23. CRACK CLOSURE ALONG THE FATIGUE CRACK FRONT OF CENTRE CRACKED SPECIMENS

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Summary - An attempt is made to asses the variation in crack opening stress S_{op}, a measure for the amount of fatigue crack closure, along the crack front of centre cracked specimens. It is shown that S_{op} is definitely higher at the specimen surface (plane stress) than in the interior of the specimen (plane strain) where still a positive value of S_{op} is found. From these results it is concluded that the amount of fatigue crack closure is affected by specimen thickness, and that differences between the results of two experimental techniques for studying this phenomenon, the use of surface clip gauges and the potential drop technique are to be expected.

1. INTRODUCTION

Since the first reports by Elber on the phenomenon of fatgue crack closure several investigators have used this concept to explain the role of various parameters influencing fatigue crack growth. Especially the influence of K_{max} [3-5] and the role of the environment [4, 6, 7] have been studied extensively, however, without conclusive results.

Besides other reasons, variation in the state of stress along the crack front during fatigue crack growth and the methods used to measure the amount of crack closure seem to be at the origin of the disagreement between crack opening stress measurements reported by various authors.

Some observations from the literature on these two parameters are summarized below. From microscopic investigations and the results of potential drop techniques Lindley and Richards [8] draw the conclusion that in steel specimens fatigued in air crack closure does not occur during plane strain fatigue crack propagation, whereas it does under plane stress circumstances. However, Buck et al [9] using ultrasonic techniques on part through cracked specimens (Al 2024, Al 2219, Ti 6-4, steel 17-4 PH) fatigued in dry nitrogen observe crack closure under plane strain conditions.

Fatigue crack growth and crack closure experiments carried out by Pitoniak et al [10] on CT specimens made of PMMA revealed that crack opening starts in the centre part of the specimens and then gradually spreads to the surfaces.

During unloading closure starts at the specimen surfaces. Pitoniak et al used interference pattern techniques to reveal this phenomenon.

Based on the results of electron fractography of fatigue crack surfaces of Al specimens Mills and Herzberg [11] have stated that crack closure only occurs in the plane stress regions of the fatigued crack, the only areas where clear traces of rubbing of the crack surfaces are found. These results indicate that the amount of fatigue crack closure is not constant along the crack front. Except for Lindley and Richards the authors mentioned before use less common methods to asses the amount of crack closure. The most widely adopted techniques are the potential drop method and the use of surface or crack mouth clip gauges. Shih and Wei [3] suggest that the onset of crack closure as detected by potential drop techniques is in reasonable agreement with the results of surface clip gauge displacement measurements. Bachmann and Munz [12], however, report that although a reasonable correspondence is found in air the potential drop technique yields much higher opening stresses than the displacement method in vacuum.

If the amount of fatigue crack closure varies along the crack front it should be expected that potential drop data, representing an average of the situation along the crack front, and surface displacement measurements yield different results.

In the present work an attempt is made to measure variations in fatigue crack closure along a crack front in a centre cracked specimen. Due to the limited accuracy of the surface clip gauge technique used the results give only qualitative picture. Still the data obtained prove the existence of a thickness effect on crack closure and can partially explain discrepancies found between different measuring techniques.

2. EXPERIMENTAL PROCEDURE

Fatigue crack growth experiments were carried out on centre cracked specimens; 295 mm long, 100 mm wide and 10.3 mm thick under constant amplitude loading of 54 ± 44 MN m^{-2} ($R = 0.1$). The material used was an Al alloy 2024-T3 unclad, chemical composition and mechanical properties are listed in table 1.

For some preliminary tests cladded Al alloy 2024-T3 specimens of 2 mm thickness were used. The cladding layer was removed by means of chemical milling which resulted in specimens with a thickness of av. 1.7 mm. All specimens were fatigued to a certain crack length after which the test was stopped and fatigue crack closure was measured with specimen surface clip gauges mounted 1 mm behind the crack tip (left, right, front and back).

