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Behaviour of Small Fatigue Cracks at Blunt Notches in Aero-Engine Alloys

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ABSTRACT This investigation studies the influence of notch stress fields on the near-threshold and mid-range FCG behaviour of small cracks in Waspaloy and Nimonic 105. Experimental estimates of K for cracks within the notch influence have been obtained using the principle of stress intensity similitude for equivalent growth rates. Fatigue crack growth data has been generated for the two nickel-base alloys at stress ratios of 0.1 and 0.5. It has been established that in common with other nickel-based alloys near-threshold FCG is strongly dependent on the stress ratio.

Cracks at the root of circular notches were generated by drilling holes behind the tips of long cracks in compact tension specimens, after achieving the required stress intensity condition. The results obtained are compared with various proposals for defining the stress intensity factor range of a crack in a notch, including finite element and the boundary between long/short crack empirical methods. It is concluded that ΔK values estimated by the finite element and empirical methods, with the exception of the Cameron and Smith based solution, yield a conservative approach to life prediction. It is confirmed that a non-propagating crack condition will not develop at a blunt notch under bulk elastic loading conditions due to a continuous increase in stress intensity factor as the crack grows.

Notation

k_T	Elastic stress concentration factor
σ_o	Nominal stress
a_n	Crack length measured from the notch root
δ	Extent of notch stress field measured from the notch root
ΔP	Load range
Y	Compliance function
Y_n	Compliance function based on length $(a_n + D)$
B	Specimen thickness
W	Distance from load line to rear of specimen
D	Notch depth
ρ	Notch radius
ΔK	Stress intensity factor range
ΔK_{eff}	Effective stress intensity factor range
da/dN	Fatigue crack growth rate

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Introduction

The initiation and growth of fatigue cracks at notches is of great practical importance in engineering components and structures. It is well known that the majority of fatigue failures occur at some form of geometric discontinuity (**1**)(**2**), and of necessity most components contain such features. A recent survey of serious aircraft accidents involving fatigue fracture clearly underlines the importance of stress concentrators at crack initiation sites (**3**).

The fatigue life of many engineering structures is spent initiating cracks at stress concentrators and the subsequent propagation of one dominant macro-crack through the highly stressed region of the notch. The conventional philosophy employed in fatigue design at stress concentrators involves the local stress–strain concept (**2**). This approach essentially represents designing against crack initiation. For the purposes of this paper, crack initiation is defined as the processes of local plastic deformation, micro-crack initiation, and subsequent growth to form an 'engineering-size crack'. If structures and components, particularly welded and rivetted components, contain inherent defects, their fatigue lives may depend on the propagation of these flaws, since their initiation period is either very small or non-existent.

In these circumstances, the fatigue integrity of the component or structure should be evaluated using the so-called defect tolerance philosophy as used in the military specification MIL-A-83444 (**4**). Briefly, this involves assessment of the fatigue life spent propagating a fictitious flaw (estimated from non-destructive testing) to some pre-defined failure condition. Estimates of fatigue life are obtained using a fracture mechanics based methodology and a knowledge of the following factors: (a) crack size (length, shape, etc.); (b) service loads; (c) stress intensity factor; (d) material properties, e.g., K_{IC}, fatigue crack growth data.

Often the determination of K requires recourse to numerical methods which are costly and time consuming. As an alternative, the application of approximate K solutions is considered in this study, which is concerned with the growth of mode I, through-thickness fatigue cracks in blunt notch elastic stress fields. Through-thickness cracks are investigated since they represent the most fatigue-critical conditions which can occur. The behaviour of such cracks has been studied here and in an earlier paper (**5**) using what effectively is a blunt notched compact type (CT) specimen geometry, see Fig. 1. Two nickel based aero-engine alloys are considered, Waspaloy and Nimonic 105. The combination of high strength associated with these alloys, and the low stress concentration factors associated with the CT specimen configuration, are the principal reasons for bulk elastic conditions being maintained.

Approximate stress intensity solutions

A pre-requisite for assessing the fatigue life for a crack at a notch where linear elastic fracture mechanics (LEFM) is applicable, is a knowledge of the stress

