particular crack length. Micrographs were then taken at various positions along the crack length for a range of loads, up to a maximum load equivalent to 6.6 MPa√m.

Measurements at various points showed that the mode II displacements were large (with maximum displacements in the order of 12 μm). Besides the large mode II displacements measured, the fracture surfaces were also very rough. Estimates of the surface roughness in terms of root mean square roughness values were difficult to make, as Talysurf machines were not capable of following the surface roughness for height variations greater than 100 μm. A roughness trace of the fracture surface, shown in Fig. 5.11 for a 25 mm thick CT specimen shows peaks and valleys which varied by at least 300 μm.

The fracture surface consisted of plate like cleavage facets for growth rates below 1 x 10^{-4} mm/cycle. A typical micrograph of such a surface is shown in Fig. 5.12a which can be compared with the fracture surface obtained for growth rates above 1 x 10^{-4} mm/cycle in Fig. 5.12b. The fracture surface obtained at higher growth rates is much less faceted and appears dimple-like on a macroscopic scale, but on a microscopic scale striations may be present.

The high level of fracture surface roughness and extensive mode II displacements in this material support the very high closure values obtained. Because most closure is probably a result of the roughness induced closure, strain intensification may be expected because of the manner in which roughness induced closure contact occurs as explained in Fig. 5.13.

5.4.2 Plasticity effects

Plasticity induced closure may generally be expected to increase with increasing K_{max}, however, Fig. 5.14 which is a plot of K_{op} vs K_{max} for 5 mm HT specimens at the various R ratios tested shows that K_{op} remains fairly constant, i.e., K_{op} is essentially independent of K_{max} in the range 5.5 to 24 MPa√m.

These results suggest that plasticity induced closure has only a minimal effect on the opening stress intensity, thus confirming the earlier premise that closure is probably controlled by the fracture surface roughness.

5.5 Growth Under Compressive Loading

The techniques used to eliminate closure in long cracks in order to characterise subsequent closure development were described in section 3.4. One of the techniques involved producing cracks under compressive loading and is discussed in this section.

It was possible to obtain fatigue crack growth by using entirely compressive loading on CT specimens. However, the load ranges required were large and it was, therefore, necessary to use parallel platens to apply the loads in order to avoid cracking from the specimen pinholes. The use of parallel platens alters the point of load application, and loading may change slightly from specimen to specimen, but this is not believed to be important in the context of the tests performed here. The specimen geometry was changed slightly from that used for tensile crack growth rate determinations. The notch length was increased from 12.5 to 17.5 mm to reduce the magnitude of the compressive loads required for crack growth, and the notch root radius was reduced below 0.1 mm to allow more rapid crack initiation.

Tests were conducted at a cyclic frequency of 40 Hz and cycling was continued for approximately 500 000 cycles or until crack length measurements indicated that growth had arrested. The crack lengths obtained under compressive loading are recorded in Table 5.1 together with the relevant loading and material conditions. A growth rate curve obtained from specimen G under compressive loading is given in Fig. 5.15.

Table 5.1 Crack growth under compressive loading

Specimen	Load Range (kN)	Condition	Crack Length (mm)	ΔK_{th} (MPa$\sqrt{m}$)	σ_y (MPa)	r_p^* (mm)
F	-6 to -0.1	AR	1.88	≈2.5	435	1.06
A-E	-6 to -0.1	HT	0.84-1.3	5	415	1.16
G	-13 then -5.5 to -0.55	HT	3.86	5	415	3.78

r_p^* Plastic zone size based on the tensile plane stress plastic zone size (i.e., approximately three times the plane strain plastic zone size) for a sharp crack. A standard method of measuring the crack tip plastic zone size under compressive loading does not exist for the CT geometry [148].

All the above specimens except specimen F were subsequently used for the closure development tests.

5.5.1 Growth mechanisms under compressive loading

An indication of the mechanisms responsible for fatigue crack growth under compressive loading, may be obtained by comparing such growth to crack growth under conventional tensile loading. For both loading conditions it was possible to produce well defined fatigue striations, examples of which are shown in Fig. 5.16. The compressive loading sequence used to produce the striations consisted of a peak compressive load of 13 kN (≈ 64 MPa√m assuming tensile conditions), followed by a reduced compressive load range from -5.5 to -0.55 KN, which gave the required high growth rates. The formation of striations supports the idea that ultimately the mechanisms for growth under the two loading conditions are the same; namely, that growth is controlled by local tensile crack tip conditions.

Local tensile crack tip conditions develop because of the stress distribution at the notch tip (see section 3.4). Thus as the load is increased to P_{max} during the loading cycle, residual tensile stresses develop which are large enough to cause plastic deformation (reverse plasticity), thereby ensuring sufficiently large crack tip strains to produce striation growth.

If the above description is accurate it should follow that the crack tip opening point should be visible on an offset displacement vs load trace. The traces produced using BFS, near tip strain, and crack mouth clip gauges were difficult to interpret and did not clearly show regions of fully open cracks under compressive loading, which was probably a result of the surrounding region of high plasticity, inherent in fatigue crack growth under compressive loading. (Closure traces essentially require linear elastic conditions to obtain clear differences between closed and open crack tip conditions.) Crack opening loads have, however, been recorded in the literature by, for example, Suresh et al [23] who additionally obtained P_{op} values which compared well with their numerically determined P_{op} values (see section 2.4.5).

