STRESS INTENSITY FACTORS FOR CRACKS EMANATING FROM NOTCHES, SUBJECTED TO FATIGUE

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ABSTRACT

Stress intensity factors for cracks emanating from notches have been determined using an experimental technique based on the Paris Law for fatigue crack growth. It is proposed that a structure dependent material parameter affects the K-calibration in the near notch tip region.

KEYWORDS

Fatigue crack initiation; Crack growth; Notches; K-calibration; Steels

INTRODUCTION

Fracture mechanics methods have proved useful to describe fatigue crack propagation (Paris, 1963). As fatigue cracks generally initiate from some form of geometric discontinuity (a notch), K-calibrations need to be modified in order to account for the presence of a notch. These calibrations can then be used to estimate the number of cycles for growth of a crack from crack propagation data based on stress intensity factors. Modified stress intensity factors for cracks emanating from notches, in specific geometries, have been derived using finite element techniques (Yamamoto, 1976; Jergeus, 1978). A feature of these calibrations is that a zero stress intensity factor is associated with the tip of a blunt notch. However, experimental work on fast fracture suggests that an effective stress intensity factor can be attributed to the notch for the purpose of assessing critical defect sizes (Spink, 1973).

Current design methods for fatigue crack initiation are based on the Neuber product applicable at a point where maximum stress concentration occurs (Topper, 1969). These are not useful in estimating further crack growth. In using the Neuber product it is assumed that, for the initiation of a fatigue crack, it is necessary that a critical stress is exceeded over a critical distance ahead of the notch tip (Neuber, 1969). This critical distance is referred to as the Neuber particle. The concept of $\Delta k/\sqrt{\rho}$ (where k is the stress intensity factor range for a notch plus crack geometry and ρ

is the notch root radius), as an effective stress intensity factor to describe fatigue crack initiation has also proved to be successful (Jack, 1970; Barnby, 1977). The present study spans the concept of the Neuber particle and the dependence of fatigue crack growth on stress intensity factor to establish K-calibration in near notch tip region.

THEORETICAL CONSIDERATIONS

Fatigue crack initiation is preceded by microplasticity at the notch tip and this can be envisaged as a slip-band structure. When subjected to fatigue loads, such a slip-band structure at the crack tip will give rise to a stress distribution, which can be described by a stress intensity factor (Barnby, 1969). This stress intensity factor at the slip-band sharpened notch tip can be described in terms of notch geometry and the microstructural features at the notch tip.

The stress intensity factor for cracks emanating from notch roots, in specific geometries have been established by Tamamoto and Ao (1976), using finite element techniques. Jergeus (1978) has also used finite element techniques to determine the stress intensity factors in question for more generalised geometries. The finite element results from this study suggest that the K-calibration was a function of notch geometry, namely notch length a, notch root radius ρ and crack length c (Fig. 1). For a through thickness crack the function suggested by Jergeus (1978) is:

$$K_I^1 = 1.122\,\sigma\sqrt{\pi\ell} \qquad (1)$$

$$\ell = a\left[1-\exp(-4(1+\sqrt{a/\rho})*c/\sqrt{a\rho})\right] + c \qquad (2)$$

The contribution from notch therefore is

$$\ell = a\left[1-\exp(-4(1+\sqrt{a/\rho})*c/\sqrt{a\rho})\right] \qquad (3)$$

The stress intensity factor for a crack with length a + c will be

$$K_I = 1.122\sigma\sqrt{\pi(a+c)} \qquad (4)$$

From equation 1 and 4

$$K_I^1 = K_I*\sqrt{\frac{\ell}{a+c}} \qquad (5)$$

The modified stress intensity factor K_I^1 thus can be written in terms of a known stress intensity factor and notch geometry. The slip band sharpening of the notch can be modelled by incorporating c_B as the starter crack length equivalent to the slip band at the notch tip. $c+c_B$ is introduced in place of c, thus leading to a stress intensity factor which is non-zero when the fatigue crack length is zero. We propose that a stress intensity factor K_I can be modified in specific cases such as three point or four point bending. An accurate description of fatigue crack behaviour can be achieved by a modification of the compliance function Y, where $Y = k/(\sigma\sqrt{\pi c})$ for long crack. For the fatigue case therefore:-