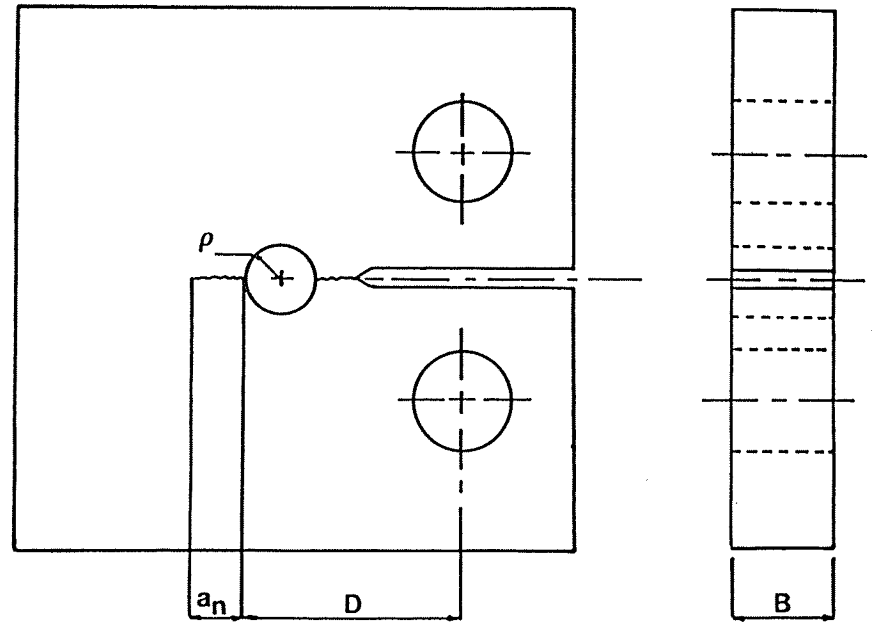

Fig 1 Keyhole specimen design with machined hole

intensity factor. When a crack is small compared to the notch size it behaves in a similar way to a crack growing from a free surface, with the FCG rate being dominated by the local stress-strain field. In these circumstances the stress intensity factor may be defined as

$$K = 1.12 k_T \sigma_o \sqrt{(\pi a_n)} \tag{1}$$

where 1.12 is the free-edge correction factor. The product $k_T \sigma_o$ represents the maximum elastic stress at the notch root. This solution (**6**) yields a pessimistic estimate of K for all crack lengths since no account is taken of the stress gradient which exists at the notch root.

Errors in K at small crack lengths can be reduced by using the stress distribution or the average stress without a flaw instead of the peak stress at the notch. Both of these approximations suffer from two disadvantages. Firstly, a detailed knowledge of the stress distribution is necessary, and secondly, non-conservative estimates of K might be obtained (**6**).

When the crack is remote from any notch influence the FCG rate is controlled by the bulk stresses. The stress intensity may be estimated using the 'long crack' solution which considers the notch to be part of the crack. For the blunt notched CT specimen geometries this engineering solution corresponds to the standard long crack solution (**7**)

$$K = \frac{P}{B(W)^{1/2}} Y \quad (2)$$

where Y represents the specimen compliance function. If the full notch depth is assumed to contribute to crack length for small cracks a very pessimistic estimate of K is obtained.

Dowling (**8**) and Rooke (**6**) proposed that a K solution for a crack at a notch can be satisfactorily obtained by combining the two approximate limiting K solutions. The transition in behaviour between the limiting solutions may be optimized to ensure that errors in K are minimized. In practice a transition occurs between notch stress field dominated 'small crack' behaviour and the bulk stress dominated 'long crack' behaviour.

Smith and Miller (**9**) proposed an empirical K solution for a crack at a notch. This solution is based on comparing FCG rates for a fatigue crack of length l growing in an unnotched specimen with a fatigue crack of length a_n growing from a notch under identical bulk stresses. Where identical growth rates exist for the two cases the same crack tip driving force must also exist, however defined, i.e., whether using K or some other parameter. Therefore, in situations where LEFM is applicable, the same stress intensity factor, K, must apply.

For a crack within the notch influence, Smith and Miller proposed that

$$K = \{1 + 7.62(D/\rho)^{1/2}\}^{1/2}\sigma_o(\pi a_n)^{1/2} \quad (3)$$

where the extent of the notch stress/strain field based on this approximate K solution is given by

$$\delta = 0.13\sqrt{(D\rho)} \quad (4)$$

Later work conducted by Cameron and Smith (**10**) suggested that a better approximation for the extent of the notch field is given by

$$\delta = 0.21\sqrt{(D\rho)} \quad (5)$$

which, following the method of Smith and Miller (**9**), yields a K solution given by

$$K = \{1 + 4.672(D/\rho)^{1/2}\}^{1/2}\sigma_o(\pi a_n)^{1/2} \quad (6)$$

Application of these empirical K solutions to compact tension specimen geometries, requires an approach utilized by Duggan (**11**). This analysis yields a general expression of the form

$$K = (P/BW)(a_n + D)^{1/2}Y_n \quad (7)$$

The modified compliance function Y_n, based on the length $(a_n + D)$, is given by

$$Y_n = 29.6 - 185.5(a_n + D)/W + 655.7\{(a_n + D)/W\}^2 - 1017\{(a_n + D)\}^3 + 638.9\{(a_n + D)/W\}^4 \quad (8)$$