Because fatigue crack growth under compressive loading occurs in regions of notch plasticity the notch plastic zone size must obviously play a prominent role in determining the crack length under compressive loading. However, as can be seen in Table 5.1 the crack lengths obtained in the AR material are greater than those in the HT material, which actually had a smaller notch plastic zone size. Thus other factors such as the material's resistance to growth is also important, just as for tensile loading.

5.6 Summary

The fatigue crack growth characteristics for the various conditions tested can be summarised as follows:

1. Growth rates decrease as specimen thickness increases.
2. Growth rates were higher for the AR condition than for the HT condition.
3. Growth rates exhibit a very strong R ratio effect.
4. All the above results could be explained by closure on a qualitative bases.
5. Roughness induced closure appears to be the dominant closure mechanism in this material for the conditions tested.
6. Fatigue growth is possible under compressive loading and occurs in a manner very similar to growth under tensile loading.

6 ELIMINATION OF CLOSURE IN LONG CRACKS AND ITS REDEVELOPMENT

Closure development tests were conducted on the AR and HT CT specimens conditions at various ΔK values. The purpose of these tests was to determine the crack increment over which closure develops to a steady state value. This closure development distance will then be compared with the distance over which short crack behaviour occurs, in order to establish the role closure development plays in determining the short crack regime.

6.1 Wake "Removal" Experiments

Besides determining closure development characteristics for various ΔK values, attempts were also made to determine these characteristics for various stress states by conducting closure development tests on thick (15 and 25 mm) and thin (5 mm) CT specimens. However, reducing and/or eliminating closure in the thick specimens proved to be difficult as these specimens developed substantial crack front curvature (see Fig. 6.1), which gave nonlinear compliance traces irrespective of the compressive overloads applied to them. Such curvature also leads to erroneous closure results, and may render the surface crack length measurements used in this work inadequate for strongly bowed crack fronts. Closure development tests were, therefore, only conducted for the 5 mm CT specimens.

6.2 Closure Redevelopment

Closure development tests were conducted on specimens in the AR condition at ΔK values of 3.4 and 6.6 MPa$\sqrt{m}$. Closure in these two tests was eliminated by firstly removing the crack wake to within 2 mm of the crack tip and then applying a compressive overload. (The ΔK

values used in these tests represent growth in the linear regime of the growth rate curve.) The development of closure vs crack length for these two tests are show in Fig. 6.2 with the results tabulated in Table 6.1. Both closure development tests show an increase in closure with crack length over the same distance of 0.19 mm, after which a steady state closure value is approached. This steady state value is, however, much less than that obtained during the load shedding process for equivalent ΔK values - possibly due to elimination of load shedding effects.

Closure development tests were also conducted on the HT specimens at the ΔK values of 3, 4, 5, 6 and 9 MPa√m for R = 0.1. Cracks without closure for these specimens were produced by growth under compressive loading. The results of these tests are presented in Figures 6.3 through 6.8, with the relevant information in Table 6.2.

The crack increment used to represent the distance over which closure reaches a steady state value, was chosen to correspond to approximately 90% of the closure value achieved at steady state. The crack length at which this closure ratio reaches this value is shown by a vertical line in the closure development figures. The maximum steady state closure ratio was not used because of the asymptotic approach to the actual steady state closure value, and because the additional closure above this value is unlikely to have much influence on the growth rate behaviour of short cracks.

Table 6.1 Closure development results for the AR material

Specimen	ΔK MPa√m	Distance (mm)	K_{op}/K_{max} Steady State	K_{op}/K_{max} Load shedding
AR1	3.4	0.19	0.4	0.75
AR2	6.45	0.19	0.18	0.5

The columns used in the above Table represent:

1) specimen number,

2) ΔK, the stress intensity range, at which the closure development tests were conducted,

3) Distance, over which closure was found to develop to a steady state value,

4) K_{op}/K_{max} steady state, the closure ratio corresponding to the

steady state closure values and,

5) K_{op}/K_{max} load shed, the closure ratios obtained during load shedding tests.

Table 6.2 Closure development results for the HT material

Spec	ΔK MPa√m	Distance (mm)	K_{op}/K_{max} steady state	K_{op}/K_{max} load shed	Comp Crack Growth (mm)	First closure (mm)
A	3	arrest	-	below th	0.86	-
	6	0.26	0.44	0.86		0.5
B	4	0.3	0.84	below th	1.32	0.26
G	5	0.28	0.56	0.96	3.54	0.84*
C	6	0.28	0.43	0.86	1.14	0.45
D	9	0.27	0.33	0.49	1.18	0.47
E	1.6-6.5	0.3	0.91	0.8-0.96	1.24	0.32

* The large amount of crack growth required before closure was detected in this specimen was due to the low P_{max} value (0.55 kN) used during cycling.

The columns in Table 6.2 are the same as those in Table 6.1 except that two columns have been added;

6) Comp crack growth, the length of crack growth under compressive loading, and

7) First closure, the distance of crack growth until closure was first detected during the tensile crack growth stage.

Specimen E in Table 6.2 represents a closure development test in which growth was initiated at the lowest ΔK possible. This test is described in section 6.3.

The closure development distances for the HT material varied between 0.27 and 0.3 mm for the various ΔK values tested, which is somewhat greater than the distances over which closure developed in the AR material. Again the steady state closure ratio was much lower than that obtained from the load shedding tests, except for specimen E.