Crack closure measurement cycles were run between 0 and 54 MN m^{-2} (mean stress in fatigue cycling). S_{op} is defined as the highest point of the non liniar part of the load displacement curve during uploading. The surface clip gauge is shown in figure 1 and is a design of the german aerospace laboratory DFVLR.

In order to obtain information on the opening stress along the crack front the specimens were thinned. At first two specimens were tested which were thinned in three consecutive steps of 2 mm each. Then three specimens were used where the thickness was reduced only 0.4 mm per step. Thinning was done by means of chemical milling except for the vicinity of the crack, which was milled mechanically in very thin layers. After each thinning step the crack opening stress was measured.

A series of preliminary tests was carried out on the 1.7 mm specimens to study the effects of repeated crack closure measurements, clamping and removing specimens from the test rig, and to asses the influences of residual stresses due to mechanical milling. In figure 2 is shown that removing a very thin layer by means of mechanical milling did not have any systematic effect on the value of S_{op}. On one specimen fatige testing was restarted at low frequency (0.1 Hz) after final thinning to a thickness of 3.7 mm. Crack closure was monitored continuously during the first 100 cycles and afterwards at intervals of 100 cycles in order to get some insight in the development of the crack opening stress.

3. RESULTS

The results obtained from the first two specimens are summarized in figure 3. Specimen I was fatigued to a half crack length of av. 12 mm at the surface and specimen II to av. 20 mm. After the first thinning step a large decrease in S_{op} is found whereas further thinning does not affect S_{op} significantly. It is generally agreed that at higher stress intensity factors a larger plastic zone is formed at the crack tip which leads to a situation where the surface plane stress region is extended in the thickness direction.

So it can be expected that after the first thinning step a significantly larger part of the plane stress plastic zone remains intact at 20 mm than at 12 mm crack length. Nevertheless this did not lead to a large difference in the variation of S_{op} along the crack front, only the total mean value of S_{op} is somewhat higher for $a = 20$ mm (23.3 compared to 21.1 MN.m^{-2}).

From these tests it was concluded that there is a variation of S_{op} along the crack front [13] but it was realized that, in order to get a better picture, the thinning steps should be smaller.

In the second test series 3 specimens were fatigued to half crack lengths of av. 9, 15 and 22 mm and the thinning steps were 0.4 to 0.5 mm. From the results summarized in figure 4 it can be concluded that although the scatter in the data is large, there exists a gradual decrease in S_{op} going from the plane stress situation at the specimen surface to plane strain in the interior of the specimen. Furthermore figure 5 shows that there is an influence of the width of the plane stress plastic region. It can be observed that the region with higher S_{op} values is larger at longer crack length where a larger part of the specimen thickness is in plane stress. Restarting the fatigue test after final thinning to a thickness of 3.7 mm while monitoring S_{op} continuously yielded the results shown in figure 6. It can be observed that the opening stress S_{op} increases from a value of av. 11.8 MN m^{-2} to a value of 28.4 MN m^{-2}, nearly the value measured on the full thickness specimen, whithin the first 100 cycles.

Studying the fatigue fractures after breaking of the specimens revealed that immediately after restarting the test shearlips were beginning to form, although the remaining part of the fatigue crack was completely in tensile mode.

From these observations it can be concluded that the value of S_{op}, measured by means of a surface clip gauge is strongly affected by the behaviour of the specimen surface in the immediate vicinity of the crack tip.

4. DISCUSSION

4.1. Crack closure along the crack front

The results of these tests show that the crack opening stress S_{op}, a measure for the amount of crack closure, is defenitely higher at the specimen surface as compared to S_{op} in the plane strain region in the interior. This conclusion which is in accordance with the results obtained by Pitoniak [10] and Mills and Herzberg [11] is also supported by the results of Mc Evily who showed that the delay period after an overload was nearly eliminated by removing the surface layer of the specimen after application of the peak load.