It follows that the modified K solution (**11**) for the CT specimen configuration gives, for Smith and Miller (**9**)

$$K = (P/BW)\{a_n + 7.69(D/\rho)^{1/2}a_n\}^{1/2}Y_n \quad (9)$$

and after the work of Cameron and Smith (**10**) for the extent of the notch stress field

$$K = (P/BW)\{a_n + 4.672(D/\rho)^{1/2}a_n\}^{1/2}Y_n \quad (10)$$

Experimental studies

In order to assess the influence of blunt notches on the behaviour of through-thickness fatigue cracks in both the near-threshold and mid-range FCG regimes, cracks were generated by pre-cracking sharp notched CT specimens. This was followed by a subsequent load shedding procedure which involved load reductions of less than 10 per cent, reducing to 5 per cent when the required crack length and stress intensity condition were approached. The crack was grown a distance of at least three times the size of the previous forward crack tip plastic zone (plane stress) before the next load reduction. After obtaining the required conditions, a hole was then drilled behind the crack tip to leave a short remnant crack. Subsequent testing was performed under constant load conditions. An Instron 1603 electromagnetic resonance machine operating between 70 and 90 Hz was used for the near-threshold programme, whilst for the mid-range FCG tests, an Instron 8032 servo hydraulic test machine operating at 10 Hz was used.

Experimental estimations of the stress intensity of a crack within the influence of a notch were obtained using the principle of stress intensity similitude for equivalent crack growth rates at the same stress ratio, R. Where appropriate, the effective stress intensity range, ΔK_{eff}, was determined by ascertaining the onset of crack opening/closure loads. Crack closure was measured using both the d.c. potential drop and backface strain compliance change methods (**12**). Crack length was measured using the d.c. potential drop technique supported by single stage acetate film replicas.

Introducing blunt holes by machining is likely to result in some strain hardening of the material and residual stresses in the vicinity of the bore. In order to offset such effects, these specimens were stress relieved at 600°C for 1 hour in a vacuum of less than 10^{-6} torr.

Materials

Two materials were used in this study, Waspaloy and Nimonic 105. These materials are nickel–cobalt–chromium alloys used for high temperature applications, which include gas turbine discs, blading, flame tubes, and casings, due to their resistance to oxidation and creep.

Waspaloy

Waspaloy CT specimens were machined from the diaphragm of an RB211-22HP turbine disc. The nominal chemical composition of the material (per cent weight) was 19 Cr, 13.5 Co, 4.3 Mo, 3 Ti, 1.3 Al, 0.08 C, and Ni (balance). The mechanical properties measured at 20°C were as follows: 0.2 per cent proof stress, 923 MPa; tensile strength, 1300 MPa; reduction in area, 25 per cent; elastic modulus, 215.7 GPa.

Nimonic 105

The CT specimens of Nimonic 105 were machined from 45mm diameter wrought bar. The nominal chemical composition of the material (per cent weight) was 20 Co, 15 Cr, 5 Mo, 4.7 Al, 1.3 Ti, 0.13 C, and Ni (balance). The mechanical properties measured at 20°C were as follows: 0.2 per cent proof stress, 888 MPa; tensile strength, 1256 MPa; reduction in area, 30 per cent; elastic modulus, 200 GPa.

Results

Base line, long crack FCG data was generated under constant load amplitude conditions for the two alloys, at two specific stress ratios, $R = 0.1$ and $R = 0.5$. Crack closure was assessed using the experimental techniques previously stated. Figure 2 gives the mid-range FCG results obtained for Nimonic 105, where only a slight R dependence was found. The data was generated on the servo-hydraulic machine operating at 10 Hz using sharp vee notched CT specimens.

Figure 3 shows the FCG results for Waspaloy, for which a strong dependence on R was found for near-threshold FCG but as with Nimonic 105 much reduced for the mid-range. This data was obtained on the resonance machine over the frequency range of 70–90 Hz.

The results for the various notch geometries were obtained at the same stress ratio of $R = 0.5$. The purpose of using this high stress ratio is to minimize the effects of crack closure. Four tests are considered in this paper, two on Waspaloy in the near-threshold regime and two in the mid-range regime, one for each material. The FCG data obtained from these tests was processed using the three point secant method. In the near-threshold regime, where FCG rates demonstrate increased scatter, an incremental seven point polynomial method was used (**13**). For comparative purposes the FCG data were converted to values of dimensionless ΔK obtained from stress intensity similitude and plotted against crack length, a_n, Figs 4–7. The dimensionless ΔK parameter ($\Delta K_{eff} B W^{1/2}/\Delta P_{eff}$) refers to the specimen compliance. In all cases values of effective stress intensity range, ΔK_{eff}, were used and the similitude principle was applied for identical R values. Each set of data pertaining to a particular notch geometry, material and FCG regime, has been plotted twice in subsequent figures. Firstly, against empirically derived solutions (i.e., that due to Smith and Miller (**9**) and that based on the work of Cameron and Smith (**10**) for the extent of the notch stress field) and secondly against finite element predictions (**14**)(**15**). In both cases the limiting K solutions represented by the small crack solution and the long crack solution are included.

