Crack Closure and the Propagation of Semi-elliptical Fatigue Cracks in Q1N (HY80)

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ABSTRACT

The results of an experimental investigation of the effect of crack closure on the propagation of semi-elliptical fatigue cracks are presented. Load-shedding fatigue threshold tests were carried out at stress ratios of 0.2, 0.35, 0.5 and 0.7. Crack closure was measured at the surface and depth positions using back face strain gauges, near-tip gauges, and a clip gauge. Differences between the surface and depth growth behaviour are explained by considerations of the effects of the transition from plane stress conditions at the surface to plane strain conditions at the depth. The effects of stress ratio are attributed largely to differences in the crack opening displacement which result in asperities coming into contact to induce crack closure.

KEYWORDS

Fatigue, propagation, semi-elliptical cracks, crack closure, transition, plane stress, plane strain, stress ratio, crack opening displacement.

NOMENCLATURE

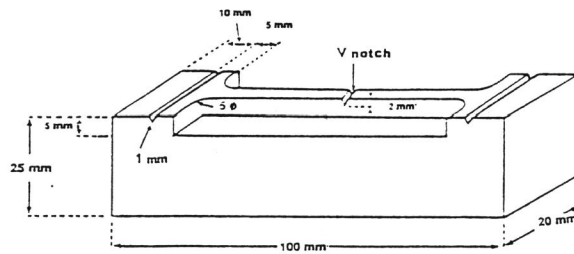|	
$2r_p$	reversed plane stress plastic zone size
ΔK	stress intensity range = $(K_{max} - K_{min})$
ΔK_{eff}	Effective stress intensity range
K_{max}	maximum stress intensity factor
K_{min}	minimum stress intensity factor
K_{cl}	crack closing stress intensity factor
R	stress ratio = (K_{min}/K_{max})
U	Elber closure ratio = $(\Delta K_{eff}/\Delta K)$
σ_y	monotonic yield stress

Fig. 1.   Single ridge specimen

Fig. 2.   Gauge locations on specimen

INTRODUCTION

Since the original discovery of crack closure (Elber, 1970) various workers
have carried out theoretical analyses (Budiansky and Hutchinson, 1978;
Newman, 1976; Ogura and Ohji 1977; Suresh and Ritchie, 1982), and
experiments (Suresh and Ritchie, 1984), to assess the effects of crack
closure on fatigue crack growth. Most of these studies have been carried
out for through-crack geometries, although the great majority of cracks
found in engineering structures and components under service conditions
tend to have "thumbnail" (semi-elliptical) shapes. Reports of work on the
propagation of semi-elliptical fatigue cracks (Fleck et al., 1983 and
Newman and Raju, 1984) have shown that there are some differences between
the fatigue growth of through-cracks and the fatigue growth of
semi-elliptical cracks. These differences are thought to be due to the

effects of crackclosure (Fleck et al., 1980 and Newman, 1982) and the
relaxation of constraint which arises from the shift in the neutral axis as
the crack grows in the depth direction.

The effects of crack closure on the growth of semi-elliptical fatigue
cracks are investigated in this paper employing load-shedding fatigue
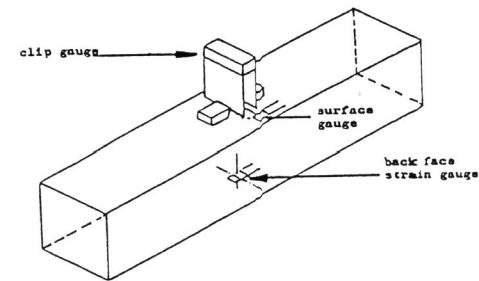threshold tests, and crack closure measurements.

EXPERIMENTAL

The material tested was Q1N, a medium strength structural steeel containing
0.18C, 2.5 Ni, 1.5Cr and 0.5 Mo. Fatigue tests were carried out on Q1N in
the as-received condition which was obtained by austenitising at 950°C for
1 hour followed by a water quench, and stress relieving at 650°C for 1 hour
before a final water quenching to give a tempered martensitic
microstructure.

Specimens with semi-elliptical cracks were obtained by fatiguing ridged
specimens (Fig. 1) using a 100KN MAND servohydraulic testing machine. The
cracks were grown until they had extended through about 1mm on either side
of the ridges which were then machined away to leave specimens with
semi-elliptical cracks of $\sim$ 4mm surface length. Load-shedding fatigue
tests were carried out at a cyclic frequency of 40Hz using a 100 KN MAND
servohydraulic testing machine. The cracks were allowed to grow through a
distance which was greater than four times the reversed plane stress
reversed plastic zone size, between load adjustments. This zone size is
given by:

$$2r_p = 0.4 \frac{\Delta K}{2\sigma_y}^2 \tag{1}$$

Crack growth was monitored using the direct current potential difference
method (Soboyejo et al, 1988 and Hicks and Pickard, 1982), and some
beachmarks were introduced onto the fracture surfaces to check the accuracy
of the p.d. calibration. These were obtained by changing the stress ratio
(R = K_{min}/K_{max}) whilst maintaining a constant K_{max}. Crack closure was also
measured using Back Face Strain (BFS) gauges, near-tip gauges, and a clip
gauge (Fig. 2). Closure plots of load versus displacment were obtained by
stopping the tests and cycling at a frequency of 0.1 Hz between K_{max} and
K_{min}. Finally, the specimens were fractured in liquid nitrogen at the end
of the tests, before measuring the roughnesses of the fracture surfaces
with a Talysurf surface measuring device.

