The term short crack is reserved for a crack whose maximum dimensions are small relative to either:-

1. some microstructurally important dimension (eg. grain size), ie. a continuum mechanics limitation, or
2. some local plastic field with which the crack might be associated, or
3. simply physically small.

Short crack growth below the threshold stress intensity found for large cracks is not surprising if one considers that cracks generally initiate from very small initial defects. Since ΔK is proportional to $\Delta\sigma\sqrt{a}$ early crack growth must involve very low stress intensity ranges [107]. This does not, however, explain why short cracks grow faster than long cracks, nor why some materials exhibit extensive short crack behaviour while others exhibit practically none [2, 108].

To summarise, short crack behaviour comprises two aspects :-

1. Short cracks grow faster than long cracks under nominally identical stress intensity ranges (ΔK) and at values below the long crack threshold.
2. Short cracks exhibit transient dips and peaks in the growth rate curve.

2.5.1 Reasons for faster short crack growth

Various reasons have been suggested to explain faster short crack growth, however, many are limited to certain situations and they may not occur concurrently.

1. Short cracks initially proceed along the most favourable slip band system, or along "soft spots" (crystallographically favourable growth) [80, 45].
2. Where plastic damage occurs prior to initiation in alloys in which initiation takes a long time, more rapid growth might be expected in the high damage area [109].
3. Crack tip strains and crack tip opening displacements for short cracks have been reported to be larger than for long cracks [79, 80, 110-113]; at low stresses these differences can exceed an order of magnitude.
4. The absence of closure due to the limited crack wake of short cracks, i.e., a higher effective driving force exists compared with longer cracks.

Other minor differences include 1) the fact that the size of short cracks means that it is easier for environmental species to get to the crack tip and therefore environmental influences might be expected to be greater, as has been observed by Gangloff [114] and Ritchie [80]; and 2) differences in rates of crack extension around the crack front, which may cause the aspect ratio to change, and if the crack length is measured on the specimen surface and the aspect ratio changes, the crack growth rate will change. Large variations in the aspect ratio have been observed, but these variations were limited to the extent of the short crack regime as illustrated in Fig. 2.24 [71].

Some of the above reasons shall now be discussed in more detail :-

1. Short crack growth is crystallographic and thus non-continuous growth is to be expected, as microstructural variations are encountered by the crack front. Furthermore because plastic constraint is lower around short cracks, growth can obviously follow the easiest crystallographic route for a longer distance before growth becomes constrained to that plane corresponding to the maximum stress. Thus short cracks may be strongly deflected at grain boundaries if the easiest slip direction in the next grain is at a large angle compared to the present grain [115]. Such growth is often, however, generally limited to very small crack sizes ($a < 25\ \mu m$) [116]. Deflections in the crack path result in a reduced driving force, eventually causing the crack to follow a straighter crack path once the advantage of growing along an easy path is outweighed by the disadvantage of large crack deflections, (see section 2.4.3). Also, the crack front samples an increasing number of grains which tends to "iron out" crack deflections on a macro scale.

If rapid short crack growth does occur because of growth along "soft spots" one would expect a smaller grain size to limit such short crack behaviour as various differently oriented grains are encountered sooner. This is indeed the case, as reported for a Ti-8Al titanium alloy [117]. Such direct comparisons can, however, be complicated by differing crack growth paths eg. growth in fine grained material has been found to occur within the grains (i.e., transgranularly), whereas growth in coarse grained material may occur along the grain bounda... (i.e. intergranularly) [104].

Rapid growth within a single grain is not limited to short cracks. Lankford and Davidson [118] showed that both long and short crack growth in a single crystal followed the same ΔK based relationship, (which was much faster than that observed for polycrystalline specimens of the same alloy). They suggested that anomalously fast growth for short cracks represents "baseline" growth rate data and that long crack growth rates in polycrystalline materials are reduced below this because growth is averaged over many disadvantageously oriented grains.

2. The sort of damage that may occur in grains and give rise to rapid growth, includes softening which may reduce the local yield strength [119]. This type of behaviour i.e., local softening, will manifest itself by causing greater crack tip strains or crack opening displacements.

3. Larger crack tip strains and COD in short cracks relative to longer cracks at the same value of K, occur because short cracks are in a situation of plane stress [112]. Morris [115] examined the size of crack tip plastic zones for short cracks and concluded that they were principally determined by the location of the microcrack with respect to the grain boundary. This aspect relates back to the non-continuum nature of short crack behaviour during growth within the first few grains.

The large degree of plasticity associated with short cracks relative to the crack size, is itself a cause for discrepencies between long and short cracks based on ΔK. This stems from the derivation of K which is a first term approximation of the elastic stresses at the crack tip, and requires that crack tip plasticity is small compared to the crack length.

4. Support for the premise that reduced closure values cause short crack behaviour comes from various authors [2, 120, 121]. A number of studies have indicated that K_{op}/K_{max} increases with crack length, with the upper limit of small crack behaviour coinciding with the attainment of "steady-state" closure values representative of long cracks. For semi-elliptical cracks this upper limit is often around 100-160 μm in steels [2], 100-200 μm for titanium alloys [122] and 100-300 μm aluminium alloys [79,103].

As closure values generally progressively decrease for long cracks, as the stress ratio increases, tests performed at high R values can be used to deduce growth rate values for short cracks. Short crack growth at R = 0.1 has been found to be comparable with long crack growth obtained at R = 0.5 - 0.8. [95, 123].

The second aspect of short crack growth relates to the transient dips observed in the growth rate curve. The general causes of these effects are;

1. Interference with grain boundaries; and
2. Closure development.

Morris [12] observed that short cracks exhibited greater closure as a grain boundary was approached. The grain boundary interaction effect arises from this fact together with the obstacle to slip that an adversely oriented grain boundary represents. It may therefore require an incubation period to propagate slip across the boundary. These two effects lead to dips in growth rate (or even total arrest) as the crack tip approaches a grain boundary.

James [2] was not able to correlate transient dips in the growth rate curve with grain boundary interactions and therefore assumed that this phenomenon was as a result of an interaction between the increase in ΔK as crack length increased and the attendant increase in closure. (It was not mentioned whether grain boundary interaction was considered along the surface as well as the crack depth.)

Although closure has been reported to play a part in the drop in growth rate for short cracks, grain boundary interference is accepted more widely as the cause for such transient perturbations [121]. The degree of crack growth retardation has been linked to the relative orientation of the adjacent grain [125]. Where the orientation is suffiently different, arrest may occur provided the stress is low enough (ie. a low stress combined with a small crack size of the order of one or two grain sizes) [79, 125]. The mechanism by which unfavourably oriented grains arrest or retard short crack growth involves reduced microplasticity as the grain boundary is approached, due to a more limited slip distance. For growth to continue into the next grain a "mature" plastic zone needs to be developed [126]. In essence, it is not the grain boundary which acts as a barrier but the relative misorientation of the slip planes in the adjacent grain.