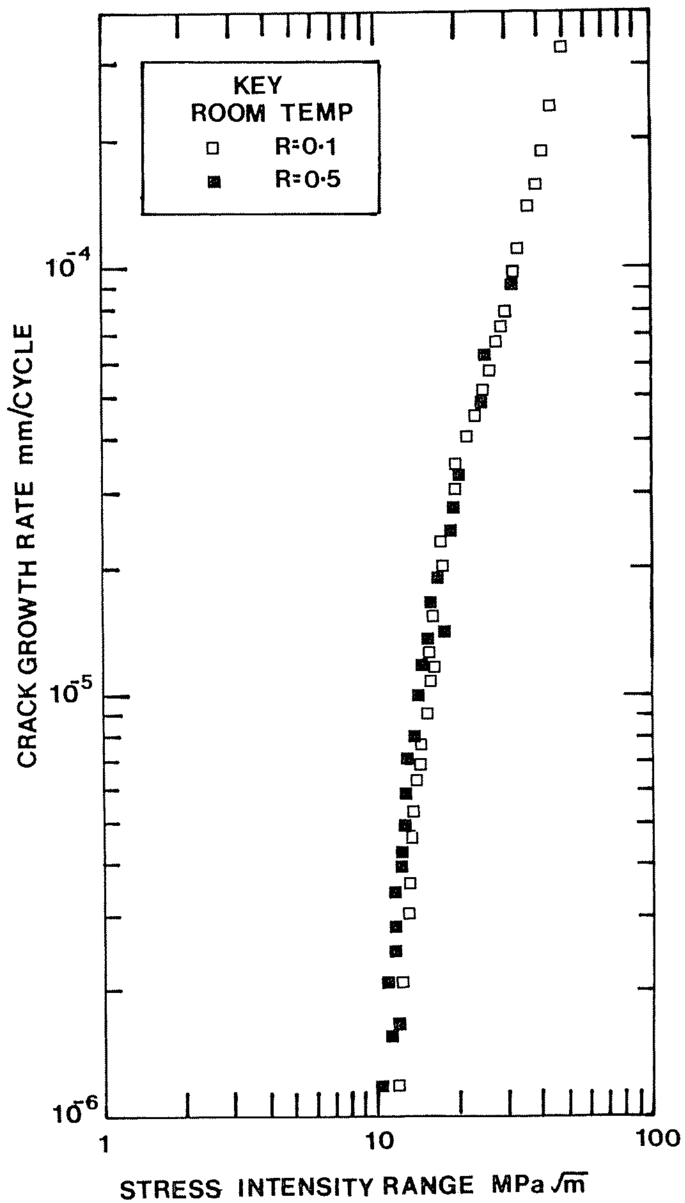

Fig 2 Fatigue crack growth data for Nimonic 105

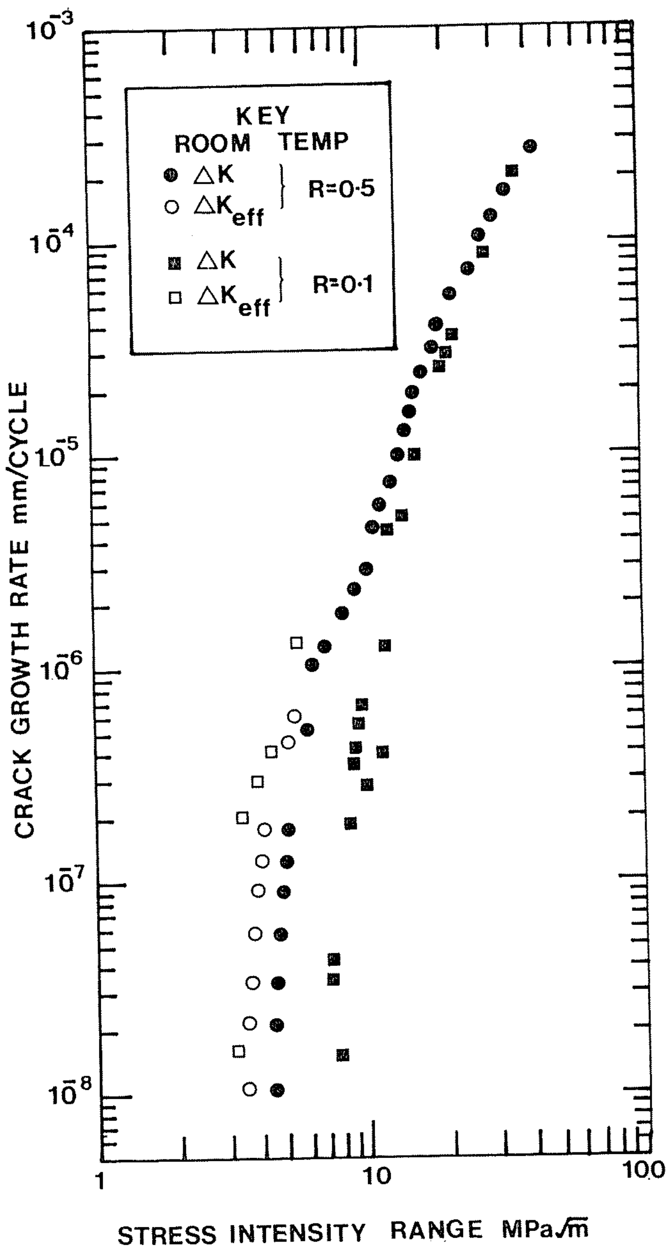

Fig 3 Fatigue crack growth data for Waspaloy