Table 1.   Fatigue Thresholds

R $=(K_{min}/K_{max})$	Semi-elliptical crack fatigue thresholds (ΔK_{th}/MPa√m)		Through-crack fatigue thresholds (ΔK_{th}/MPa√m) (James and Knott, 1985)
	Surface	Depth	
0.20	6.3	4.3	4.8
0.35	8.7	5.2	3.5
0.50	4.8	4.0	3.0
0.70	3.5	3.2	3.2

RESULTS AND DISCUSSION

The fatigue thresholds and growth-rate data are compared with through-crack data from previous tests (James and Knott, 1985) in Tab. 1 and Fig. 3 respectively. Note that the stress intensity factors for semi-elliptical cracks were obtained from solutions published by Scott and Thorpe (1981) with finite width correction factors given by Holdbrook and Dover (1979). In the Paris Law region, agreement was found between the surface and the depth growth-rates, and the through-crack rates. However, some differences were observed in the near-threshold regime where closure mechanisms are

known to have a significant effect on fatigue crack growth (Suresh and Ritchie, 1984). Surface growth-rates were observed to be generally lower than the depth growth-rates in this region, in agreement with the results of Fleck et al., (1983). Similarly, the surface thresholds were higher than the thresholds at the depth position, and higher thresholds were obtained at low stress ratios.

The crack closure data are presented in Fig. 4 in which Elber closure ratios, U = ΔK_{eff}/ΔK, are plotted against stress intensity values. The higher levels of crack closure at the surface, and the agreement between semi-elliptical crack depth and the through-crack (plane strain) closure data obtained from previous tests, confirm the effects of the plane stress/plane strain transition on variation of crack closure around the crack. Note that the Back Face Strain (BFS) and clip gauge measurements were taken to correspond to closure behaviour at the depth postion whilst the near-tip gauges were used to measure the closure at the surface. Fleck et al., (1983) successfully employed a similar configuration of gauges to measure crack closure in semi-elliptical cracks. They found that near-tip gauges and clip gauges were able to detect closure at the surface and the depth positions respectively. However, they were unable to detect closure with their BFS gauges. In the present work, closure was detected by all the three different types of gauge (Fig.2) c.f. Fig.5 in which typical load versus displacement plots are presented.
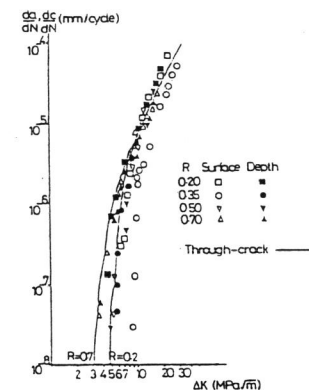

Fig. 3.   Fatigue crack growth-rate versus ΔK

The differences between the surface and the depth thresholds and growth-rate data are probably due to the transition from unconstrained (plane stress) conditions at the surface to constrained (plane strain) conditions at the depth (Fleck et al., 1980), and differences between the asperity heights at the surface and depth positions (Tab. 2) The higher levels of residual plasticity generally associated with plane stress regions increase the plasticity-induced component of closure at the surface. They will also have the effect of increasing the roughness-induced component of closure (Minakawa and McEvily, 1981; Suresh and Ritchie, 1982; Walker and Beevers), since more asperities will be brought into contact under plane stress conditions. Note that the rougher asperities at the surface (Tab.2.) will enhance this effect. Higher levels of oxide-induced closure (Suresh et al., 1981) might also be induced when more asperities come into contact. The resulting mode II components of displacment induce oxide formation through fretting, since the rubbing of mating asperities exposes clean surfaces to the autocatalytic formation of oxide layers (Romaniv et al., 1987). These can induce closure by wedging open the crack. Hence there will be a variation of crack closure along the crack front due to the different effects of crack closure.

The "intrinsic" threshold data are presented in Tab. 3. There appears to be an "intrinsic" threshold ΔK_c of ~ 3MPa√m for Q1N in the tempered martensitic condition, although a lower value of 2.4MPa√m was obtained for R = 0.2 at the depth position. Also, with the exception of the R = 0.2 data, plots of fatigue crack growth-rate versus effective stress intensity fell within the same scatter band on a straight line (Fig. 6). Reasons for the discrepancies with the R = 0.2 data are not entirely clear at present.

