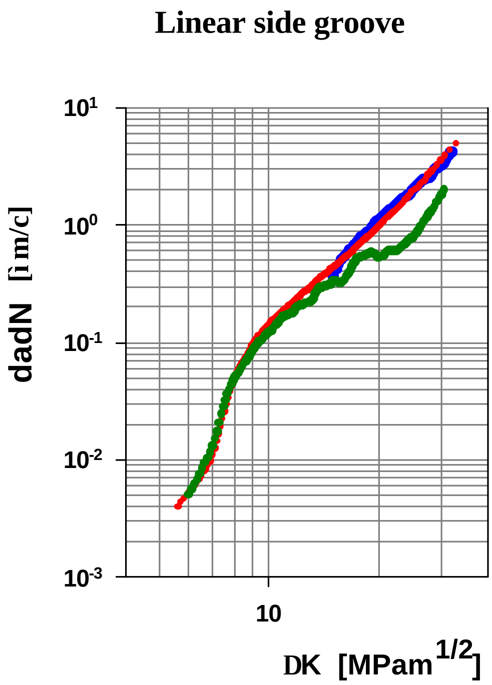
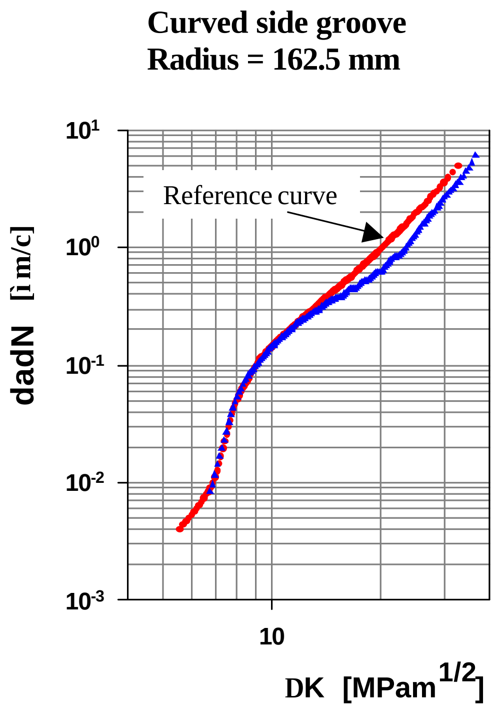


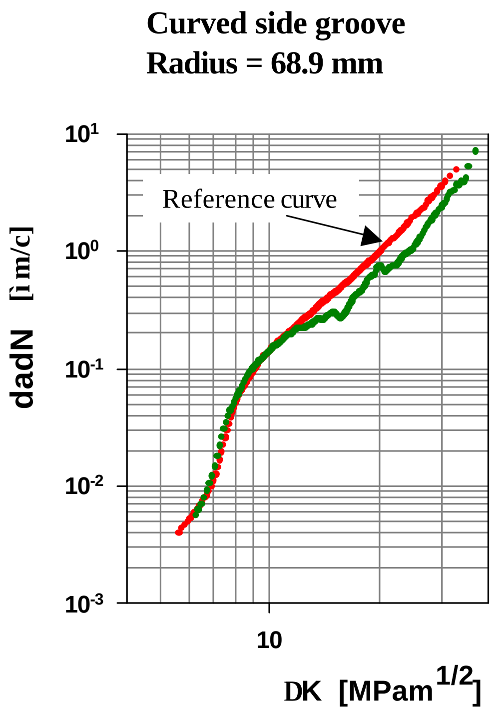
Figure 5. da/dN-ΔK relation for linear side grooved and non-side grooved specimens. The photo shows the crack surface for suppressed shear lip (lowest sample) and normal slant crack surface.

Test Series 4: AA2024, Curved Side Groove

Figures 6 and 7 illustrate the effect of the curved side grooves. The fatigue crack growth rates in specimens with small and large curvatures were compared by plotting a reference line of 1 Hz in the same da/dN-ΔK diagrams.

Figure 6b shows a picture of the crack surface in case of radius=162.5 mm. It can be seen that the crack follows the side groove. From a crack length of 25.7 mm, which corresponds with a ΔK of 15.9 MPa√m the natural shear angle is smaller than that forced onto the specimen by the curved side groove. At this point the start of a crack growth retardation process is observed.