6.3 Tensile Growth Following Compressive Loading

Suresh et al [23] observed that crack growth under tensile loading immediately following crack growth arrested under compressive loading was not influenced by any residual stresses. This observation was based on a comparison between the growth rate data for R = 0.75 obtained from a) conventional load shedding sequences and b) load increasing sequences following crack arrest under compressive loading, as shown in Fig. 6.9. (See also section 2.4.5).

They therefore suggested an accelerated threshold determination procedure in which the load shedding process is eliminated, i.e., a crack is developed under compressive loading (at a suitable notch), after which tensile loads are applied incrementally until growth is detected, giving ΔK_{th} for the material. The rest of the growth rate curve may then be determined using an increasing ΔK method.

In this work, the above method could not be applied directly. After a fatigue crack had been obtained under compressive loading, tensile load ranges were applied to the specimen, beginning at a ΔK of 0.7 MPa√m and R = 0.1. Two tests were conducted for which growth was first detected at ΔK values of 1.56 and 1.6 MPa√m respectively, (ΔK_{th} for this material at R = 0.1 was 5.0 MPa√m). However, almost immediately after growth had initiated, it arrested again and it was necessary to repeatedly increase loads to maintain growth until ΔK was above the threshold value of 5 MPa√m. The stress intensity ranges applied and the resulting growth rates obtained from this test are presented in Fig. 6.8b, in which the arrows show the sequence of stress intensity ranges applied.

Ritchie and Yu [80], also obtained similar growth rate results in which ΔK had to be increased continually for growth to proceed. However, their results, shown in Fig. 6.10, were for physically short cracks in a 2124 aluminium alloy. The physically short cracks were obtained by removing the crack wake to within 50 μm of the crack tip. Growth initiated at a ΔK of 0.58 MPa√m, with initial growth rates exceeding 10^{-5} mm/cycle which decelerated and arrested at 0.67 MPa√m over a crack extension of about 140 μm. This sequence of events was repeated several times until the crack length reached 450 μm, whereupon the physical short crack growth rates merged with the long crack growth rates. No closure data were given with their results.

The closure development results of the experiment in this work are presented in Fig. 6.8a, which shows that closure could only be detected after 0.32 mm of growth, even though growth rates decreased almost immediately. The closure data was thus unable to explain the above effect even though the sensitivity of the closure measuring system was such that closure should have been detected long before 0.32 mm of growth if it did occur.

Once closure did become measurable the closure ratio K_{op}/K_{max} increased rapidly to a value of 0.88. As ΔK and thus K_{max} varied with crack increment, the closure development results still show a monotonically increasing closure ratio, which develops to a maximum over a distance very similar to that obtained from the other closure development tests.

The stress intensity range at which growth was first observed for these tests was 1.56 and 1.6 MPa$\sqrt{m}$ which is very similar to the intrinsic threshold of this material. Thus cracks arrested during compressive cycling appear to exhibit no closure, and crack growth during subsequent tensile cycling at $R = 0.1$ occurs under initial conditions of zero closure.

Based on the fact that the intrinsic threshold of this material is about 1.5 MPa$\sqrt{m}$, it is reasonable to assume that residual tensile stresses equivalent to approximately 1.5 MPa$\sqrt{m}$ must still exist at the crack tip when the crack arrests under compressive loading. These residual tensile stresses would have to be overcome before closure manifests itself, which would explain why 0.26 to 0.84 mm of crack growth was necessary before closure was detected. Christman and Suresh [133] likewise found that significant crack growth (approximately 0.5 mm) was necessary before closure became detectable in a A542 Cr Mo steel tested at $R = 0.1$ after arresting under compressive loading.

The above analysis is not, however, able to explain why growth rates decreased immediately after initiating under tensile loading, for specimen E. However, if the sensitivity of the closure measurement system and the mechanism of roughness induced closure is considered, an explanation is possible.

For the near threshold growth rates which were measured during this specific test, significant mode II displacement occurred. The occurrance of mode II displacement increases the roughness and/or the oxide induced closure components, both of which produce closure contact very near the crack tip. Thus the closure that caused the growth rates to decrease could not necessarily be detected by the compliance methods used (refer to section 4.3).

If we now consider the results given in Fig. 6.3 for which growth occurred at $\Delta K = 3$ MPa$\sqrt{m}$ and then at 6 MPa$\sqrt{m}$ after arrest, we notice again that growth arrested without any closure being detected, possibly because closure occurred very near the crack tip. Subsequent growth rates at $\Delta K = 6$ MPa$\sqrt{m}$ were relatively constant for a distance of 0.3 mm, after which they decreased concomitant with an increase in closure. The fact that growth rates remained constant for 0.3 mm may be a result of the higher growth rates for which the mode II displacements decrease thereby reducing the near tip closure substantially.

The above analysis appears to ignore an earlier finding i.e., that residual tensile stresses exist at the crack tip, which should prevent closure developing immediately. However, it is possible that even in the presence of residual tensile stresses at the crack tip, closure may develop if the fracture surface is sufficiently rough and sufficient mode II displacement occurs. Thus for near threshold growth rates the closure development occurs on a different scale to that at higher growth rates.

6.4 Discussion

6.4.1 Closure elimination

A fatigue crack which has experienced compressive loading or growth under compressive loading is probably very similar to a fatigue crack in welded material in which residual welding stresses are present. For both situations sufficiently high residual tensile stresses may exist which could prevent the crack from closing for positive applied loads.

Compressive loads do, however, also have another effect, namely the crushing and compaction of asperities. Although, this will decrease closure, the fact that 1) a significant amount of crack growth is necessary before closure develops, and 2) residual stresses are expected after a crack has arrested under compressive loading, suggests that the residual stresses are the dominant mechanism whereby closure is eliminated.