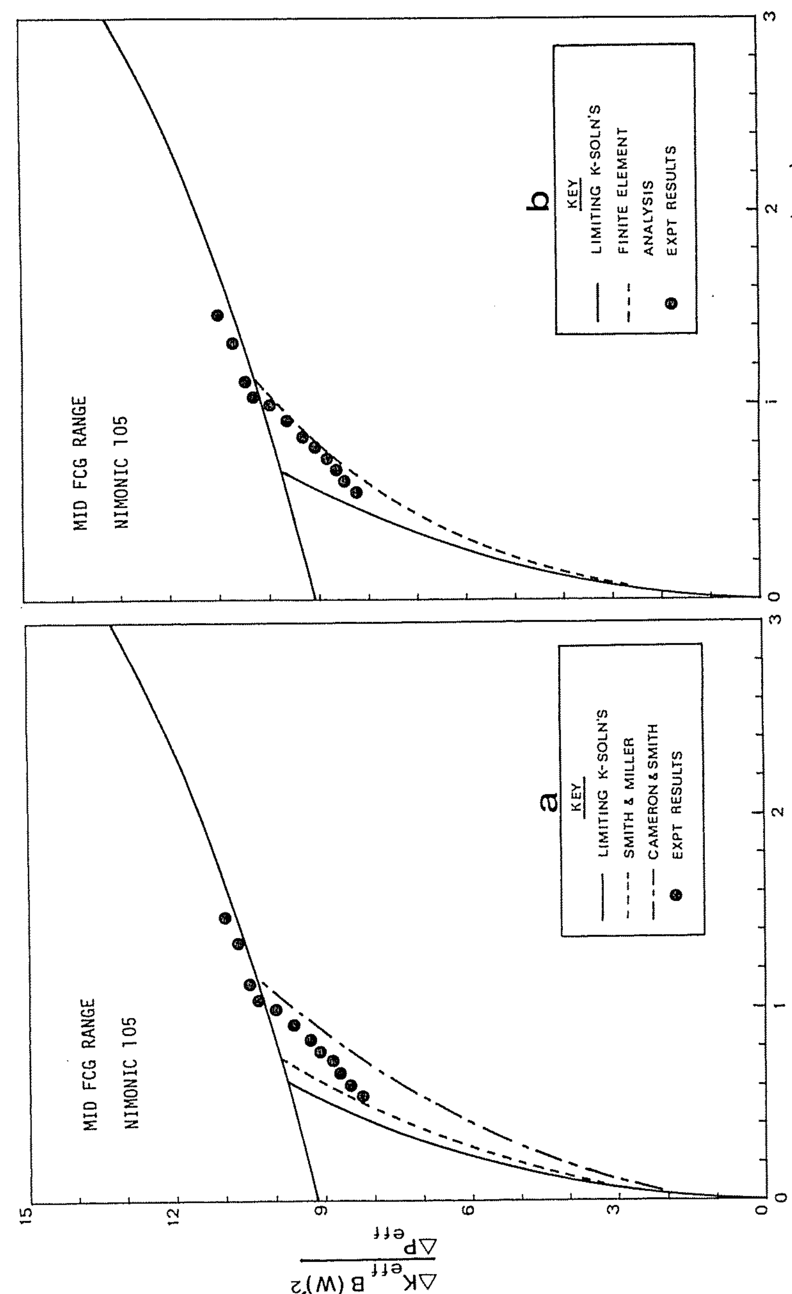

Fig 4 Comparison of (a) analytical, and (b) finite element solutions with mid-range experimental FCG data for Nimonic 105
$D = 12.5$ mm; $\rho = 2.75$ mm