Since the S_{op} measurementsin the plane strain region yielded positive opening stress values the authors conclude that crack closure does occur under full plane strain conditions.

However, for a specimen with mixed plane stress plane strain conditions along the crack front the question arises whether it is possible that crack closure away from the surface is prevented by the shear lips at the specimen surface (plane stress). The observations of Lindley and Richards [8] seam to point in this direction.

On the other hand, recent observations by Bowles, using a vacuum infiltration technique to study the fatigue crack growth mechanism, indicated that crack closure in the form of pointwise contacts does occur under plane strain conditions, but to a lesser extend than in the plane stress region of the crack. Although these results do not answer the question whether the plane strain parts of the mixed mode crack are closed or not conclusively, it can be argued that if crack closure occurs in the plane strain region of a mixed mode crack it will do so in a later stage than the plane stress parts at the surface. This indicates that, besides an influence on the measured value of S_{op} discussed in the next paragraph, a thickness effect on crack closure does exist and a smaller overal amount of crack closure and less retardation after a peak load (as reported by Shih and Wei [17])are to be expected for thicker specimens. Furthermore it has to be concluded that an expression of the form $da/dN = C[U.\Delta K]^n$; $U = C_1 + C_2 * R$, as introduced by Elber [1] maybe useful to fit a certain data set but does not adequately describe the influence of crack closure on fatigue crack growth behaviour since the thickness effect is completely ignored.

For the same reason care should be taken in using crack growth prediction models for variable amplitude loading based on retardation effects [18] when dealing with thick sections.

4.2. Crack closure measurement techniques

In this investigation only surface clip gauge displacement and no potential drop measurements are used but on the basis of the present results and literature data some remarks can be made with respect to both techniques.

Since it has been shown clearly that there ia a variation of the amount of crack closure along the crack front one can expect discrepancies between the results obtained by means of the potential drop technique and the surface clip gauge method.

It will be difficult, however, to indicate the exact sources for these differences due to several advantages and drawbacks of both methods. The surface clip gauge technique indicates a difference in compliance of a cracked specimen and as such measures directly the phenomenon of crack closure. On the other hand the results obtained in this investigation show that S_{op} as measured by this technique can be strongly influenced by surface effects in the direct vicinity of the crack tip (S_{op} behaviour after restarting the fatigue test).

The potential drop technique measures the amount of electrical contact between the crack surfaces which is an indirect measurement for a change in compliance and can be influenced by two factors. Under plane stress conditions rubbing, caused by sliding along each other of the slant crack surfaces is often observed. During this proces there will be good electrical contact, but it is not known to what extend sidewise displacement of the slant fracture surfaces occurs, leading to a less effective load transmission through a crack which is electrically closed. The results of Bachmann and Munz [12] indicate that such an effect can play a role. On the other hand an oxide layer formed on the crack surfaces can electrically insulate the crack surfaces partly while it is mechanically fully closed.

Depending on the definition of S_{op} when using the potential drop technique the influence of surface effects can be reduced.

In this investigation S_{op} is defined as the highest point of non liniair part of the load displacement curve during uploading measured at the specimen surface. Although the point of crack opening will be influenced by the total strain distribution (lowering S_{op} found at the surface) one must expect that in principle the overall S_{op} is overestimated. If in using the potential drop technique S_{op} is defined as the point where the apparent crack length becomes constant with load (Shih and Wei [3]) S_{op} is defined more or less in the same manner as in this investigation and, besides the drawbacks due to the indirect type of measurement, the same S_{op} values should be found. So using this type of S_{op} definition the clip gauge technique will yield more reliable results. If however crack closure is defined as a certain amount of crack area reduction (lindley and Richards [8]) in principle an overall measurement is carried out missing the chance of overestimation of S_{op} due to surface effects but still an indirect measurement. This must lead to a different result if compared to the surface clip gauge method.