$$Y_F = Y\left[a(1-\exp(-4(1+\sqrt{a/\rho})*\frac{c+c_B}{\sqrt{a\rho}})+(c+c_B))\ /\ (a+c)\right]^{\frac{1}{2}} \qquad (6a)$$

and

$$K_I^1 = \sigma*Y_F*\sqrt{a+c} \qquad (6b)$$

EXPERIMENTAL METHOD TO DETERMINE Y_F

The experimental method is based on the fact that the fatigue crack propagation rate is dependent on the stress intensity factor range so that two fatigue cracks in the same material, but in two different geometries, will exhibit the same propagation rate when subjected to the same stress intensity factor range (Paris, 1963). Thus:-

$$\frac{da}{dN} = C(\Delta K)^n \qquad (7)$$

For the materials under consideration the material constants C and n remain the same. The Paris law provides a convenient means to determine experimentally the stress intensity factors for uncalibrated geometries. First, values of C and n are established from a fatigue test on specimen geometries with known stress intensity calibrations. Further, uncalibrated crack geometries are subjected to fatigue under identical loading conditions and crack propagation rates are determined. Using equation 7 corresponding K values are evaluated. This procedure has been used successfully to determine K-calibrations for uncalibrated crack geometries (James, 1969).

From equation 7 crack propagation rates for our uncalibrated and calibrated geometries could be written as follows:-

Uncalibrated

$$\frac{da^1}{dN} = C(\Delta K^1)^n = C\ (\Delta\sigma*Y_F*\sqrt{a+c})^n \qquad (8)$$

Calibrated

$$\frac{da}{dN} = C(\Delta K)^n = C\ (\Delta\sigma*Y*\sqrt{a+c})^n \qquad (9)$$

Dividing equation 8 by 9

$$(\frac{da}{dN})^1\ /\ \frac{da}{dN} = (Y_F/Y)^n \qquad (10)$$

$$Y_F = Y*\left[\frac{da^1}{dN}\ /\ \frac{da}{dN}\right]^{1/n} \qquad (11)$$

Equation 6a should describe experimental values determined from equation 11.

MATERIALS AND EXPERIMENTAL METHODS

Materials

The steels investigated were BS970 080M15 (En32) and 080A47 (En8) wrought steels.

Fatigue Testing

Fatigue tests were carried out in a servohydraulic fatigue machine at a frequency of 20 Hz. Extensive details of fatigue testing are given in

(Nadkarni, 1981; Zhou, 1982). Specimens were 22 mm wide (W), 10 mm thick (B), notched to either 5 mm or 10 mm (Notch Depth a) and had root radii of 0.13 mm, 0.76 mm, 1.52 mm and 3.17 mm. Fatigue tests were carried out at ambient temperature in three point bending using a support span of 88 mm (Fig. 2).

Crack lengths were monitored continuously using the direct current potential drop method. A constant current of 30A was used. The voltage across the notch was monitored using wire probes spot welded on either side of the notch. Changes of 1μv could be detected reliably giving a measurement accuracy of 0.01 mm. A change of 5μv was selected arbitrarily to indicate crack initiation. Specimens broken open after a 5μv shift showed one or more small central cusps which was the form of the initiated fatigue crack. These cusps were semi-ellipital in shape with semi-major axis of 1 mm and semi-minor axis of 0.5 mm (Fig. 3).

Calibration curves for crack lengths were established experimentally by breaking open specimens after different voltage increases. Cusps were represented on the calibration plot by showing the length of a through thickness crack of the same area as that of a cusp.

RESULTS

The Paris law constants for the two steels tested are shown in Table 1. The crack propagation rate is in mm/cycles and K is in $MPam^{1/2}$. Specimens with notch root radius of 0.13 mm were employed for determining these constants.

TABLE 1 Paris Law Constants

Steel	C	n
BS970 080M15	$1.3 * 10^{-9}$	3.1
BS970 080A47	$2.1 * 10^{-10}$	3.6

Figures 4, 5 and 6 illustrate the K-calibration for cracks emanating from notches. The data is derived from equation 11. Y values are calculated for crack lengths equal to a + c using the Srawley equation (13).