2.5.2 Through-thickness short cracks

Through-thickness short cracks are different to semi-elliptic short cracks in that they are short in two dimensions only, i.e. their crack fronts sample many grains even at small lengths. It is, therefore, not surprising that short crack behaviour is different for the two types of cracks. The difference may generally be explained in terms of wake closure [127-128], and the different crack generation techniques used for their generation.

2.5.3 The extent of the short crack regime

The distance over which rapid short crack growth occurs is not necessarily the same as that over which dips in growth rate are exhibited. The most severe case of such growth transients, namely, total crack arrest, is limited to cracks of the order 1 or 2 grains. The maximum length of non-propagating cracks are presented in Table 2.1 for various materials and grain sizes.

Although short crack growth appears to be strongly influenced by grain boundaries, no clear trend relating grain size to the limit of short crack behaviour is generally obvious. Numerous authors have nevertheless presented their results in terms of the grain size. It seems more appropriate that the limit generally be seen in terms of the interplay of a number of factors (e.g., closure and microstructure) and not just grain size. Distances over which short crack behaviour have been reported are presented, together with grain size data, in Table 2.2.

The extent of short crack behaviour may also be influenced by the magnitude of the applied stress range [79] and/or the maximum stress in the cycle. This is presumably related to the increasing ease of slip propagation past grain boundaries as either of these parameters increases.

Table 2.1 Maximum dimensions of nonpropagating cracks

Reference	Max Crack Depth (μm)	Grain Size μm	No of Grains	Material
[80]	15 - 30	-	-	cast iron
[71]	30	91	1/3	HSLA SCM 435
[71]	10	15	1	" " "
[103]	20	18	1	7075 T6 Al
[104]	25	24	1	low C steel
[104]	175	84	2	" "

Heat treatment also plays a role in short crack behaviour and its effect on both the extent and the degree of microstructural dependence of short crack behaviour is illustrated by the following results.

James and Smith [14] studied a quenched and tempered 0.4% carbon steel with a ferrite grain size of 10 μm. They observed no microstructural dependence on small crack growth, with Stage II growth being established very early on in life. Enhanced growth rates were found for cracks whose surface length was less than 100 μm. The short crack effect was explained by changes in closure. In a study of a normalised 0.4% carbon steel with a prior austensite grain size of 140 μm however, de los Rios et al [129] observed microstructurally dependent growth with cracks arresting at ferrite/pearlite interfaces. Short crack behaviour was observed for cracks with surface lengths in the range of 200-300 μm, which corresponds to the lengths of ferrite allotriomorphs in which the cracks had initiated. This illustrates clearly that changing the microstructure can change the dominant mechanism behind short crack growth and also the extent of such behaviour.

Table 2.2 Crack lengths for which short crack behaviour has been reported

Reference	Crack Length (μm)	Grain Size (μm)	No of Grain Sizes	Material
[79]	110	25	4	Al 2024 T3
[79]	40-45	20	2	Al 7475 T761
[103]	88	18 and 80*	5	Al 7075 T6
[130]	74	15** and 5	7	High Strength Ti alloy
[130]	1500	70	20	Ti-8 Al
[104]	950	24	40	low C steel
[104]	1200	84	14	low C steel
[102]	127	-	-	-
[118]	20	7	3	Al 7075
[118]	100	55	2	Al 7090 PM
[118]	225	5	45	Fine grained Astroloy
[118]	500	50	10	Coarse Grained Astroloy
[131]	150	20	8	Al 2024 T4
[107]	300	-	-	Al Bronze

* 18 μm in depth and 80 μm along the specimen surface
** this is a duplex structure with one grain size = 5 and the other 15 μm.

Data for several alloy systems has indicated a straight line relationship between grain size and the crack tip plastic zone at the point where short and long crack growth converges as shown in Fig. 2.25 [118]. This figure shows that if the grain size is known the plastic zone size may be deduced, which can be used to calculate a stress intensity, and assuming a certain stress range the extent of the short crack regime can be obtained. (Because a certain stress range has to be assumed the figure suggests that the extent of the short crack regime is dependent on the applied stress range.)

2.5.4 Closure and closure measurement in short cracks

Few closure results for short cracks have been presented in the literature, probably because measurement is difficult as conventional techniques for long cracks are generally not sensitive enough.

However, Larson [130] has used an interferometric technique to measure the crack compliance in a titanium alloy, from which closure values were obtained. His data show that closure increased in sudden jumps as the crack length increased. These sudden jumps were suggested to be related to crack bifurcations. If the jumps were not related to crack bifurcations but rather to grain boundary interactions the results agree with those obtained by Morris [124] who found closure to increase as the grain boundaries are approached. The closure behaviour found by the two authors appear similar when the results of Morris are compared to those of Larson over the first 20 000 cycles as shown in Fig. 2.26.

James and Morris [122] used measurements of residual crack opening at zero load to deduce that crack closure values decreased as the crack length (2c) decreased below 160 μm (for a titanium alloy of yield strength σ_y = 1140 MPa). For cracks greater than 160 μm a steady state closure value was achieved.

An attempt has been made by Blom et al [79] using FEA to determine how, and over what distance, closure develops for small cracks considering only plasticity effects. The numerical results obtained are presented here in Fig. 2.27, and show that closure develops over a distance of approximately 400 μm. Experimental results by the authors showed the limit of short crack growth to occur at 2c > 400 μm which agreed very well with their numerical results, suggesting closure may be responsible for the short crack behaviour in the specific material used.

2.5.5 Short crack characterisation

To compare crack growth for two different cracks using LEFM and ΔK requires similitude [132] between; CTOD, strain and plastic zone size, growth mechanisms, and small scale yielding (ie. a small plastic zone compared to the crack size). It is clear therefore that the concept of similitude is violated with small cracks and the validity of K as a description of crack tip conditions is questionable [110, 133]. However, because the stess intensity concept currently provides the most convenient deterministic basis for fatigue life predictions, it is desirable to extend this concept to include as many situations as possible.

An obvious route through which ΔK may be modified to ensure a better correlation between long and short crack growth is by using ΔK_{eff}. However, as has been indicated, closure measurement of short cracks is difficult and time consuming.

In an attempt to consider the relatively large amount of plasticity sometimes associated with short cracks and which is one of the causes of short crack behaviour, Dowling used the elastic plastic fracture mechanics parameter ΔJ and successfully correlated long and short crack growth [134], see Fig. 2.28. However, the use of ΔJ requires crack tip strain measurements [110] and this is somewhat more difficult to use than the LEFM parameter, and is still the subject of controversy in its applicability to fatigue. The incorporation of closure effects in ΔJ measurements is also much more difficult, which in general does not make ΔJ a very easily usable parameter.