6.4.2 Closure traces

The offset-displacement vs load traces produced after closure was eliminated by wake removal and a compressive overload, were straight horizontal lines which indicate no closure. The closure traces produced following growth under compressive loading were totally different and, as mentioned in section 6.2, were difficult to interpret. Examples of such traces are shown in Figures 6.11. Such curvature in the traces is indicative of either a bowed crack front or the presence of significant plasticity. In this case it is believed to be a result of the peculiar residual stress distribution due to the (large) notch plastic zone. As the crack propagates the traces become straighter and eventually it is possible to detect a linear portion corresponding to a linear elastic situation.

Hysteresis complicates the process of determining the closure value from a compliance trace because it produces non-linearity which is usually assumed to indicate closure. In addition, high magnification is necessary to detect closure when K_{op} has near-zero values, which increases the apparent hysteresis. In some of the closure development experiments it was only possible to measure closure on the load increasing trace as the load decreasing trace was too curved.

When closure is first detected the distance over which closure contact occurs behind the crack tip is very short, with the result that the change in curvature of even a highly magnified offset displacement vs load trace is very small. Thus the error in measuring P_{op} when closure is first detected is fairly high and may be of the order of 20%. As the length of wake contact increases, the change in curvature becomes greater and P_{op} can be measured more accurately. Even though the accuracy of the measuring system is so low, the compliance methods used were still the most accurate for detecting closure. (See section 2.4.5.6).

The closure development and growth rate data presented in Fig. 6.8 may also be used to approximate the sensitivity of the closure measurement system. In other words, the minimum distance of crack wake contact required behind the crack tip, to ensure a change in the offset compliance curvature. This may be deduced by comparing the crack length at which growth rates decrease, indicated as line a_1, and the distance at which closure is first detected indicated by line a_2. This distance between the point at which growth rates begin to decrease and where closure first begins is 0.04 mm, which gives a first order approximation of the sensitivity of the closure measurement system.

6.4.3 Closure and the closure development distances

Closure develops over 0.19 mm in the AR material and over about 0.28 mm in the HT material for all the ΔK values tested. However where growth occurs at near threshold rates the measurement system may be unable to detect the relevant closure (i.e., near tip closure). Thus closure development at near threshold growth rates cannot be adequately characterised. The steady state closure ratios K_{op}/K_{max} to which closure developed in the closure development tests are significantly lower than the corresponding values obtained at similar ΔK values during load shedding, (except specimen E). This is particularly the case for the closure development test conducted for $\Delta K = 4$ MPa$\sqrt{m}$ which represents a value below the long crack threshold for $R = 0.1$ of 5 MPa$\sqrt{m}$, yet growth still occurred after closure had developed to its steady state value. The fact that growth was still possible at $\Delta K = 4$ MPa$\sqrt{m}$ and the fact that the steady state closure ratios were generally low supports the suggestion that the high closure present in long cracks at low ΔK in normal threshold tests is related to the load shedding scheme employed.

For specimen E, the steady state closure ratio reached a value similar to that obtained during the load shedding tests. In fact the closure ratio at steady state for a ΔK of 6.5 MPa$\sqrt{m}$ was 0.88 which is even greater than the value obtained from the load shedding scheme. This high closure ratio may be the result of extensive growth at near threshold growth rates which could have increased the fracture surface roughness (because of mode II growth) thus increasing closure. (This greater roughness induced closure is not to be confused with the near tip closure which cannot be measured by the available compliance methods.)

6.5 Summary

Closure develops over 0.19 mm in the as-received material and 0.27-0.3 mm in the heat treated material. This closure development distance is independent of ΔK. The magnitude to which closure develops was found to depend strongly on the growth rate. For high growth rates (greater than 10^{-6} mm/cycle) closure develops to approximately one third to two thirds of the values obtained from the load shedding tests, whereas for near threshold growth rates (less than 10^{-6} mm/cycle), closure develops to values which may even be greater than those obtained from the load shedding procedure. This effect was thought to be due to extensive mode II growth contributions at near threshold growth rates.

7 COMPARISONS WITH SHORT CRACK DATA

In this chapter short crack results are reported and analysed. The short crack regimes for the AR and HT material are compared with the corresponding closure development distances found in long cracks. From this comparison, conclusions are drawn with respect to the role of closure development in determining the short crack regime.

7.1 Short Crack Growth

Short crack data were obtained in both the AR and HT conditions at R = 0.1. These results are plotted as da/dN vs 2c and as da/dN vs ΔK in Figures 7.1a and b and 7.2a and b respectively. The data points were obtained from various cracks in numerous specimens under slightly differing stress ranges, thus it was not possible to plot both da/dN vs 2c and da/dN vs ΔK on the same graph. Short crack growth data were also obtained at R = 0.55 for the HT material, which are also plotted in terms of 2c and ΔK in Fig. 7.3a and 7.3b.

Long crack data is included in the graphs of da/dN vs ΔK which show that short crack growth rates are much higher than for long cracks, and that growth occurs at stress intensity ranges well below the intrinsic material threshold of approximately 1.5 MPa√m (at least for the HT material). Growth rate data at high and low R ratios are compared in Fig. 7.4 for the HT material, which shows a distinct difference between the two conditions for ΔK values greater than approximately 2.8 MPa√m.