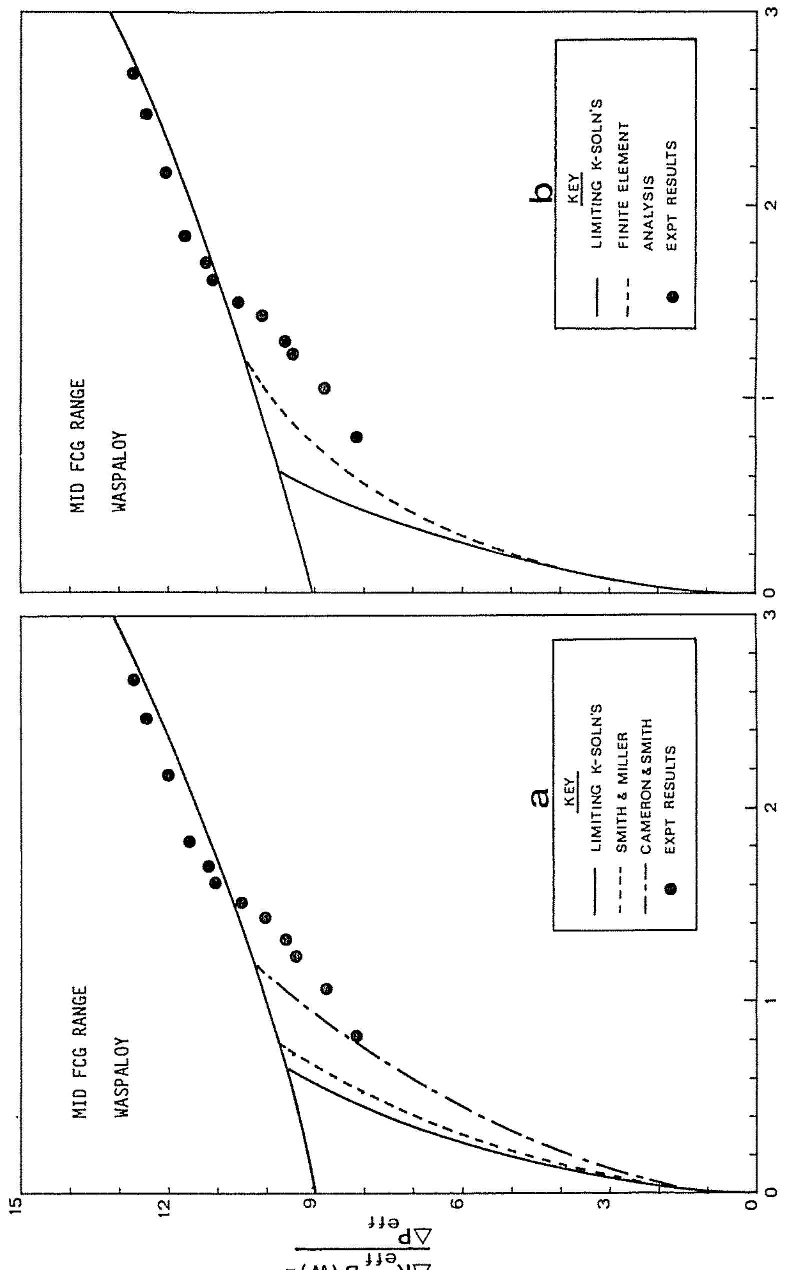

Fig 5 Comparison of (a) analytical, and (b) finite element solutions with mid-range experimental FCG data for Waspaloy $D = 12.5$ mm; $\rho = 2.75$ mm