To summarise, when trying to ascertain the cause for short crack growth it is important to remember that microstructural, plasticity and closure effects may be responsible, and although some authors have explained their observations exclusively in terms of one parameter, the relative areas of influence of all three need to be determined for any given material. LEFM analyses can be extended to cover sitations where closure is dominant through the use of ΔK_{eff} but, irrespective of material, the very early stages of crack growth are likely to be amenable only to the existing S-N approach. In the future, however, probabilistic analyses may be able to treat this area adequately. Luckily, for a number of common structural materials, closure appears to dominate the short crack regime over most of its extent, offering the hope of extending defect-tolerant life analyses to smaller initial sizes.

2.6 Closure Reduction and Redevelopment

Of great significance in fatigue crack growth predictions is the material threshold below which growth occurs at experimentally undetectable rates. In the presence of a crack, the threshold value can be used as an "endurance limit" for stress intensity values. Equally, the majority of the life of a crack is spent at near-threshold growth rates and an accurate estimate of its value under a given set of experimental conditions is thus of great importance. Because of this, numerous authors have concentrated their research on factors affecting the threshold (and closure) values, included amongst which are compressive overloads, and the effect of removal of part of the crack wake. (This latter factor is important in relation to understanding the data reported for a large number of studies of artificially generated short cracks and in understanding the manner in which closure develops in the crack wake).

The most frequently encountered situation where compressive loads reduce closure and hence threshold values arise when growth rate data are determined at $R < 0$. ΔK_{th} values in such tests are generally lower than for $R = 0$, because the compressive portion of the cycle reduces the closure value [135], possibly by compacting the fracture surface asperities. Gan and Weertman [68] (on a 7075 T6 aluminium alloy) showed that it was not even necessary to apply compressive loads to reduce closure, but that this could be accomplished just by reducing K_{min} below K_{op} (i.e. to zero) during cycling. Thus any cycles on a component or structure in which the minimum K value in the cycle experiences an "underload" is likely to decrease closure.

Ritchie and co-workers [28, 136, 137] applied compressive overloads on cracks arrested at threshold ($R = 0.1$ using CT specimens) and observed no effect for small compressive loads (two to three times the tensile peak load corresponding to the threshold). A compressive load of five times the tensile load at threshold did, however, result in recommencement of growth, concomitant with a reduction in closure, and evidence of abrasion was found on the fracture surface for a 7075 aluminium alloy in the underaged, peak-aged and overaged condition, and a 7150 aluminium alloy in the overaged condition. Similar tests at $R = 0.75$ produced no growth, consistent with the fact that closure occurred below K_{min} for $R = 0.75$.

Yu et al [99] using CCT specimens observed the threshold to decrease linearly for both a SAE 1010 steel and a 2024 aluminium alloy with the application of progressively greater compressive overloads, up to 100% of the respective material yield strength. As the thresholds decreased the intrinsic threshold component (see section 2.4.1) remained constant while K_{op} decreased. Thus the results were explained in terms of a decrease in closure level.

It appears that the increase in driving force following compressive loading can be attributed to two principal factors:

1. The crushing and compaction of asperities as verified fractographically, which showed clear indications of abrasion, resulting in a decrease in the roughness and oxide induced closure contributions [28, 136, 137] (see section 2.4.5).
2. A redistribution of residual stresses ahead of the crack tip. In

other words, the formation of residual reverse tensile stresses at the crack tip [99].

The effectiveness of compressive overloads is limited to near-threshold growth [82, 137, 138] where K_{op}/K_{max} is greatest and where, because near threshold growth is very sensitive to changes in ΔK, slight changes in closure may result in large changes in growth rate which can therefore be easily detected. Maximum effectiveness of a compressive overload is obtained when the crack tip is very near the loadline. Under such conditions the crack tip experiences tensile residual stresses following overloads, and crack growth may occur even under compressive loading. If loading is applied behind the crack tip the compressive load will reduce or eliminate closure depending on the magnitude of the compressive load, but as the crack tip moves further from the load line, the effect of the compressive load is diminished.

The results of Ritchie and co-workers, given above, showed that compressive loads could reduce closure and cause recommencement of growth of a crack which was previously arrested at threshold. However, the growth rate at ΔK_{th} soon decreased as closure redeveloped and re-arrest occurred after 60 μm, 130 μm and 170 μm respectively for underaged, peak-aged, and overaged 7150 alloy, and 230 μm for the overaged 7475 alloy, as shown in Fig. 2.29. The distance over which closure developed and re-arrest occurred was found to be inversely proportional to the fracture surface roughness. Thus the authors suggested that roughness induced closure was largely responsible for the redevelopment of closure and re-arrest.

In analogous experiments to the above, Zaiken and Ritchie [139] reduced closure in underaged, peak-aged and overaged tempers of a 7075 aluminium alloy by removing the crack wake to within 0.5 mm of the crack tip for cracks arrested at threshold. In these studies crack growth recommenced and grew over roughly 2-10 grain sizes followed by a reduction in growth rate. Minimum growth rates were measured after 20, 50 and 100 μm of growth for the underaged, peak-aged and overaged tempers respectively.

The underaged structure again exhibited the largest reduction in closure values when the wake was removed, and significant closure re-developed over the smallest distance in this structure, as occurred in the experiments using compressive overloads. Thus it appears that the compressive overload and the wake removal process reduce crack closure in the wake which acts far from the crack tip.

In another wake removal experiment where load shedding had been conducted, Minakawa et al [25] removed the crack wake to within 0.86 mm of the crack tip in a 7090 P/M aluminium alloy, also resulting in the recommencement of growth at threshold load ranges. The crack arrested 0.8 mm later but only because the stress intensity range had been reduced from 2.2 MPa√m to 2 MPa√m. For both cases ΔK_{eff} at threshold remained the same, implying again that the test technique induced closure far from the crack tip.

Numerous experiments have been conducted involving crack wake removal, or the application of compressive loads to reduce closure. The former experiments have enabled estimates of the closure contribution arising from various portions of the crack wake. Some results of such tests are given in Table 2.3. The application of compressive loads, however, does not give any information regarding the position of closure along the crack wake, but it does give an indication of the distance over which closure develops sufficiently to cause crack arrest or to reach a steady state closure value.

Table 2.3. Change in closure with wake removal

Reference	Material	Wake Removal Distance (mm)	Change in Closure	Majority of Closure
[73]	7090 P/M	0.86	22%	< 0.86 mm
[29]	7075	0.5	60%	> 0.5 mm
[63]	Parent plate	0.5	30%	< 0.5 mm
[63]	Coarse grained	0.5	0%	<< 0.5 mm
[128]	A508 Steel	0.6	80%	>0.6 mm
[139]	Al 7075 UA	0.5	58%	<0.5 mm
[139]	Al 7075 PA	0.5	57%	<0.5 mm
[139]	Al 7075	0.5	36%	>0.5 mm

Minakawa et al [53] successfully eliminated closure in a 9Cr-1Mo alloy steel, following growth at R = 0.05 by removing the wake to within 1.3 mm of the crack tip, and applying a residual stress relief anneal at 570°C for 2 hours in vacuum. Having eliminated closure the authors then examined closure re-development at ΔK applied = ΔK_{th}. Closure developed rapidly for the first 200 μm and reached the original value after a total crack increment of 500 μm. The results of the above test are presented in Fig. 2.30. A few other workers also successfully eliminated closure and were able to examine its redevelopment, as shown in Fig. 2.31. The the distances over which closure developed for the various metal alloys varied from 250 μm for a 2024 T351 aluminium alloy [140] to 1.5 mm for a nodlar cast iron [141].