7.2 Discussion

The short crack data presented in figures 7.1a and 7.2a, show a significant amount of scatter. Scatter in the AR material (Fig. 7.2a) decreases for crack length values greater than 250 μm (indicated by the line in the figure). For the HT material tested at R = 0.1 (Fig. 7.1a), a reduction in the scatter is only apparent for crack lengths greater than approximately 700 μm.

If comparisons are made between the crack length at which the scatter in growth rate has decreased, with the closure development distances measured in long cracks, the crack depth a should be used, and not the surface crack length 2c. Thus for the AR material the closure development distance is 0.19 mm and the short crack depth a is 0.155 mm. Similarly for the HT material the closure development distance is 0.28 mm and the short crack depth is 0.35 mm. These comparisons do not show a good correlation. However on a qualitative basis, the crack length at which growth rate scatter decreases in the heat treated data is greater than for the as-received data, which corresponds with the fact that a greater distance is required to reach steady state closure for the heat treated material.

The short crack data for R = 0.55 also shows a significant amount of scatter, however, it is less than for the R = 0.1 data. A noticeable feature of the R = 0.55 data are two distinct regions of growth, one for crack lengths below 60 μm in depth and one for cracks lengths above 60 μm in depth. The grain length in the direction of crack growth was approximately 60 μm, from which it may be deduced that the difference in growth behaviour is a result of a change in growth mechanism from Stage 1 to Stage 2.

It was fortunate that growth rate data could be obtained at high R ratios, as most alloys require stresses greater than the macroscopic yield strength to initiate cracks at such R ratios. This violates the conditions under which LEFM are applicable, which means that the cracks cannot be characterised by ΔK. The stresses required to initiate cracks in this material were, however, low enough to enable short crack growth tests to be performed at R = 0.55 without adverse effects from plasticity. The maximum stresses applied were still 70 MPa below the material yield stress (= 412 MPa). The reason why the initiation stresses are so low is probably because of the presence of large impurity inclusions (≈5 μm) which are generally present in 2XXX and 7XXX series Al alloys. Where much smaller particles exist (0.1 - 0.2 μm) crack nucleation becomes more difficult, because these particles help disperse slip [120].

The main differences between growth at high and low R relate to 1) the possibility of closure development at low R, and 2) the fact that P_{max} is greater at high R which may reduce the arresting effect of the grain boundaries (due to the relative change in grain orientation). These differences are both expected to reduce the scatter at high R ratio, which is indeed the case.

If one assumes that the reason why grain boundaries act as a greater barrier to growth at low P_{max} (low R ratio) is related to closure, (as was suggested by Morris [121]) then the only difference between the two situations (assuming that the material does not exhibit an intrinsic R ratio effect) is the development of closure at low R. The point at which growth rates for the different R ratios begin to differ, can then be used to indicate the length at which closure becomes important in short crack growth. Fig. 7.4 shows that growth rates at R = 0.55 become slightly higher than at R = 0.1, once ΔK increases above 2.8 MPa√m (indicated by the solid line on Fig. 7.4). On converting 2.8 MPa√m to a crack length 2c it was found that 2c was approximately 260 μm for the R = 0.1 data and 400 μm for the R = 0.55 data (the crack lengths differ because different stress ranges were used.) Thus for cracks that are around 130 μm in depth, (a ≈ 2c/2 = 260/2), closure had developed sufficiently at R = 0.1 to lower the growth rates compared to R = 0.55. The above result does not, however, imply that the distance over which closure develops to a steady state value is 130 μm, but only that the effect of closure on growth rates becomes noticeble after 130 μm.

Although Fig. 7.4 shows that short crack growth at R = 0.1 occurs at lower growth rates than for R = 0.55, (due to closure development), Fig. 7.1b shows that the growth rates are still higher than for the same R ratio in long cracks. This result is also suggested by the long crack closure development results, which show that the steady state closure value achieved by an initially closure-free crack (approximating the short crack situation) is significantly lower than the closure value obtained while employing a load shedding scheme at an equivalent ΔK. It is worth noting that the closure magnitude in long cracks becomes significant relative to K_{max} only when growth rates decrease below 10^{-5} mm/cycle. Thus it is not surprising that the effect of closure development on short cracks is not that marked, as by the time the short cracks approach the steady state crack length growth rates are generally greater than 10^{-5} mm/cycle. From this it follows that if growth rates could be maintained at near threshold values the closure development should be much greater, as was the case for long crack closure development (Fig. 6.8).

The effect of closure development on the short crack results presented here does not show a clear trend, such as a reduction in the scatter as the crack grows to the length over which closure developed in long cracks. It is also difficult to establish the length of the short crack regime, because growth rates were always greater than those for long cracks. The above could, however, be clarified if more short crack data were obtained.

8 SUMMARY OF CONCLUSIONS

The primary objective of this thesis was to establish the role played by closure development in determining short crack behaviour in a high strength aluminium alloy.

This objective was achieved through the following:
1. Characterising fatigue crack growth with particular emphasis on the manner in which closure affects such growth.
2. Characterising closure development in this material for "long" cracks in CT specimens.
3. Determining short crack growth behaviour, and
4. Comparing the distance over which closure develops in long cracks with the short crack regime.

The conclusions derived from the above work were:

1. Fatigue crack growth in this material exhibits extensive closure and consequently growth rates are a strong function of the R ratio. Although the growth rates did decrease significantly because of closure the K_{op} values that were measured overestimated the closure magnitude. This was found to be the result of extensive strain intensification below K_{op}.