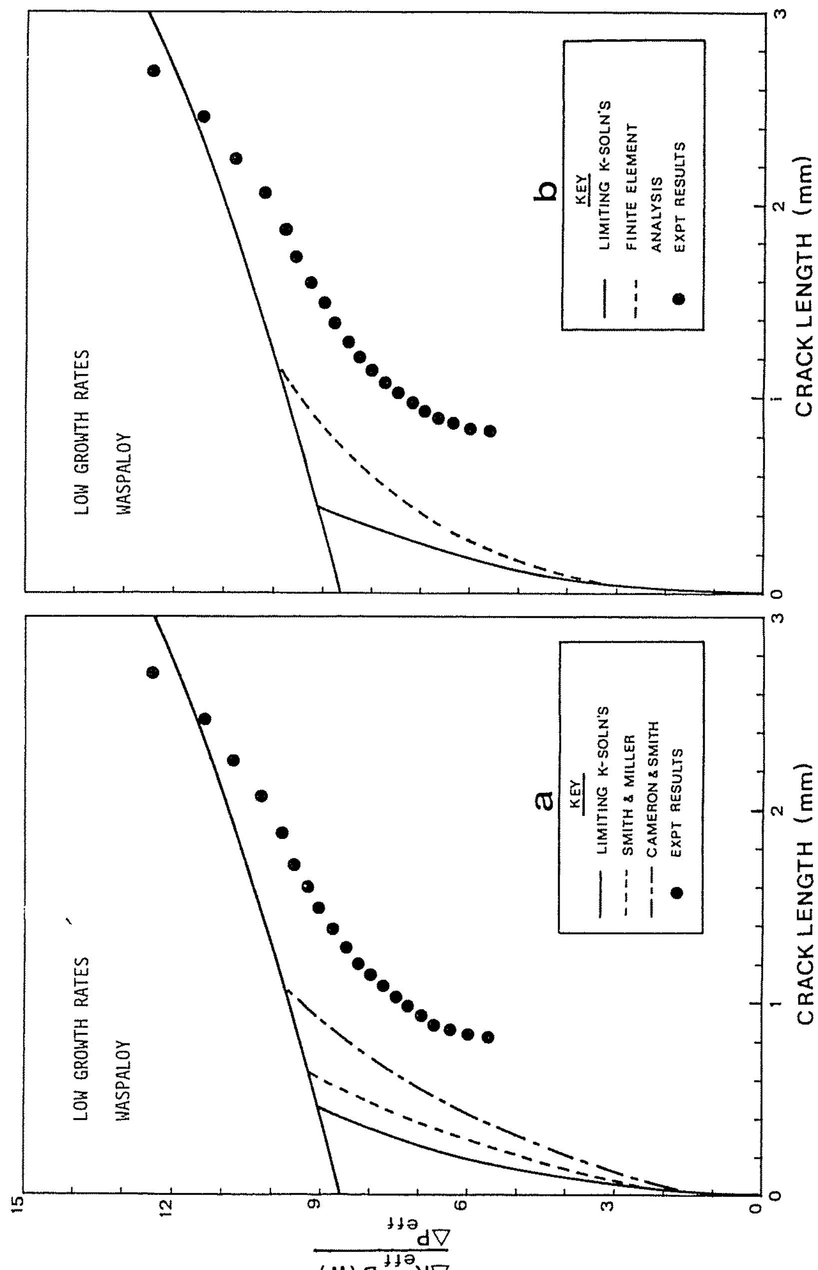

Fig 6 Comparison of (a) analytical, and (b) finite element solutions with low range experimental FCG data for Waspaloy $D = 12.1$ mm; $\rho = 1.75$ mm

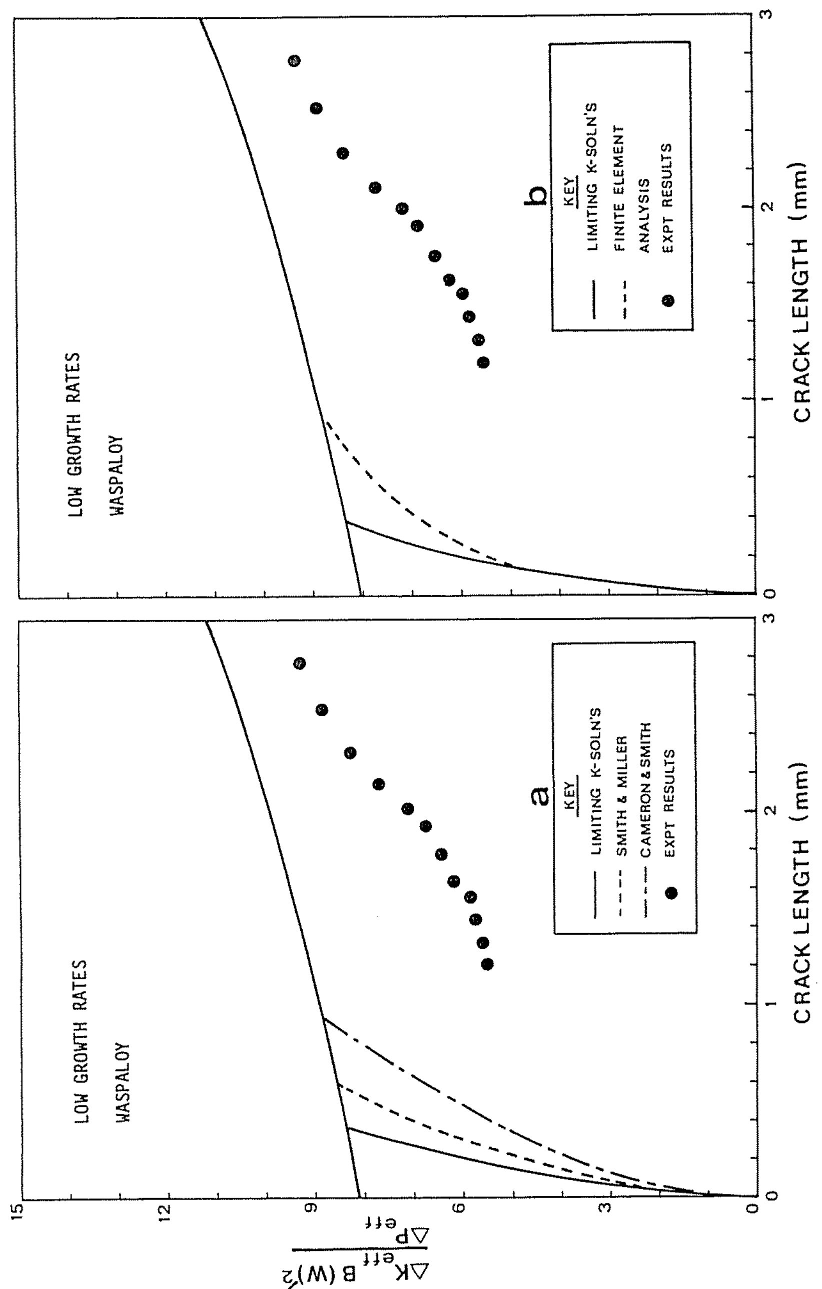

Fig 7 Comparison of (a) analytical and (b) finite element solutions with low range experimental FCG data for Waspaloy $D = 11.4$ mm; $\rho = 1.75$ mm