In summarising the contents of this section it can be said:

Compressive loading causes closure to decrease (but does not generally eliminate it totally) and cracks arrested at ΔK_{th} recommence growing for a small distance but then they re-arrest which is a result of the closure redeveloping.

Following removal of the crack wake .. less than 1 mm from the crack tip, cracks arrested at threshold values of stress intensity also recommence growing.

The distance over which closure redevelops to its steady state value depends on the amount by which closure is reduced (which depends on the methods used to eliminate closure), the material type, heat treatment conditions and the specimen type (the crack increment has been calculated to be least for SEN bend specimens followed by CT and then CCT specimens [37]). In all cases reported in this section the distance over which closure developed was much greater than the plastic or reverse plastic zone size. Thus the distance over which closure develops does not appear to be directly related to the plastic or reverse plastic zone sizes.

From experiments in which closure is completely eliminated, it should be possible to make comparisons between the distance over which closure redevelops and the extent of short crack behaviour, and draw conclusions as to the domination of such behaviour by closure.

3 EXPERIMENTAL PROCEDURES

3.1 Material Characterisation

The material used in this work was a 7017 aluminium alloy obtained in the form of rolled plate, 65 mm thick in the peak-age temper (T6) with the composition given in Table 3.1. Testing was conducted in two heat treatment conditions, the as-received peak-age temper (AR) and a re-solution heat treated temper (HT). The latter involved solution treating at 440°C for 1hr and quenching, followed by a pre age at 95°C for 10 hours, and a further ageing treatment at 135°C for 8 hours, resulting in a slightly over-aged temper. The mechanical properties of the two peak age tempers are presented in Table 3.2.

The HT specimens were not all heat treated at the same time and thus hardness measurements were made in order to determine whether the individual heat treatments were consistent, i.e., only hardness values of 171 ± 2 HV were acceptable.

Table 3.1 Chemical composition of 7017 aluminium

Mg	Fe	Si	Mn	Ti	Cu	Zn	Cr	Zr	Pb	Bi
2.434	0.23	0.11	0.23	0.042	0.336	4.485	0.06	0.11	0.025	0.025
Balance Aluminium										

Addendum

The second heat treatment was applied to specimens in an attempt to eliminate the uneven crack growth evident during near threshold crack growth in the as received specimens. The uneven crack growth was thought to be as a result of residual machining stresses, and subsequent growth in the heat treated specimens was a lot more even.

Table 3.2 Mechanical properties of the as-received and heat treated Al 7017 alloy

	σ_y (MPa)	UTS (MPa)	Elongation %	Vickers Hardness
As-received (T6)	435	520	9 %	176
Heat treated	415	495	2-7%	172

Growth rate data from CT specimens in the as-received condition were limited to growth rates above $1x10^{-6}$ mm/cycle because of uneven crack growth along the crack front, i.e., as near threshold conditions were approached growth tended to arrest on one side. A possible reason for this behaviour was thought to be residual machining stresses, which were subsequently reduced by the re-solution heat treatment. However, data from the as-received material condition was still used for comparative purposes.

The material exhibited a pancake microstructure typical of rolled aluminium plate. The etchant used to reveal the structure was a combination of Kellers and Tuckers reagent in a 5:1 ratio (see Table 3.3 for the compositions). Kellers reagent is generally used for microscopic etching while Tuckers reagent is used to reveal the macroscopic grain structure. The large variation in grain size and shape, and the incomplete recrystallisation caused by the original heat treatment following rolling made it impossible to precisely quantify grain sizes; the approximate grain dimensions being 350 x 60 x 20 μm. A composite three dimensional micrograph of the material microstructure is given in Fig. 3.1. The grain sizes for the AR and HT conditions were identical because the re-solution temperature was low enough to prevent recrystallisation and grain growth.

Table 3.3 Composition of Etchant used

Kellers	Tuckers	Combined
2.5 ml HNO_3	15 ml HNO_3	4.7 ml HNO_3
1.5 ml HCL	45 ml HCL	8.9 ml HCL
1.0 ml HF	15 ml HF	3.4 ml HF
95 ml H_2O	25 ml H_2O	83. ml H_2O

3.2 Growth Rate Characterisation

3.2.1 Long crack growth

Growth rate experiments were conducted on ESH servohydraulic testing machines of 50 and 250 kN capacity, at cyclic frequencies of 30 to 40 Hz. Compact tension (CT) specimens were used with dimensions as given in Fig. 3.2, which were machined from the as-received plate in the orientation shown in Fig. 3.3. Testing was carried out in the S - T orientation (i.e., loading was parallel to the S direction, while the crack growth was in the T plane). Specimen thicknesses of 5, 15 and 25 mm were used, in an endeavour to determine the extent to which plane strain and plane stress conditions affected closure. Chevron starter notches were used for the 15 and 25 mm thick CT specimens, to encourage a straighter crack front. However, in this study the chevron notches did not ensure a straight crack front, nor did they reduce crack front bowing, which were two major obstacles encountered during testing.

Growth rate data was obtained in accordance with the ASTM standard for threshold determination (i.e. manual load shedding with load reductions of less than 10% and a crack growth increment greater than 3 times the monotonic plane stress plastic zone size.) To prevent transient effects from affecting growth rate data, the following steps were taken:

a) The initial stress intensity range for crack initiation was kept as low as possible.

b) When testing was halted for some time during the load shedding sequence the loads were increased by 10 - 20% above that used when the test was halted, before continuing with the load shedding sequence.

c) Closure measurements were made using as few cycles as possible, especially when loads were decreased below K_{min} in the loading cycle.

d) The crack increment used to calculate growth rates was never less than 0.15 mm; this figure represents an attempt to reduce the scatter observed in growth rates which is a result of surface crack length measurements and the large grain size of this material.

Crack length was measured optically using travelling microscopes situated on both sides of the specimen. The potential drop technique for measuring crack growth, even though much quicker and less tedious, could not be used because the sensitivity level of this method is too low for aluminium alloys. (The change in voltage per crack increase $\Delta Pd/\Delta a$ given in mV/mm is 0.007 for aluminium compared to a value of 0.15 for steel [142].) For optical measurements a 2 μm grit size surface polish was required to obtain a crack length resolution of about 0.01 mm.