2. Closure development proceeded over relatively short distances of 0.19 mm for the AR material and over about 0.28 mm for the HT material for growth rates in the linear regime of the growth rate curve. For near threshold growth rates, closure development could not be measured, possibly because closure contact occurred very near the crack tip and hence could not be detected by the closure measurement system used.

3. Short crack growth occurred at rates well above those for long cracks and at stress intensity ranges far below the threshold stress intensity range for long cracks. Short crack behaviour was exhibited over crack lengths 2c of about 0.16 mm for the AR material and 0.35 mm

for the HT material. These distances were similar to the distances over which closure was found to develop in long cracks. Qualitatively the greater closure development distance corresponded with the greater distance over which short crack behaviour was exhibited, thus suggesting that closure development does play a major role in short crack behaviour in this aluminium alloy.

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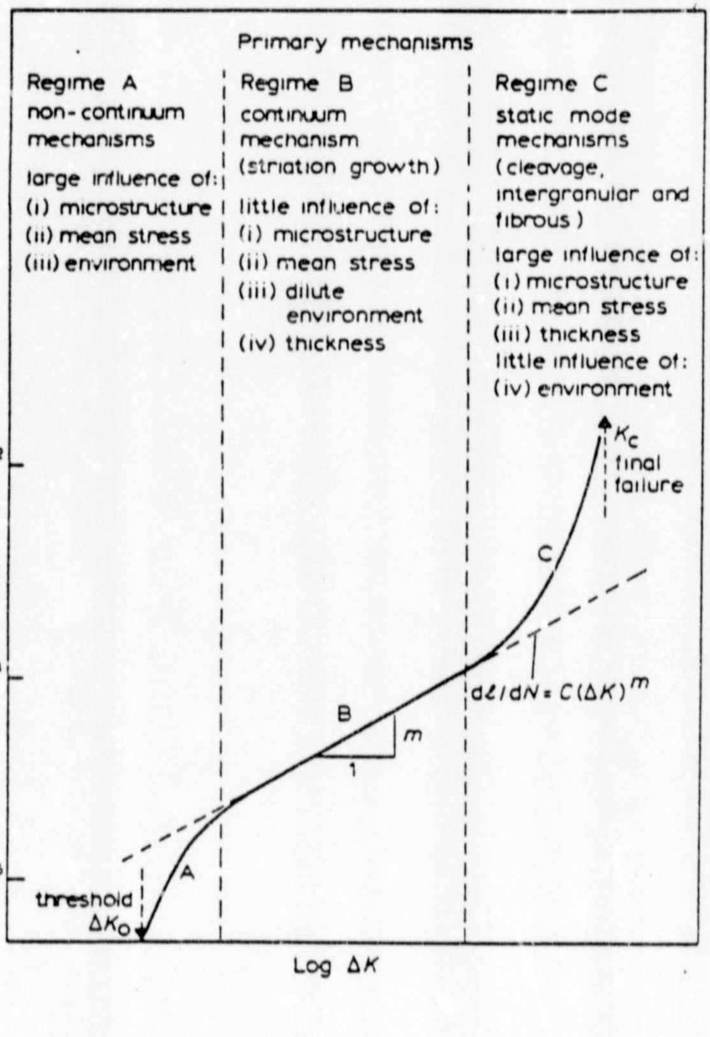


Figure 2.1 Schematic illustration of the three regimes of fatigue crack growth rates and the corresponding mechanisms and characteristics. (After Ritchie [12]).

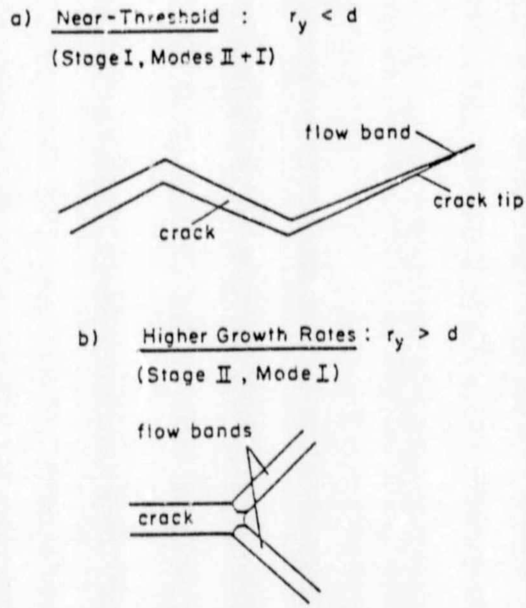


Figure 2.2 Crack opening profiles representing near a) threshold (regime A) b) and higher growth rate (regime B) fatigue crack propagation (after ref. [13]).

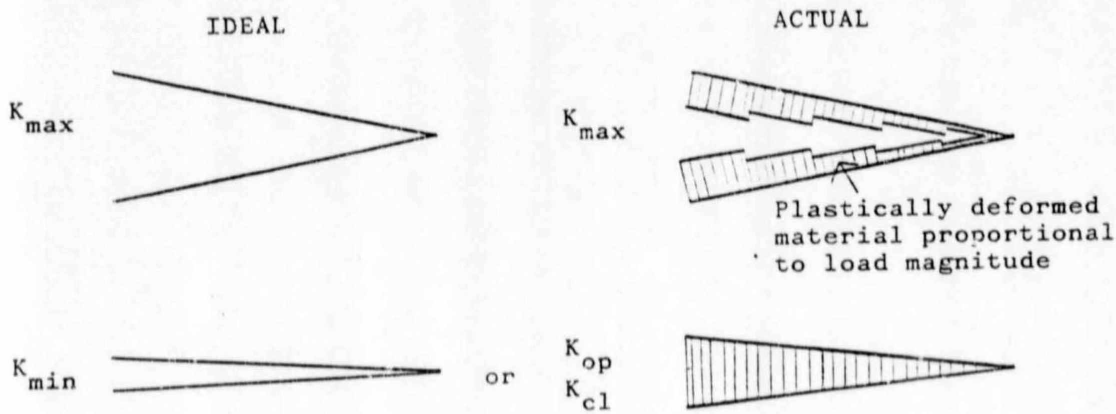


Figure 2.3 The effect of load shedding on plasticity induced closure, in a fatigue crack.