Although the surface clip gauge method and the potential drop technique in itself are yielding reproducable results, it has to be concluded that discrepancies in the results of the two methods are to be expected due to completely different sources of error.

Attempts to make quantitative predictions based on crack closure measurements will be influenced by the shortcomings mentionned above.

5. CONCLUSION

In this study the following conclusions were reached:

- S_{op}, a measure for the amount of crack closure, varies along the crack front of centre cracked specimens having a high value at the specimen surface and gradually decreasing to a considereably lower but still positive value in the specimen interior.
- There is some correlation between the extend in thickness direction of the plane stress region and the region of with higher S_{op} values.
- Earlier indications from literature that the occurence of crack closure is more pronounced near the specimen surface have been confirmed by this study. This means that there is a thickness effect on crack closure.
- When comparing results obtained by means of a surface clip gauge with results of potential drop techniques differences will occur due to several sources of errors.
- Extreme care should be taken when making quantitative predictions on the basis of crack closure measurements.

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Mech. properties

$\sigma_{0,2}$ (MN.m^{-2})	σ_{uts} (MN.m^{-2})	δ(%)
405.0	500.1	23.8

Chem. composition (%)

Cu	Mg	Mn	Si	Fe	Cr	Zn
4.88	1.41	0.65	0.15	0.22	0.01	0.05

Table 1: Mechanical properties and chemical composition of the Al 2024-T3 alloy used in this investigation.