Stress intensity factors for the CT specimens were calculated using the calibration

$$K = \frac{P\ (2+\alpha)}{BW\ (1-\alpha)^{3/2}} \left[0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4\right]$$

given in the appropriate ASTM standard [143]. (This equation is valid for a/w ratios of 0.3 to 0.7 while the equation given in the British Standards Institute (BSI) [144] is only valid for a/w ratios between 0.45-0.55.)

3.2.2 Short crack growth

Short crack data were required for comparisons between the distance over which closure develops in long cracks and the distance below which short crack growth exibits "anomalous" behaviour. Short crack specimens similar to those used by Larson [130], shown in Fig. 3.4 were used in this study, and tested in both heat treatment conditions. They included a centrally waisted portion to limit the crack initiation region and thereby simplify crack detection. The specimens were orientated in such a way that cracks grew in the transverse direction in which the grain size was approximately 60 μm in depth. This orientation was the same as that of the CT specimens relative to the crack growth direction, i.e. in the S - T direction see Fig. 3.3. The stress concentration factor for this geometry is about 1.03 [145] and the stress intensity range for comparison with long cracks was calculated from the equation $\Delta K = 1.32\ \Delta\sigma \sqrt{a}$ [146].

The specimens were fatigued using a 20 kN Amsler Vibrophore. The cycling frequency was about 150 Hz and the stress ratio, R was 0.1. The specimen surfaces were hand polished (electro-polishing produced too many pits at inclusions) and lightly etched to reveal the surface microstructure. Crack length was measured using cellulose acetate replicating tape with a thickness of 35 μm, and growth rates were obtained for various stress ranges. Although the applied stress ranges varied, cracking initiated within 5 000 to 20 000 cycles and the specimens failed after 70 000 to 200 000 cycles. Short crack data was rejected when more than one major crack occurred or when two small cracks interfered with each other. Generally only one crack initiated which is typical of tests involving stress ranges not too far above the endurance limit. Short crack growth data were plotted as dc/dN vs 2c and as da/dN vs ΔK. In the latter case it was necessary to determine the aspect ratio, a/c where a is the crack depth and c is the surface crack length. This was done by breaking open specimens containing cracks of various sizes. A typical fractograph of a short crack is shown in Fig. 3.6. The measured a/c values were found to generally decrease from a maximum of 1.4 to 0.7 as surface cracks increased from 300 to 1000 μm, however, these values showed significant scatter. (Similar values for aspect ratios have been reported by Pineau [147].) An average value of a/c = 1 was used in the calculations in this study because of the scatter.

3.3 Closure Characterisation

Fatigue crack closure was measured using compliance methods, specifically BFS, crack mouth clip (CMC) gauges and near tip strain (NTS) gauges. Positions of the various gauges on the CT specimen were as shown in Fig. 3.6. In all cases care was exercised when applying the gauges with regard to both position and complete contact between the strain gauge and the metal. The BFS and NTS gauges were connected to a strain gauge amplifier in a single gauge arrangement, while the CMC gauge was connected in a full bridge arrangement. The output from the strain gauge amplifier was then connected to an X-Y chart recorder, together with the load output from the load cell of the test machine, to produce load vs displacement voltage traces. The cycling frequency had to be reduced to values between 0.05-0.1 Hz, while the traces were being drawn. An offset elastic displacement circuit was incorporated into the system to improve the resolution of the crack opening point, (which is explained in section 2.3) A low-pass filter with a cut-off frequency of 1.0 Hz was used to condition the load and displacement signals when high magnification was required. Comparisons with the unfiltered traces were made regularly to ensure that the filter was not affecting the signal itself. In all cases shielded wire was used to minimise electrical noise. The layout of the experimental equipment is shown graphically in Fig. 3.7.

The closure values P_{op} and P_{cl} were obtained from either the load-displacement or load-offset displacement traces. These values were chosen at the point where the trace deviates from linearity as shown in Fig. 3.8 on an experimental trace. Closure interpretation under these conditions should be straight forward, but in practice, particularly when the crack tip plastic zone is large (high loads), the experimentally obtained curves are not as well executed and their interpretation requires a certain degree of subjectivity based on previous experience.

3.4 Closure Development

To examine the manner in which closure re-develops with crack increment for a long crack (in a CT specimen) it is necessary first to eliminate closure without eliminating (completely) the crack wake, (as the aim is a natural crack with little, or no closure magnitude). Two methods were adopted to achieve this end.

1. A fatigue crack was initiated, and grown under manual load shedding until the applied stress intensity values were near ΔK_{th}. The fatigue crack wake was then removed to within 2 mm of the crack tip by sawing. This distance was sufficiently far from the crack tip to prevent residual sawing stresses from affecting further growth, yet close enough to concentrate loading at the crack tip. A compressive load was then applied which reduced the closure (possibly by crushing and compacting the asperities). The compressive load required for maximum removal of measureable closure was approximately 5 times the previous maximum tensile load at the end of the load shedding sequence. It was deemed important to use the lowest compressive overload possible, so as to minimise residual tensile stresses forming at the crack tip, which could complicate analyses of subsequent growth.

   Using this method it was not possible to entirely eliminate closure in the 15 and 25 mm thick specimens. This is attributed to excessive crack tip bowing which occured in these specimens and to a significant plane strain effect, which reduced the effectiveness of the compressive load.

   This technique removes closure because the geometry of CT specimens is such that the loading contains a bending component. The effect of a compressive load on a long crack therefore compresses that portion of the fatigue crack around the starter notch as illustrated in Fig. 3.9. In order to remove closure in the near crack tip region using a compressive load, that part of the wake near the notch needs to be removed (refer to section 2.6).

2. The second technique used to obtain a "long" closure-free wake, involved fatigue crack growth under compressive loading, which is discussed in section 5.5. Because such growth occurred under entirely compressive loading, there should not be any closure for tensile applied loads.

A third method to remove closure was attempted based on the work of Minakawa and Mc Evily [53]. They re-heat treated a steel specimen with a fatigue crack and found that closure was eliminated. In this work an AR CT specimen with a fatigue crack was heat treated in the same manner as the HT specimens (section 3.1), but the reduction in closure was only minimal. Thus this method could not be used for the materials used.

In the tests performed using the first method of closure removal, the closure magnitude increased again over a period of a few hours (See section 2.4.6) The application of a second compressive overload of the same magnitude at this point in the test, did not further reduce the closure value to the same extent as the original one. To eliminate complications which might arise due to the increase in closure with time, the closure development tests were carried out immediately after closure removal.

Both methods produced cracks with little, or no, detectable closure based on measurements by all three compliance gauges used in this work Following closure elimination fatigue crack growth rates and closure development were monitored at various constant stress intensity ranges. Crack length measurements were made using optical methods; i.e. either travelling microscopes and/or surface replicas (cellulose acetate replicating tape, softened in acetone,) with resolutions of 10 μm and 2 μm respectively. Although surface crack length measurements do not accurately represent internal growth, these methods were thought to be suitable as only the 5 mm thick CT specimens were used, and measurements were made on both sides of the specimens (on highly polished surfaces). The fact that closure development distances were fairly consistent also indicates that this method of crack measurement was adequate, even though the total closure development crack increment was small (0.19 to 0.3 mm).