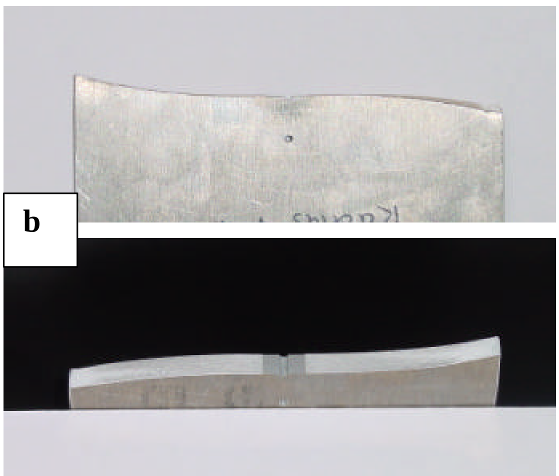


Figure 6. Results for linear side groove with radius 162.5 mm.

Figure 7. Results for linear side groove with radius 68.9 mm.

Figure 7b shows some pictures of specimens with side grooves with a radius of 68.9 mm. Again a retardation is observed. The natural shear lip angle is smaller than the angle the crack is forced into by the curved path. The crack breaks away from the side groove at a crack length of 24.5mm, which has a ΔK of 15.3 MPa√m. At this location several black spots are visible in the crack wake, which indicate crack surface fretting and thus increased crack closure.

DISCUSSION AND CONCLUSIONS

Both Plasticity Induced and Shear Lip Induced crack closure have a significant effect on the fatigue crack growth behaviour. The crack growth rate versus ΔK relations in AA2024 at higher frequencies with suppressed shear lips are the identical to those at lower frequencies (e.g. smooth shear lips). The results of test series 3 show that linear side grooves eliminate both the shear lips and the frequency effect in 2024.
By suppressing the rough shear lip at the higher frequencies, it is becomes possible to make separate the contributions of Plasticity Induced and of Shear Lip Induced closure and to calculate their relative contribution on the total crack closure.

The relationship between t_s and c_r and the crack length is shown in figure 8. The prescribed path follows more or less the natural shear lip. From a crack length of 25.7 mm c_r is greater than $t_{s,z.}$. It means that the artificial shear exceeds the natural shear from this point. As a result crack growth retardation is introduced, as shown in figure 6.

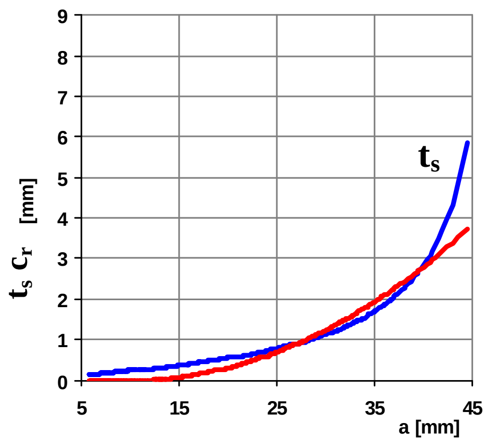


Figure 8. Crack length versus t_s and c_r .

The relationship between c_r, $t_{s,}$ r_p and the crack length is shown in figure 9. From 1 to 2 we have the same situation using a radius of 162.5mm; the artificial shear angle exceeds the natural shear angle. A small retardation is observed as a result. However, after point 2, where the crack length is 24.5mm and ΔK is 15.3 MPa√m, the situation is different. The crack breaks away from the side groove when c_r starts to become greater than the "normal" monotonic plastic zone size. In energy terms it becomes more efficient to change direction. During the process of breaking away form the side groove the crack

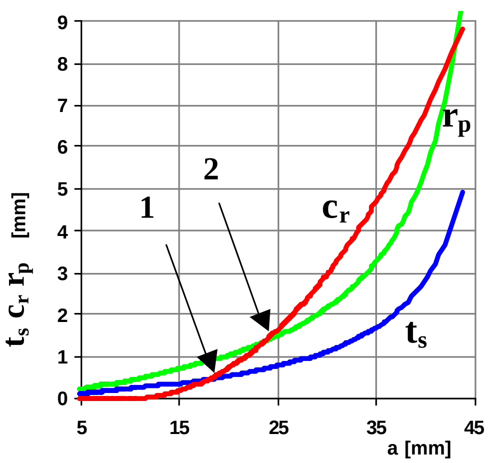


Figure 9. Crack length versus t_s c_r and r_p .

reinitiates, making an angle of 90° with the artificial shear lip. This “zig zag effect” guarantees a significant closure effect due to shear lips. Thus breaking away leads to large Shear Lip Induced crack closure effects, which are comparable to those found at higher test frequencies in AA2024. The crack growth rate versus ΔK plot is similar to that found at 25 Hz in specimens without side grooves.

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