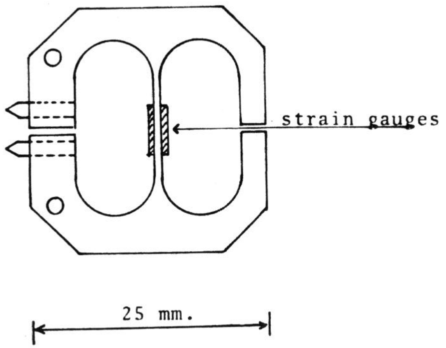


Fig. 1: the clip gauge design DFVLR

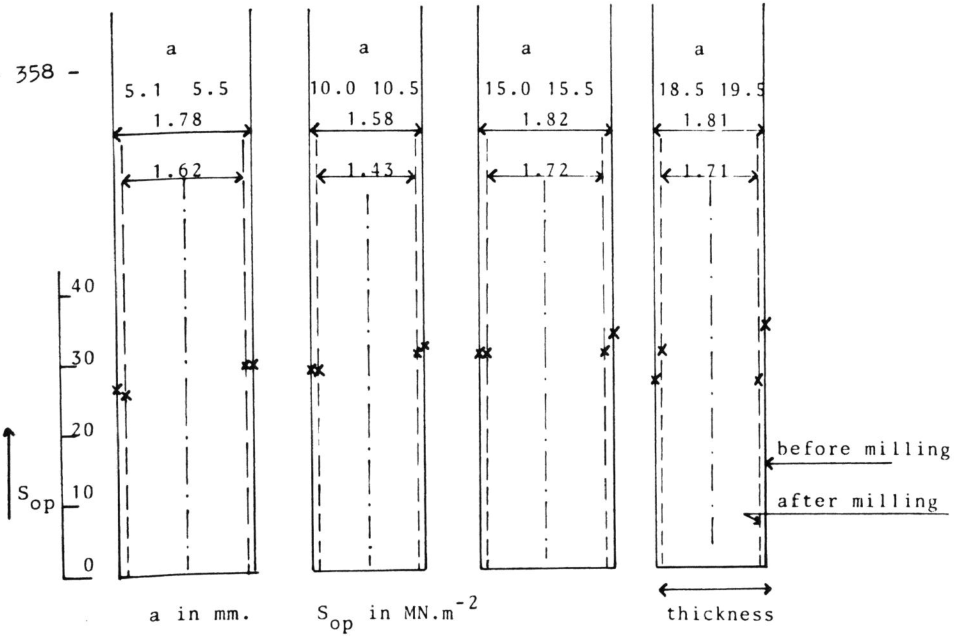


Fig 2: Influence of mechanical milling on the crack opening stress S_{op}

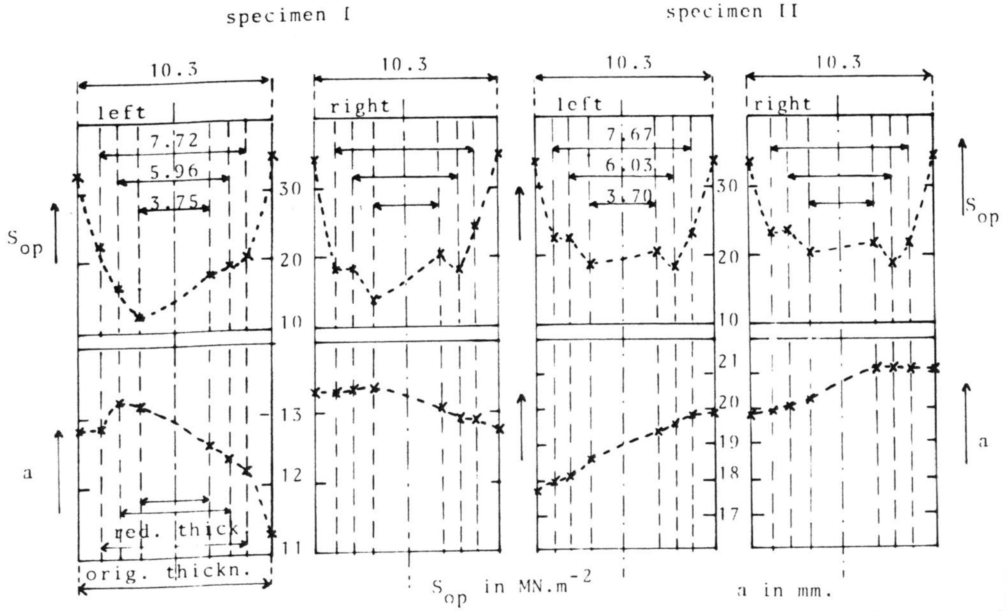


Fig. 3: Variation of the opening stress S_{op} along the crack front first series thickness red. 2 mm. per step