4 PROBLEMS WITH CLOSURE MEASUREMENT AND INTERPRETATION

This project is primarily concerned with the manner in which closure manifests itself under various conditions. To obtain a better perspective of the results which are to follow the difficulties associated with closure and closure measurement should be well understood. Hence this section precedes the bulk of the experimental results but draws on some results for illustrative purposes.

4.1 The Parameter ΔK_{eff}

The concept behind the use of the parameter ΔK_{eff} as defined by Elber is based on the assumption that that part of the stress intensity range below K_{op} does not contribute in any way to crack growth (see Section 2.2). In this work, as in much of the literature (Section 2.4) ΔK_{eff} was not always found to correlate growth rate data for different R values, or for various specimen thicknesses, or for the two heat treatment conditions used.

In the literature the tendency has been to use closure to explain certain aspects of growth rate behaviour, most of which are concerned with R ratio effects. In cases where closure concepts have been unsuccessful in explaining the growth behaviour, this has generally been attributed to either the operation of factors such as environmental interactions, or to strain intensification below K_{op}, both of which complicate attempts to quantify ΔK_{eff}. Overall, very little attention has been paid to the question concerning the degree to which closure is effective in reducing the strain range experienced at the crack tip. (According to Elber no strain range is experienced at the crack tip for loads below P_{op}). Insight into strain intensification effects would assist in rationalising the cases where the closure idea appears to fail.

4.2 Experimental Testing

As a check on the reliability of the closure values obtained in this study and to determine whether, in fact, ΔK_{eff} completely characterises crack growth rates, the following experiments and tests were carried out.

a) The various compliance gauges used to measure closure were compared, namely back face strain (BFS) gauges, crack mouth clip (CMC) gauges and near tip strain (NTS) gauges. The BFS and CMC gauges gave similar K_{op} values, while the NTS gauge gave slightly higher K_{op} values for identical testing conditions. The higher K_{op} values obtained using the NTS gauges are to be expected considering that plane stress conditions pertain to surface measurements (see section 2.3). Thus the measured closure data are reliable indicators of crack wedging.

b) Two tests were conducted to determine whether strain intensification does occur at loads below K_{op}, and to what extent it contributes to crack growth.

4.2.1 The R ratio test

This test was formulated to examine the assumption that that part of the fatigue cycle below K_{op} does not contribute to crack growth. More specifically cycling between K_{min} and K_{max} should produce the same growth rate as K_{min} varies provided that K_{min} is kept below K_{op}. (This assumes that, if closure is accounted for, the same ΔK value gives the same growth rate irrespective of R ratio).

A CT specimen was pre-fatigued under cyclic loading, and a load shedding scheme was applied down to a ΔK of 6.4 MPa√m (K_{max} = 7 MPa√m). Fatigue crack growth rates were then measured while keeping K_{max} constant at 7 MPa√m, and varying K_{min}. K_{min} was increased from 0.7 to 3.5 MPa√m to produce R ratios of 0.1, 0.25, 0.33, and 0.5. The actual closure value K_{op} for these tests was between 6 - 6.5 MPa√m, thus K_{min} was kept well below the K_{op} value and should therefore, not have affected growth rates, as shown in Fig. 4.1.

The growth rate results for the various R ratios are given in Table

4.1, from which it can clearly be seen that growth rate is strongly affected by variations in K_{min} (R ratio) even if P_{min} is kept below K_{op}. Thus the portion of the cyclic load below K_{op} definitely contributes to crack growth.

TABLE 4.1 Growth rate variations with increasing R ratio

R	da/dN (mm/cycle)	K_{op} (MPa $\sqrt{m}$)
0.1	1.5×10^{-5}	6.5
0.25	1.2×10^{-5}	6.5
0.33	9×10^{-6}	6
0.5	4.5×10^{-6}	6

4.2.2 The wedge test

For this second test a triangular shaped wedge made of mild steel was placed in the notch of a pre-cracked CT specimen which had been load shed down to a ΔK value of 6 MPa$\sqrt{m}$, and held in position by a clamp as shown in Fig. 4.2.

The loads at which contact occurred at the wedge could be determined because of the greater change in slope in the offset-displacement vs load trace compared to that resulting from naturally occurring closure, as illustrated in Fig. 4.3.

The wedge contact points were set at $K_{op,wedge}/K_{max}$ ratios of 0.0, 0.4, 0.6 and the natural K_{op}/K_{max} ratio of 0.8 This was done via a judicious movement of the wedge until the perturbation of the "wedge P_{op}" point coincided with the desired load on the offset displacement-load trace. Growth rates were then determined for these wedge positions and are given in Table 4.2. The growth rates decreased continuously as the contact ratio $K_{op,wedge}/K_{max}$ was increased to 0.8, even though no wedge contact occurred above K_{op} and thus ΔK_{eff} (as determined in the usual manner), remained the same for all wedge positions. The wedge, therefore, had an affect on the growth rates even well below K_{op} which suggests that most of the fatigue cycle is still significant to crack growth.

TABLE 4.2 The effect of wedge contact on growth rates

	da/dN (mm/cycle)	Wedge Contact Relative to K_{max} (See Fig. 4.3)	Natural Closure K_{op}/K_{max}
no wedge	1.6×10^{-5}	wedge/K_{max} = 0.0	0.8
position 1	9×10^{-6}	wedge/K_{max} = 0.4	0.8
position 2	7×10^{-6}	wedge/K_{max} = 0.6	0.8
position 3	5.4×10^{-6}	wedge/K_{max} = 0.8	0.8

The fact that the relative change in slope in the offset-displacement vs load trace was a lot greater for closure due to the wedge, compared to that for naturally occuring closure, suggests that a greater change in slope can be used to indicate greater closure below K_{op}. Although, a steeper slope does not imply more effective closure but only that closure contact occurs further back, it may in generally be accepted that if contact occurs further behind the crack tip less strain intensification occurs. Thus the slope may be used to judge the effectiveness of closure contact, i.e., the greater the change in slope the lower the contribution to growth of the load cycle below K_{op}.

In order to be able to predict growth rates from closure considerations it is important to establish how closure actually affects the stress intensity range experienced at the crack tip.

A comparison beween the change in ΔK and the change in growth rate for the various R ratios in Table 4.1 show that the portion of the fatigue cycle immediately below K_{op} causes a greater variation in growth rate, than the portion of the fatigue cycle far below K_{op}, for the same change in ΔK. In other words the change in growth rate between R = 0.1 and 0.25 was 1.25 while ΔK was reduced by 1.17 MPa$\sqrt{m}$. This can be compared to the change in growth rate between R = 0.33 and R = 0.5 which was 2.0, while ΔK was reduced by 1.33 MPa$\sqrt{m}$. To compare the two changes in growth rate, they can be divided by 1.17 and 1.33 respectively which give changes in growth rate of 1.07 between R = 0.1 and 0.25, and 1.5 for R = 0.33 and 0.5.

