FATIGUE MICRO-CRACK GROWTH BEHAVIOUR IN 0.16% CARBON STEEL

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ABSTRACT

Fatigue micro-crack growth from a through the thickness single edge micro-notched specimen of 0.16% Carbon Steel was studied under pure bending and constant amplitude loading conditions with the help of a carefully calibrated pulsed direct current electric potential technique.

The micro-cracks were initiated sporadically from irregularities present on the notch surface and they grow in a non-uniform manner immediately after initiation, after which their propagation becomes more stable. For a given stress level, the crack propagates faster along the surface than along the depth direction.

INTRODUCTION

Recent industrial experience have shown that the rupture/failure of most engineering members such as rotors, pinions etc is not necessarily produced from the propagation of through-the thickness cracks, but from that of the small part-through surface micro-cracks which often develops from defects and irregularities present in the material matrix and which propagates in a funny manner when subjected to a cyclic loading.

The complete understanding of the behaviour of such micro-cracks then becomes essential, as such is necessary for the:

i) development of materials of good fatigue resistance.

ii) selection of materials for a given engineering application.

iii) formulation of improved methods of predicting fatigue lives of structures by combining crack initiation and crack growth.

Through the use of conventional Fracture Mechanics concepts, different recent studies (1-8), have shown that during the early lives of such cracks they propagate in a manner different from that of the large through cracks. Moreover, in certain situations once a small crack is initiated, it propagates for a certain length, then, stops propagating entirely. Such cracks have also been shown to have the values of their stress intensity factors k less than the conventional threshold stress intensity factor for long fatigue crack growth k_{th} habitually considered to be a material constant and below which no detectable crack propagation occurs.

The principal objective of this paper, is to present some experimental findings on the growth behaviour of small part-through fatigue cracks from a Vee Shaped (notch angle = 60°) micro-notched single-edge bend specimens of high yield strength (of 1070 MPa) low alloy martensitic steel. The detection and the growth of the cracks were carried out with the aid of the pulsed direct current (d.c.) electric potential technique.

EXPERIMENTAL PROCEDURES

Material

The experimental materials is a high strength low alloy martensitic (Nickel-Chromium Molybden) steel called the 16NCD13 according to the French Standard, and principally used in the fabrication of mechanical parts such as the pinions in the gear box of an helicopter. The material was supplied in the plate form. Its chemical composition as well as the longitudinal mechanical and metallurgical properties are as presented in Tables 1 and 2.

Specimen Preparation:

Specimen were cut in the L-T orientation (Rolling direction), so that the crack propagates in the transverse direction. The specimen (Fig. 1) is of the single-edge micronotched bend type of dimensions 80 x 20 x 10mm. The notch is V-shaped and it is O.1mm deep and of 45 microns root radius and was carefully machined with an electro-discharge machining. The notches in the specimens were mechanically polished first with abrasive papers and then with alumina paste down to 1m. Four pairs of potential probes were positioned on the notch. Thin copper wire probes were then micro-welded to the specimen surface.

Crack Growth Monitoring:

The specimen was mounted on a ±100kN Instron servo-hydraulic testing machine. Constant amplitude fatigue crack growth tests were carried out in laboratory air with a stress ratio of 0.1 and a frequency of 20Hz in the same machine. The specimen was subjected to pure bending and the crack growth was monitored using the pulsed direct current electrical potential drop technique (9). The four pairs of potential probes enabled the detection and monitoring of cracks at various points along the notch. At the end of the test, the specimen was fractured and its fracture surface examined with a Cambridge Stereoscan 100 type of Scanning Electron Microscope.

Table 1: Percentage Weight Composition of the Material

	C	SI	Mn	S	P	Cr	Ni	Mo	Cu	Fe
16NCDI3	0.16	0.28	0.48	0.003	009	0.96	2.14	0.23	0.10	Bal.