These experimental results can be described by, (curve fit based on equation 6a)

$$Y_F = Y * \left[\frac{a*\tanh\left[\frac{2*\sqrt{(1+a/\rho)}*(c+c_B)}{\sqrt{a\rho}}\right] + (c+c_B)}{(a+c)} \right]^{\frac{1}{2}} \qquad (12)$$

The Jergeus equation (equation 1) is also shown for comparison. Taking c = o, the value of c_B could be calculated from equation 12. Rearranging equation 12. When c = o :-

$$a \tanh\left[\frac{2\sqrt{1+a/\rho}}{\sqrt{a\rho}} c_B\right] + c_B - a\left[\frac{Y_F}{Y}\right]^2 = 0$$

The solution of this equation gives value of c_B for the materials tested.

Mean values of c_B deduced from the crack growth results are listed in Table 2 and the structural features of this size are indicated in the table.

TABLE 2 The Values of the Structural Parameter c_B

Steel	c_B μm	Structural Feature
BS970 080M15	22	Grain size
BS970 080A47	22	Mean free path in ferrite

It can be seen that equation 12 describes the experimental results more accurately than equation proposed by Jergeus (1978) (equation 1).

DISCUSSION AND CONCLUSIONS

Initiation of fatigue cracks generally occurs in the form of a single or multiple cusps. Maximum cusp sizes were 1 mm deep with 3 mm surface length with equivalent area of a through thickness crack of 0.6 mm depth. Due to the lack of a universal calibration available to deal with such cracks or to include notches with cracks, calibrations were established experimentally. Thus equivalent crack lengths are used. These are applied to cusps which arose both in experiments and in the calibrations. This assumption has produced some scatter in the near notch tip region. The fatigue cracks emanating from notches grew in the ferrite phase in both steels. It is proposed that as fatigue damage leading to the formation of slip bands or intrusions/extrusions is localised to individual grains or to a phase which renders the least resistance, c_B could be taken as the grain size or mean free path. This correlates very well with the experimental results obtained.

The distance over which the notch effect is present has been found to extend as far as $0.5\sqrt{a\rho}$ in this investigation, compared to $0.13\sqrt{a\rho}$ in plane stress, suggested by Smith and Miller (1979). This supports Jergeus's finite element calculations (1978). Initiation and propagation of fatigue cracks from notches is of particular importance in materials where the critical crack length for fast fracture is small. The expression (equation 12) established in this study is useful in determining the number of cycles to initiation using expression $Ni = B(\Delta K)^m$ (Nadkarni, 1981; Zhou, 1982) and the number of cycles for propagation through integration of the Paris law using the appropriate K-calibrations (Zhou, 1982). In some structures, small cracks already exist at notches. Growth of such cracks is also of considerable interest and the experimental calibrations apply to such cracks.

Much remains to be done concerning the extension of the present method into strain cycling, variable amplitude cycling, and high temperature fatigue. The method has been successfully applied to steels and aluminium alloys in a surface hardened condition (Nadkarni, 1981; Zhou, 1982). We conclude that the experimental method used could be employed successfully to determine K-calibrations for cracks emanating from notches in any material, provided notch plasticity effects are not large.

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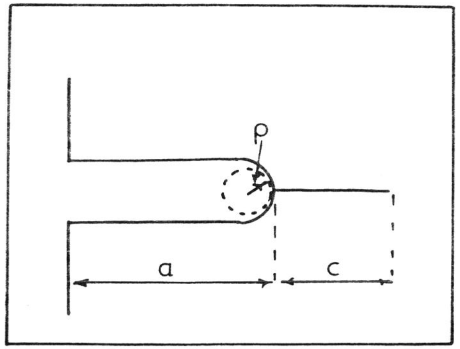