Discussion

In order to preserve the validity of applying the principle of stress intensity similitude it must firstly be shown that residual stresses introduced by drilling do not affect the FCG rates and secondly that LEFM is not invalidated by the generation of plasticity at the notch root. The removal of possible residual stresses by stress relieving is considered precautionary rather than essential. Work conducted by Forsyth (**16**) on RR58 extrusions has revealed that drilling and reaming holes produces deformed material; the surface only being affected to depths of between 40 and 50 μm, an order of magnitude smaller than the initial crack lengths considered in this study, which were between 0.3 and 0.9 mm. To ensure that elastic conditions were obtained at the notch root, the maximum notch root stresses were estimated for each specimen using k_T values predicted from finite element analyses (**14**)(**15**). In no case has the maximum stress at the notch root exceeded 70 per cent of the 0.2 per cent proof stress.

Blunt notch FCG results

The mid-range results obtained for Nimonic 105 plotted against the empirical solutions, Fig. 4(a), show that the K solution based on the work of Cameron and Smith (**10**) can yield non-conservative estimates of K and slightly over-predict the crack length over which there exists a notch effect. The same results correlate very closely with the finite element prediction for the extent of the notch influence, Fig. 4(b).

The result obtained for Waspaloy in the mid-range, Fig. 5, support the experimental observations found for Nimonic 105, i.e., a reasonably close correlation with both the finite element prediction of the extent of the notch field and that found more simply and cheaply by the Cameron and Smith based solution. The experimental results later coincide with the long crack solution. Figure 5(a) shows that both the empirical solutions gave conservative estimates of K when compared with the experimental results.

The results for Waspaloy (Figs 6 and 7) obtained in the near-threshold regime indicate considerably lower values of ΔK than expected from the various K solutions. The attenuation of the experimental K values in this regime may in fact be accounted for by the observed crack branching, a common feature in nickel-based alloys in the near-threshold regime. A further contributory factor may be incurred by prolonged cycling at a fatigue threshold condition. It is possible that some form of hysterisis may occur, e.g., by crack tip blunting, requiring higher loads to be applied to cause further crack propagation than was necessary prior to reaching a threshold condition. A further possibility is that the methods used to monitor closure may not be sufficiently sensitive at $R = 0.5$.

General observations

The experimental results clearly confirm that a non-propagating crack condition will not develop at a blunt notch under elastic conditions since a continuous increase in K accompanies crack growth. The short crack and the empirical Smith and Miller solution (**9**) both provide consistently conservative estimates of stress intensity at small crack lengths. At longer crack lengths the long crack solution provides an accurate stress intensity characterization of the crack outside the influence of the notch. In certain cases the experimental results provide higher K solutions than theoretical long crack solutions. This may result from inherent inaccuracies in the compliance function.

In practical situations where more complex component configurations exist than those considered here, the Smith and Miller approximate solution may prove difficult to manipulate and the finite element method may be too expensive. In these situations the small crack solution which yields only a marginally more pessimistic estimate of K may be used.

Conclusions

For through-cracks at blunt notches under elastic conditions.

(1) The results obtained from both Waspaloy and Nimonic 105, for mid-range FCG rates, are reasonably consistent. They show that the extent of the notch influence for various geometries compares favourably with both the finite element solutions and the simple Cameron and Smith based solution.

(2) The Nimonic 105 results show that the Cameron and Smith based solution can yield non-conservative estimates of the stress intensity factor in the small crack growth phase.

(3) The Waspaloy results obtained in the near-threshold regime, however, infer much lower values of stress intensity factor than those predicted from any of the available K solutions.

(4) The attenuation of the inferred stress intensity values obtained for a crack in the near-threshold regime emanating from a notch in Waspaloy may be caused by:
   (i) crack tip branching reducing the effective stress intensity;
   (ii) retardation of FCG rates after threshold load shedding as a result of crack tip blunting;
   (iii) crack closure effects.

(5) The experimental results confirm that a non-propagating crack will not develop at a blunt notch since a continuous increase in the stress intensity factor accompanies crack growth.

(6) The use of the long crack solution in conjunction with the small crack approximations (with the possible exception of the Cameron and Smith

based solution) has been shown to be a safe method of estimating K for both near-threshold and mid-range fatigue crack growth regimes.

Acknowledgements

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