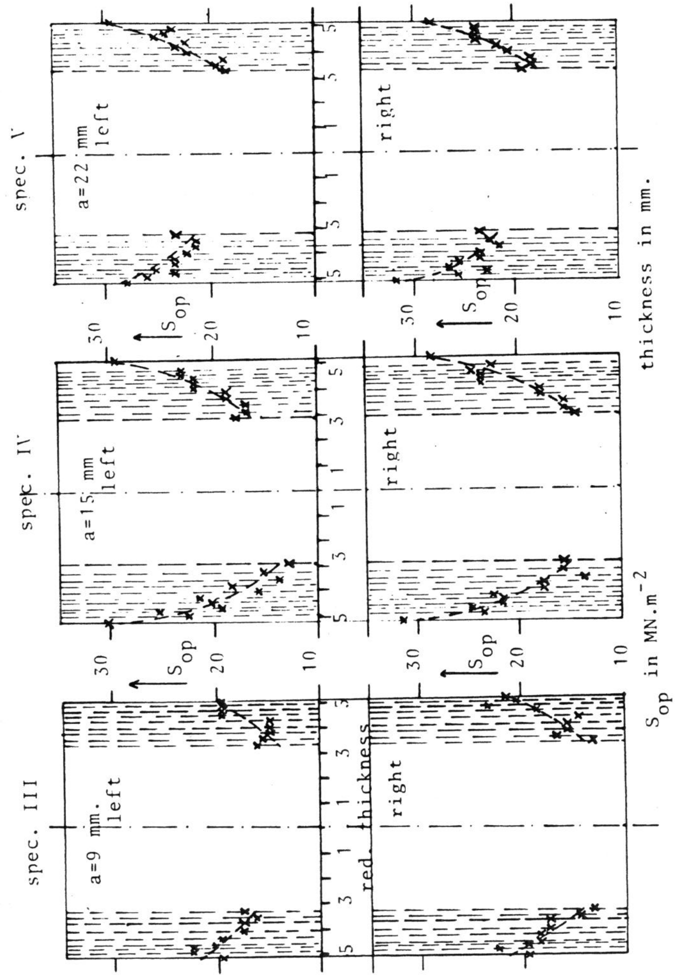
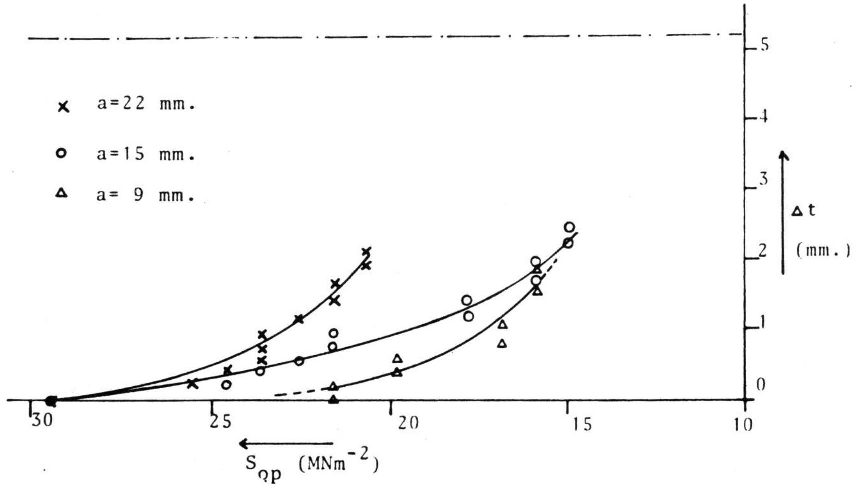


Fig.4: Variation of the opening stress S_{op} along the crack front second series thickness red. .5 mm. per step



(Δt is the reduction in thickn.)

Fig. 5: Summarized distribution of S_{op} along the crack front for 3 crack lengths (the data plotted are the statistical redistributed values see F. Gatto IUTAM symp. 1955)

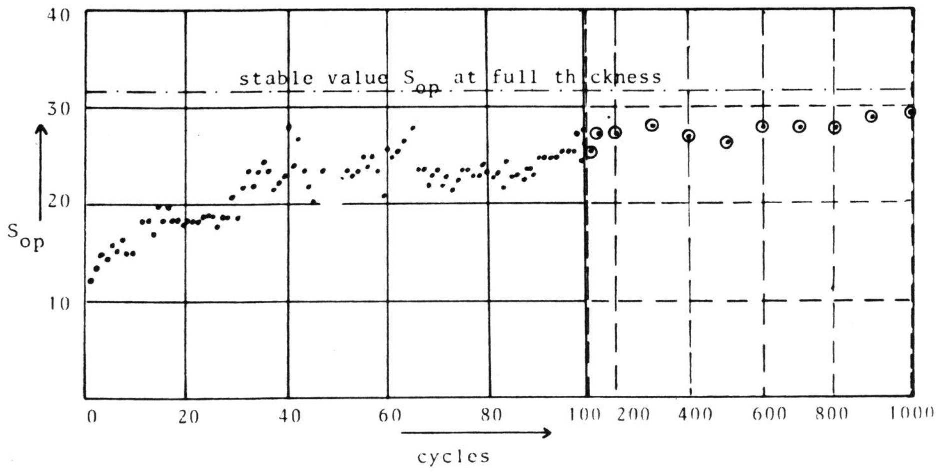


Fig.6: S_{op} plotted against number of cycles after restarting the fatigue test (S_{op} in MN.m^{-2})