From this discussion the actual effective stress intensity range $\Delta K_{actual,eff}$ could be represented by an equation like Eq. 4.1. The integral in this equation gives greater weight to that part of the cycle immediately below K_{op} compared to that far below K_{op}. The above effect may also be deduced by considering the change in compliance or offset compliance trace. Because the length of closure contact increases gradually (indicated by a gradual change in slope as opposed to an abrupt change in slope), there is a continuous change in compliance.

EQUATION 4.1

$$\Delta K_{eff\ act} = \Delta K_{eff} + C \int_{K_{min}}^{K_{max}} (1/x)^a \, dx \qquad \text{(Eq. 4.1)}$$

where ΔK_{eff} is measured in the usual way, as suggested by Elber [1], $(1/x)^a$ is an inverse relation which favours that portion of the loading cycle just below K_{op} rather than that far below K_{op}, and C and a are constants.

Other authors have suggested modifications to ΔK_{eff} approach by measuring the crack mouth opening displacement, section 2.3.2.2. In essence this parameter is gives a value less than ΔK but greater than ΔK_{eff} and can therefore take into account some strain intensification effects.

It is interesting to note that in cases where part of the cycle below K_{op} does contribute to crack growth, defining K_{op} as the intersection of the tangents of the two linear portions of the compliance trace may give a more realistic "ΔK_{eff}" than that derived in the usual way.

The above two tests clearly show that strain intensification exists below K_{op}. Further, an idea of the degree of strain intensification may be obtained by the relative change in curvature in a displacement vs load or an offset-displacement vs load trace.

4.2.3 The particle test

The next step in investigating the significance of the closure point K_{op}, was to establish whether any additional closure may exist above K_{op}. In other words determining whether the measuring system may underestimate closure under certain conditions. Thus a third test was conducted which examines the effect of additional particles between the crack faces (possibly representative of roughness induced closure.)

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A specimen was prepared by initiating a crack and applying a load shedding scheme in the usual manner until a ΔK of 7 MPa√m was reached. The corresponding growth rate was 9×10^{-6} mm/cycle. A metallographic polishing liquid with an average particle size of 1 μm was then applied on one side of the specimen in the region of the fatigue crack while the specimen was still undergoing cyclic loading. A polishing liquid was used, as the liquid assists in transporting the particles to the crack tip. The liquid itself generates environmental effects, which could obscure interpretation of results. However, this effect is probably small, as environmental effects are generally limited to cyclic frequencies much lower than the 40Hz used for this test. Growth rates were then measured after various crack length intervals.

Growth rates remained constant at 9×10^{-6} mm/cycle over the first 0.36 mm, for which the corresponding K_{op}/K_{max} value was 0.81. The next 0.05 mm of growth occured at a substantially reduced growth rate of 1×10^{-6} mm/cycle for the same ΔK, but producing a very similar closure ratio K_{op}/K_{max} of 0.83. However, after this low growth rate, the growth rate increased to the initial value and the closure value again showed no significant variation. These results are tabulated in Table 4.3.

TABLE 4.3 Variation in growth rate after the application of a polishing liquid on the specimen surface

	ΔK	Cycles	Growth (mm)	da/dN (mm/cycle)	K_{op}/K_{max}
Average Data	7	-	-	$8\text{-}15 \times 10^{-6}$	0.75-0.85
Applied Liquid	7	20 000 20 000	0.36	9×10^{-6}	0.81
	7	16 000 15 000	0.05	1.6×10^{-6}	0.83
	7	20 000 15 000	0.31	9×10^{-6}	0.83

Note: The number of cycles applied were chosen to produce 0.15 mm of growth at 9×10^{-6} mm/cycle.

A possible reason for the different growth rates measured during this test may be explained as follows:

Growth over the first 0.36 mm following the application of the polishing liquid was identical to the growth rate measured prior to the application of the polishing liquid. This is likely to be due to the fact that a certain time and number of cycles were necessary for the liquid with its particles to penetrate to the crack tip by means of a capillary action. The next 0.05 mm of growth, then proceeded at a much reduced growth rate of 1×10^{-6} mm/cycle, possibly because of interference by the particles close behind the crack tip causing wedging to occur as illustrated in Fig. 4.4. Subsequent crack growth then followed at the original rate. This could be a result of the crack tip growing beyond the influence of the particles, as shown in Fig. 4.4b. At all stages closure remained virtually constant and was therefore, unable to explain the variations in growth rate.

Possible reasons for the inability of closure to explain the variations in growth rate are the following:
1. The measuring system could not detect closure within, say 0.05 mm of the crack tip, or
2. the particles may have acted in a similar manner to the wedge used for an earlier experiment, where they ensured less, or no contribution to growth below K_{op}, or
3. the fluid may have introduced a hydraulic wedging action below K_{op} which would limit the strain intensification.

Although numerous explanations exist for the results obtained above, the test still illustrates that the closure ratio K_{op}/K_{max} or ΔK_{eff} is not always able to explain the variations in growth rates.

4.3 Summary

In summary, the first two tests indicate that the portion of the fatigue cycle below K_{op} does contribute to crack growth in this [illegible], while all three tests confirm that ΔK_{eff} as defined by Elber [1] is not necessarily the best parameter to characterise fatigue crack growth, either because strain intensification occurs below K_{op} and/or because K_{op} cannot be measured accurately.

Generally speaking, there may be other factors which contribute to anamolous closure behaviour that warrant mention.
1) If mode II contributes strongly to growth, ΔK_{eff} will always underestimate the actual stress intensity range experienced at the crack tip.
1) Some materials exhibit an intrinsic R ratio effect, ie. for the same ΔK two R ratios may produce different growth rates, even if K_{min} is greater than K_{op} in both cases (see Section 2.4.2).
3) The K_{op} and K_{cl} values generally differ slightly on the compliance (offset-compliance) traces because of hysteresis, and it is not clear which one (if either) gives a true closure value.
4) Significant crack front bowing may lead to erroneous closure results [64], (such a situation can however, be minimised by using thinner specimens i.e., less than 15 mm).

Thus in order to use closure to modify ΔK, and to make quantitative predictions of growth rate, its correct interpretation is essential, despite the complexities involved in this.

5 GROWTH RATE AND CLOSURE DATA

This chapter discusses the growth rates and the corresponding closure magnitudes that were obtained under various conditions of ΔK and R ratio. The closure data were critically analysed to determine whether, and to what extent they were capable of explaining any differences in growth rates. Attempts were also made to separate out the various closure mechanisms, in order to facilitate understanding with regard to the differences in closure magnitude between the as-received and heat treated material conditions.