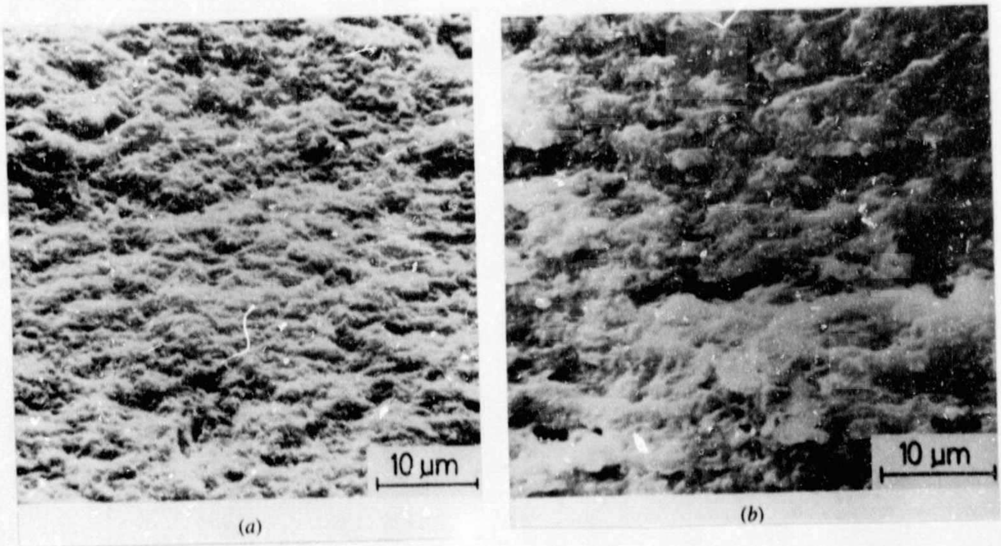


Figure 2.4 The change in fracture surface roughness with R ratio on a IN 9021 T4 alloy a) R = 0.05 b) R = 0.8 (after ref. [25]).

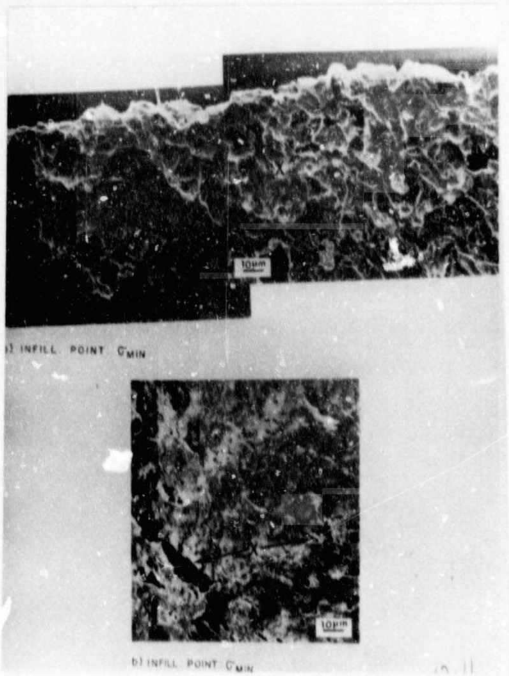
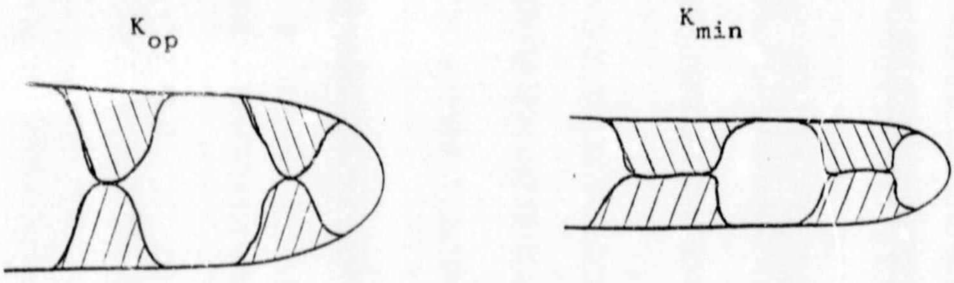


Figure 2.5a Illustration of the contact evident from the infiltration technique (after ref. [35]).



Crack tip experiences a change in strain while loading decreases from K_{op} to K_{min}.

Figure 2.5b Elastic and plastic deformation of asperities resulting in strain intensification for stress intensity ranges below K_{op}.