The effects of stress ratio on the fatigue crack growth-rate are illustrated using the surface growth data shown in Fig. 7. The trends can
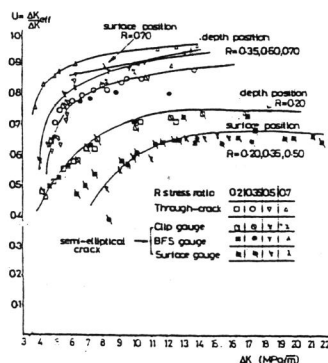
Fig. 4.   Elber closure ratios ($U = \Delta K_{eff}/\Delta K$) at
different stress ratios

Fig. 5.   Typical closure plots of load versus
displacement

be explained by considering the variations in the Crack Opening
Displacements (COD) and the asperity heights around the crack front and
their effects on crack closure. Talysurf measurements of the asperity
heights show that stress ratio and stress intensity factor range have a
very small effect on the root mean square fracture surface roughness
although rougher asperities were observed at the surface when compared to
these in the depth positions. This is shown in Tab. 2. The predominance
of crack closure at lower stress ratios is therefore mainly due to the
lower COD values which tend to bring more asperities into contact.

The effects of crack closure on the crack shape development at different
stress ratios are illustrated in Fig. 8 using plots of aspect ratio versus
normalised crack lengths. These show two distinct 'Preferred Propagation
Paths' (PPP) (Corn, 1971) which are strongly influenced by stress ratio.
Similar trends in the crack shape development at different stress ratios
have also been reported by Jolles and Tortoriello (1983) for the case of
pure tension.

Although the above discussion has focussed mainly on the effects of crack
closure on the fatigue growth of semi-elliptical cracks, it would be
misleading to suggest that other factors do not affect the growth of these
cracks. It is therefore important to note that the fatigue growth of
semi-elliptical cracks can also be significantly affected by the type of
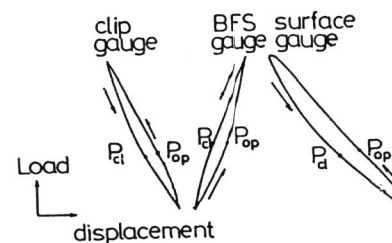loading (Scott and Thorpe, 1981), residual stress fields (Braid, 1982), and
constraint.

CONCLUSIONS

1.   There exists an intrinsic threshold for Q1N in the tempered
martensitic condition which is ∿ 3MPa√m.

2.   The differences between the fatigue crack growth rate data at the
surface and the depth positions can be explained largely by
differences in fracture surface roughness, and the effects of the
transition from plane stress conditions at the surface, to plane
strain conditions within the specimens, and its effect in crack
closure mechanisms.

3.   The effects of stress ratio on the fatigue growth of semi-elliptical
cracks can be explained largely by crack closure arguments.

ACKNOWLEDGEMENTS

Table 2.   Talysurf measurements of r.m.s. fracture surface roughness

$R = (K_{min}/K_{max})$	Talysurf r.m.s. fracture surface roughness (microns)	
	Surface	Depth
0.20	6.28	3.96
0.35	5.05	4.43
0.50	5.74	3.84
0.70	6.07	3.90

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Soboyejo, W.O., Read, R.C. and Knott, J.F. (1988). Submitted to Int. J. Fract.
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Suresh, S., Zamiski, G.F. and Ritchie, R.O. (1981). Met. Trans., 12A, pp.1435-1443.
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Table 3.   "Intrinsic" Thresholds

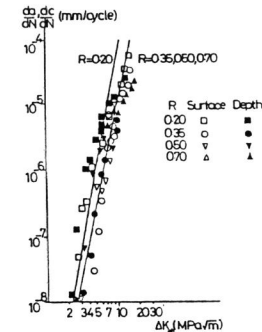| $R = (K_{min}/K_{max})$	Semi-elliptical crack "intrinsic" thresholds (ΔK_c/MPa√m)		Through-crack "intrinsic" thresholds (ΔK_c/MPa√m) (James and Knott, 1985)
	Surface	Depth	
0.20	3.6	2.4	3.2
0.35	3.2	3.3	2.8 2.9
0.50	3.1	2.9	3.1
0.70	3.0	3.0	3.3

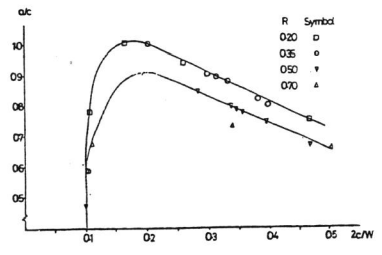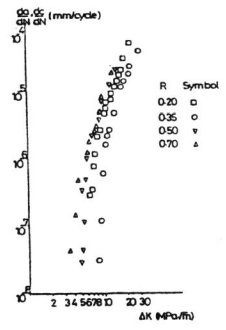Fig. 6.   Fatigue crack growth-rate versus ΔK_{eff}

Fig. 7. Surface growth-rates at different stress ratios

Fig. 8. Aspects ratio development at different stress ratios