Fig. 1. Schematic diagram of notch geometry

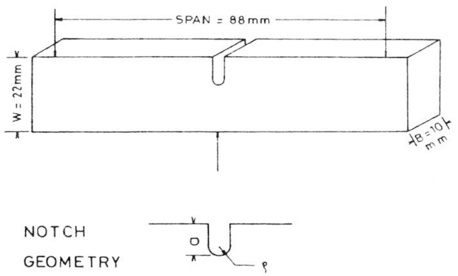

Fig. 2. Specimen geometry of fatigue specimens

Fig. 3. Fatigue crack shape at initiation. Mag. x24

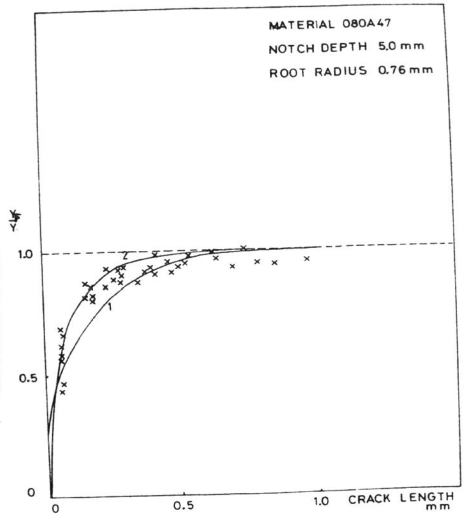

Fig. 4. Comparison between equation 12 (curve 1), Jergeus equation (4) (curve 2) and experimental results

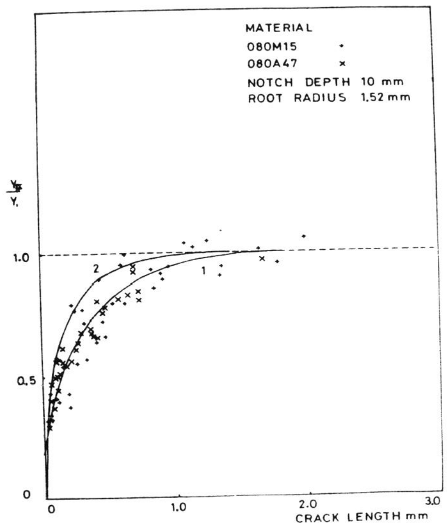

Fig. 5. Comparison between equation 12 (curve 1), Jergeus equation (4) (curve 2) and experimental results

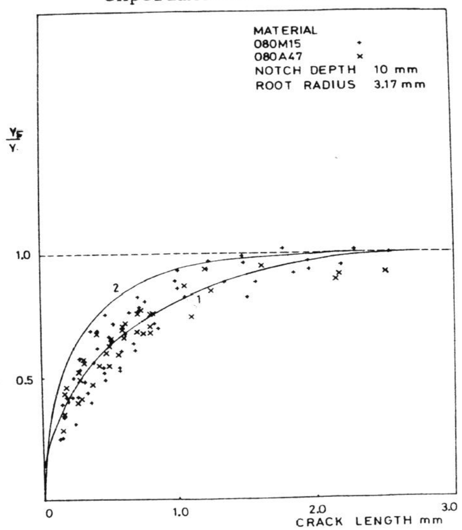

Fig. 6. Comparison between equation 12 (curve 1), Jergeus equation (4) (curve 2) and experimental results

FATIGUE PROPAGATION OF SHORT CRACKS

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ABSTRACT

Short cracks fatigue behaviour was studied at room temperature in CT specimens of 316L stainless steel with two notch root radii : 1,25 mm and 10 mm. The increase of the crack area was followed using a potential drop system and the change of the compliance. The evolution of the shape of the crack was observed from beach marks. After a conventional crack depth was defined, the crack propagation rates were plotted against various ΔK parameters derived from linear elastic fracture mechanics. Except for high load levels, the points fall on the standard power law curve.

KEYWORDS

Fatigue ; short crack ; crack initiation ; stainless steel.

INTRODUCTION

The present study is concerned with the behavior of short fatigue cracks initiated at notch roots in 316L stainless steel at room temperature. Major conclusions about near notch tip concerns the initial distance which the fatigue crack is enhanced by the presence of a blunt notch (Novak, 1976). It is a common factor of fatigue theories to assume that a usual stress intensity factor cannot be associated with the tip of a blunt notch, so we present fatigue crack propagation rates versus modified ΔK parameter with a ΔK calibration for cracks emanating from notches which falls to zero at the notch tip (Yamamoto, 1974 ; Yamamoto, 1976 ; Jergeus, 1978 ; Barnby, 1981). It is now also usual to calculate a strain intensity factor ΔK to take into account the strain field of the mechanical notch (Kitagawa, 1979). One important aspect of the short cracks problem is concerned with cracks initiating and growing in plastically strained materials such as occurs in high strain fatigue studies and at notch roots.