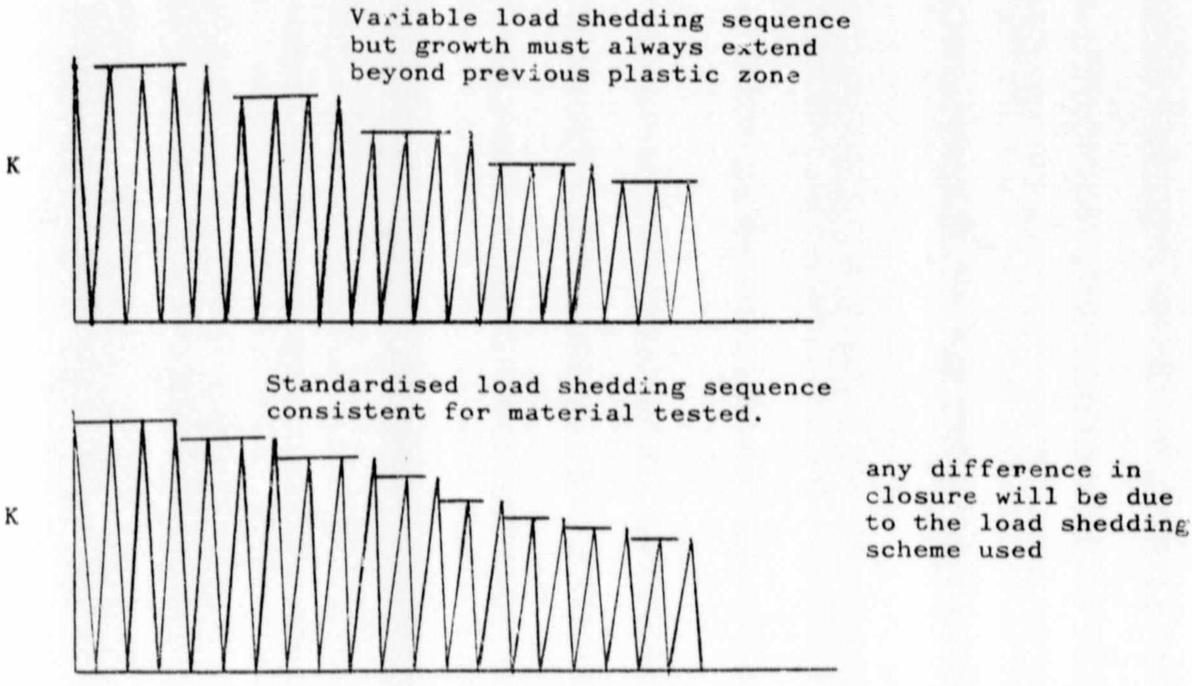


Figure 2.6 Variations in load shedding sequences used to determine the effect of plasticity induced closure on the overall closure magnitude.

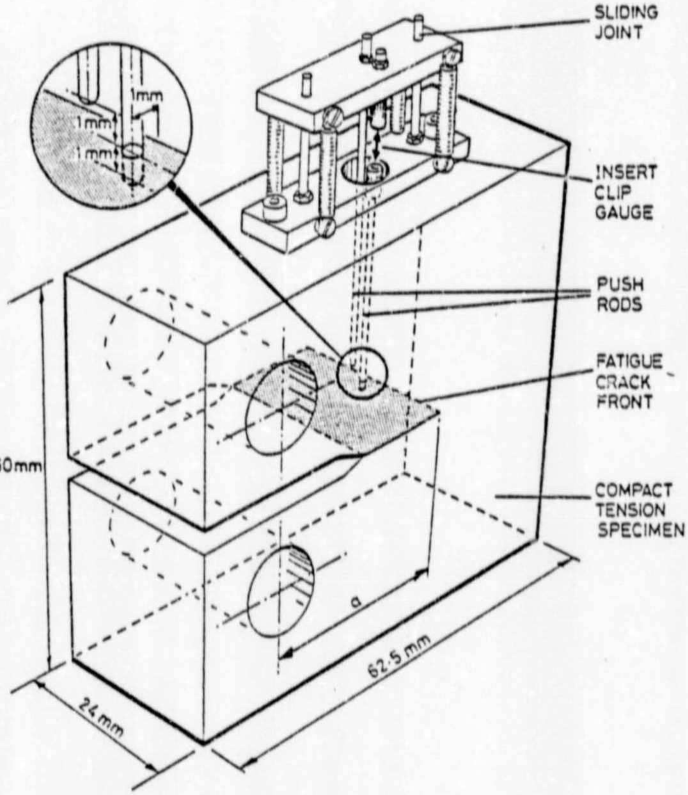
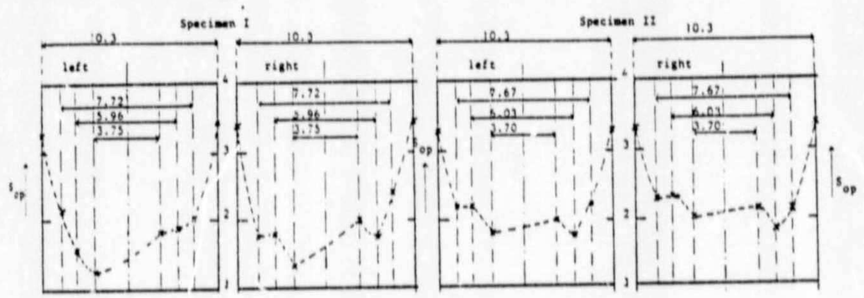


Figure 2.7 The push-rod assembly used by Smith .d Fleck to measure the magnitude of closure under plane strain, i.e., closure in the centre of a specimen [43].



Specimen Thickness

Figure 2.8 The effect of surface removal on the closure stress along a CT specimen [48].