Table 2: Metallurgical and Mechannical Properties of the Material

		0.2% Yield Strength σ_{ys} MPA	Ultimate Tensile Strength σ_{ys} MPA	Elongation
16NCDI3	Austenitised at 825°C for 0.5h, Oil quenched and tempered at 190°C for 2h average grain size 25μm	1070	1360	13

Calibration of the Electrical Potential Measuring System:

The details of the experimental and the calibration procedures of the electrical potential measuring system had earlier been reported (9-10). However a brief summary of the procedure is given as follows: the variation in electric potentials measured by the pairs of probes were summed and averaged and then normalized (11 - 13) with a reference potential,. V_{ref}. Here, V_{re}, refers to the potential difference measured at the beginning of a test and at a distance of 2W from the centre of the specimen, where W is the specimen width. The averaged and normalized potential difference V_m/V_{ref} was then plotted as a function of the total cracked area measured from the microscopic observation. The calibration curve was obtained from several specimens cracked under the same experimental conditions.

Analysis of crack dimension & growth:

From the experimentally determined calibration of voltage against cracked area (10), equation [1] was obtained:

$$V_m/V_{ref} = K_1 A \quad (1)$$

where

$$A = \frac{\pi}{2}ac \quad \text{(for semi elliptical crack)} \quad (2)$$

or $\frac{\pi}{4}ac$ (quarter elliptical crack) (3)

a = crack depth

c = half of the total surface length of crack

k_1 = constant determined from the calibration curve.

Assumption:

In order to simplify the 3-dimensional nature fo the cracks, it was assumed that for any type fo crack, the ratio a/c remained constant through the growth period of the crack, so that

$$a/c = a_i/c_i = a_f/c_f = k_2 \text{ (constant)} \quad (4)$$

Equations [1] to [4] were used to calculate the depth and the surface length of the cracks. The minimum detectable crack depth from the notch root measured by the system was of the order of 30μm (10) when the crack formed exactly opposite a probe wire, and of 50μm when it was formed in between probe wires. Moreover, the calculated crack depths were found to be approximately ± 10% in ttheir actual values in the formaer cases and ± 15% in the latter.

The values of the crack dimensions obtained were then used in the computation of the stress intensity factor range ΔK. This is calculated with the help of the NEWMAN's formula (11) for surface cracks under pure bending condition. This we recall here as

$$\Delta K = S_t + H S_b \sqrt{\left(\frac{\pi a}{Q}\right)} F\left(\frac{a}{t}, \frac{a}{c}, \frac{c}{b}, \varphi\right) \quad (5)$$

with the following conditions

$0 < a/c \leq 1$

$0 < a/t \leq 1$

$c/b < 0.5$

and $0 \leq \phi \leq \pi$ (semi elliptical)

$0 \leq \phi \leq \pi/2$ (quarter elliptical

where

S_t = tension stress

S_b = bending stress

H, F & Q are functions of a/t and a/c

φ = parametric angle of ellipse.

RESULTS AND DISCUSSIONS

It was observed that nearly all the tests carried out at the different stress levels resulted in the growth of one or several micro semi-elliptical cracks, except in some cases where a corner crack was observed.

The micro-cracks were initiated sporadically from irregularities present at any location on the notch surface. The Figures 2a and 2b show for example, the fractured surface of some of the cracks that were initiated from irregularities on the notch surface. However, whether a semi-elliptical crack or a corner crack is generated, the crack growth was followed and analysed accordingly,

Table 3 shows the crack dimensions with the number of cycles at crack initiation and at the end of the test at the different stress levels considered. From the Table and from the Figures 3a and 3b which show the evolution of the crack along the depth directions respectively, it is observed that as the stress amplitude σ_n (the nominal stress) decreases in value from 420 MPa to 300MPa, the number of cycles at crack initiation increases from 28000 cycles to 175000 cycles. This implies that the resistance of the material to crack initiation and crack propagation or the damage tolerance defect of the material is higher at lower stress levels. Moreover, from Table 3, it is seen that the least detectable crack growth in the tests is of the order of 40 microns. Finally, from Figures 3a and 3b and from the analysis it is observed that at nearly all the stress levels and immediately after the crack initiation the crack propagates in a non-uniform manner up to a certain length (of the order of 180 microns) particularly in the depth direction before its propagation become stable.