5.1 Growth in the As-Received Material

The growth rate data for the AR material condition at $R \sim 0.1$ are plotted in Fig. 5.1, for 5 mm, 15 mm, and 25 mm thick CT specimens with the corresponding closure data presented as K_{op}/K_{max} vs ΔK, given in Fig. 5.2. Growth rate data below 10^{-6} mm/cycle were ignored because skew crack fronts developed below these growth rates. Skew crack fronts only became problematic at low growth rates because of the sensitivity of crack growth to slight variations in ΔK, caused by possible machining residual stresses.

The data in Fig. 5.1 show a higher growth rate for the 5 mm CT specimen compared with the 15 and 25 mm thick CT specimens. This trend is supported by the closure data which shows that closure is less for the 5 mm thick CT specimen than for the 15 and 25 mm thick CT specimens. The growth rates for the various specimen thicknesses can be explained in terms of closure in a qualitative manner. But when closure is used in a quantitative manner by plotting da/dN vs ΔK_{eff}, is unable to reduce the data onto one line, as shown in Fig. 5.3.

5.2 5 mm Heat Treated CT Specimens

Crack growth rate data were determined for 5 mm thick CT specimens at R = 0.1 and are shown in Fig. 5.4. The growth rate data were obtained using both K increasing and K decreasing tests. The corresponding closure data are plotted as K_{op}/K_{max} vs ΔK in Fig. 5.5a. From this figure it can be seen that closure is generally very high and reaches a maximum K_{op}/K_{max} value of 0.96 at threshold. Although the closure ratio increases substantially, the closure magnitude K_{op} remains fairly constant as ΔK decreases down to threshold, seen in Fig. 5.5b. The high closure ratio obtained at threshold is not unusual, as K_{op}/K_{max} ratios of 100% have been reported in the literature, (see section 2.4.1). The closure data obtained from the above tests are also plotted as da/dN vs ΔK_{eff} in Fig. 5.5c, which, however, produced a rather disjointed set of data points, indicating that ΔK_{eff} does not appear to be a very useful parameter for characterising growth rates in the material used. The results of Chapter 4 indicated that this may be related to the presence of significant strain intensification.

Growth rate tests were also conducted at high R ratios i.e., R = 0.75, R = 0.85 and R = 0.9 shown in Fig. 5.6. The growth rates for R = 0.85 and R = 0.9 are practically identical, which suggest that the closure variation for these conditions must be the same, (i.e., no closure). But growth rates for R = 0.75 decreased slightly for ΔK values below 2 MPa$\sqrt{m}$, compared to growth rates for R = 0.85 and 0.9, suggesting the presence of closure for ΔK values below 2 MPa$\sqrt{m}$. The closure data for these tests are presented as K_{op} vs ΔK in Fig. 5.7. Three lines representing the K_{min} values for each R ratio are drawn on this figure, thus it can clearly be seen that closure was only measured above K_{min} for the R = 0.75 test and then only at ΔK values below 2 MPa$\sqrt{m}$, which correlates with the decrease in growth rates for R = 0.75 at ΔK values below 2 MPa$\sqrt{m}$. The data in Fig. 5.7 also shows that K_{op} is independent of ΔK or K_{max} for high R ratios.

Because no closure was measured for crack growth data at R = 0.85 and R = 0.9, the threshold values at these R ratios may be assumed to represent the intrinsic threshold for the material conditions used, which is approximately 1.5 MPa$\sqrt{m}$.

5.3 Discussion

5.3.1 Closure effects

If da/dN is plotted vs ΔK_{eff} for the various R ratios tested i.e., R = 0.1, 0.75, 0.85, and 0.9 as shown in Fig. 5.8, $\Delta K_{eff,th}$ is much less for R = 0.1 than for R = 0.75, which in turn is less than for R = 0.85 and 0.9. The results appear to indicate that the K_{op} values measured are too high and thus overcompensate for closure, producing an erroneously low ΔK_{eff}. This effect was confirmed in Chapter 4 and attributed to the existence of strain intensification below K_{op}.

5.3.2 The effect of heat treatment on crack growth

Crack growth rate data for R = 0.1 are compared between the AR and HT 5 mm thick CT specimens in Fig. 5.9a. Growth rates are generally lower for the HT material especially in the near threshold region where ΔK_{th} for the HT material is approximately twice as large as for the AR material. These lower growth rates for the HT material are supported by the closure data given in Fig. 5.9b which shows much higher closure values for the HT material. The large difference in closure between the heat treated and as-received material is surprising in view of the fact that the grain sizes are identical and the material yield strengths are similar namely; 415 MPa√m and 435 MPa√m for the HT and AR conditions respectively. Thus differences in closure due to grain size (roughness induced) and yield strength (plasticity induced) variations should be minimal. As has been mentioned earlier (section 3.3) oxide induced closure is not expected to play a large role in this type of aluminium alloy especially at non-near threshold growth rates. Thus the large difference in growth rates between the two material conditions is likely to be related to differences in ageing i.e., the HT material is slightly overaged while the AR material is in a peak-aged condition. These differences are expected to manifest themselves in the roughness induced closure contribution for the two material conditions.

5.3.3 Thickness effects

The trend observed in the growth rate and closure data for the different specimen thicknesses, namely that growth rates decrease and closure ratios increase as the thickness increases, is in direct contrast to the generally accepted trend which favours an increase in growth rates with specimen thickness. This trend has been explained in terms of the stress state at the crack tip which changes from plane stress to plane strain conditions with specimen thickness, thereby decreasing the closure value, and increasing growth rates (and ΔK_{eff}). An exception to the above trend are the results by Romaniv [43] who reported a decrease in growth rates with increasing specimen thickness for a low alloy steel. He was able to positively identify an increase in oxide debris with specimen thickness which he used to explain the increases in closure magnitudes. The reason for the increase in oxide with specimen thickness was not clear except that it only occurred under conditions of plane strain which obviously increases with specimen thickness. (Plane strain implies a smaller CTOD which may enhance fretting thereby producing more debris.) In this work, however, the fatigue fracture surfaces showed no oxide debris either on the thin or thick CT specimens, thus the only means whereby closure could increse as specimen thickness increases must be a result of a change in surface roughness effects due to a decrease in CTOD.

5.4 Separating out Closure Effects

5.4.1 Roughness induced closure (Mode II)

Attempts were made to determine the variation in mode II movement with ΔK, specifically, between the near threshold and high growth rate regimes. These measurements were attempted to give some indication of the contribution of roughness induced closure in this material, and to help explain why closure values in this work, were so high.

Mode II displacements were measured on a CT specimen which had been pre-cracked and load shed down to a ΔK of 6 $MPa\sqrt{m}$. A specially adapted straining gauge, depicted in Fig. 5.10, was used to strain the specimen. The loads applied by the straining gauge were calculated from the output of a BFS gauge which had been calibrated for the