This early non-uniformity in the crack growth (ref. to Figure 3a) is believed to be due to the effect of the notch on the very short propagating crack especially when its depth is still less than the magnitude of the notch depth. Thus, as the crack initiates, it propagates in the zone of influence of the notch, while the notch itself is situated in an entirely elastic field. As the crack depth approaches the magnitude of the notch depth, the influence of the notch on the propagating crack becomes less and thus the propagation becomes more and more stable.

On the other hand, the initial non-uniformity in crack growth along the surface of the specimen (Figure 3b) could be explained from the micro-structural influence (as suggested by Fathula et al (12)) on the propagating crack, which was interpreted as the interaction between the grain boundaries of the material and the short propagating cracks which results in intermittent arrest of the crack especially in the early crack growth arrest.

The Figures 4a and 4b show the crack growth as a function of the stress intensity factor variation ΔK, also along the surface as well as along the depth directions respectively compared with the growth rate of long through thickness crack. In the curves, it is noted that there was an initial diminution of crack speed with the increase in the value of ΔK of about 8 MPa/m before the speed increases uniformly with increase in the value of ΔK.

It can also be seen that, at the beginning of crack propagation all the values of ΔK were slightly superior to the threshold values of ΔK of the material, while after the intersection of the short and long cracks they were nearly the same. This behaviour further confirms that small fatigue cracks behaves in a manner different from the long through cracks, and that they can have the values of their ΔK inferior to the threshold values of the ΔK of the long-through cracks.

Lastly, from Figures 4a and 4b, it is noted that at any given stress level the crack propagates faster along the surface than along the depth directions.

CONCLUSION

Initiated fatigue micro-crack propagation behaviour from micro - notched single-edge specimens (SEN) of 0.16% Carbon Steel has been investigated with the help of the pulsed direct current electric potential technique.

The main results were:

1) At the different stress levels considered, one or several micro semi-elliptical or corner cracks were initiated sporadically from irregularities present at any location along the notch surface.

2) Immediately, after crack initiation, the crack propagates in a non-uniform manner up to a certain crack length of the order of 180 microns, after which the propagation becomes more stable. This results in an initial diminution of the crack growth with increase in the value of ΔK on the da/dN versus ΔK plot.

3) Finally, for a given stress level the crack growth rate is faster along the surface than along the depth direction.

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REFERENCES

1. Hudak, S.J. Jr. (Jan. 1981) Small Crack Behaviour and the Prediction of the Fatigue Life. Journal of Engineering Materials and Technology, Vol. 103, pp. 26 - 35.

2. Tanaka, K., Nakai, Y. (1983) Propagation and Non-propagation of Short Fatigue Cracks at a Sharp Notch. Fatigue of Engineering Materials and Structures, Vol. 5, 4, pp. 315 - 327.

3. Heubaum, F. and Fine, M.E. (1984) Short Fatigue Crack Growth Behaviour in a High Strength Low Alloy Steel, Scripta Metallurgica, Vol. 18, pp. 1240 -1245.

4. Klesnil, M. Polak, J. and Lisjutin, P. (1984) Short Crack Growth Close to the Fatigue Limit in Low Carbon Steel. Scripta Metallurgica, Vol. 18, pp. 1231-1234.

5. Hoshide, T, Yamada, T. Fujimura, S. and Hayashi T. (1985) Short Crack Growth and Life Prediction in Low Cycle Fatigue of Smooth Specimens. Engineering Fracture Mechanics, Vol. 21, No. 1, pp. 85 - 101.

6. Tanak, k. and Wei, R. P. (1985) Growth of Short Fatigue Cracks in HY 130 Steel in 3.5% NaCl Solution. Engineering Fracture Mechanics Vol. 21, No. 2, pp. 293-305.

7. Suh, C.M. Yuuki, R, and Kitagawa H, (1985) Fatigue-Micro Cracks in a Low Carbon Steel, Fatigue and Fracture of Engineering Materials and Structures, Vol. 8, No. 2, pp. 193-203.

8. The Proceeding of the Behaviour of Short Fatigue Cracks EGF. Pub. 1 (Edited by K. J. Miller and E. R. de Los Rios) 1986 Mechanical Engineering Publications, London.

9. O. Oni (1986) Contribution to the Study of Short Fatigue Crack Propagation in Steels (in French). Dr. Ing. thesis, University of Technology, Compiegne, France.

10. O. Oni and C. Bathais (1986) Fatigue Crack Growth in Micro-Notched Specimens of High Strength Steels. The Behaviour of Short Fatigue Cracks, EGF Pub. 1 (Edited by K. J. Miller c. d. E. R. de Los Rios) Mechanical Engineering Publication, London. pp. 295-307.

11. Newman, J. C. Jr. and Raju, I.S. (1984) Stress Intensity Factor Equation for Cracks in Three Dimensional Finite Bodies Subjected to Tension and Bending Loads, NASA Technical Memorandum 85, 793.

12. Fathula, A. Weis, B. and Stickler, R. (1984) I Initiation and Propagation of Short Cracks under Cyclic Loadings near Threshold in Technical Alloys. The International Spring Meeting of the Societe Francaise de Metallurgie, Paris, pp. 160-172.

Table 3: Micro-crack Initiation Levels and Dimensions

Specimen	Crack Depth a μm	Crack half surface length c μm	Number of cycles	Maximum stress at notch σ_{max} MPa	Nominal Stress σ_{nom} MPa
1B	59	72	27000	1242.08	420.00
	214	258	82000		
2B	66	378	30000	1242.08	420.00
	207	1186	61700		
2M	61	138	84000	1064.64	360
	210	382	93000		
A4	40	85	172000	958.17	324
	156	350	190200		
A3	64	118	175400	887.20	300
	197	368	281000		

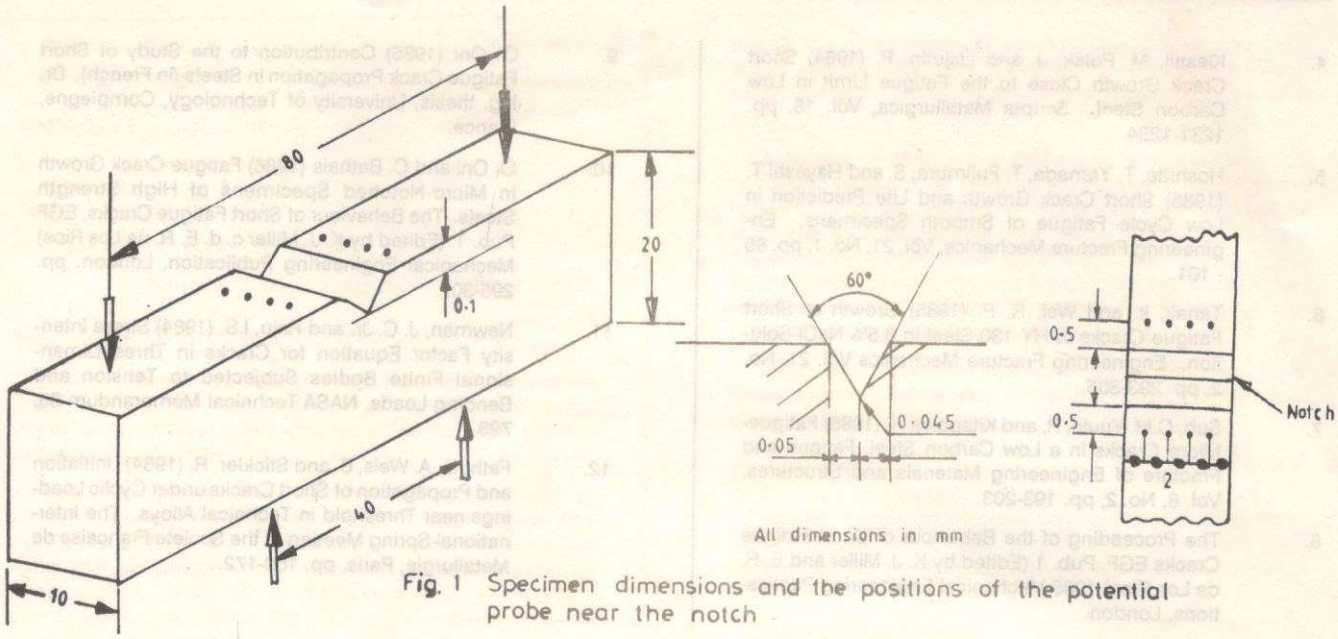
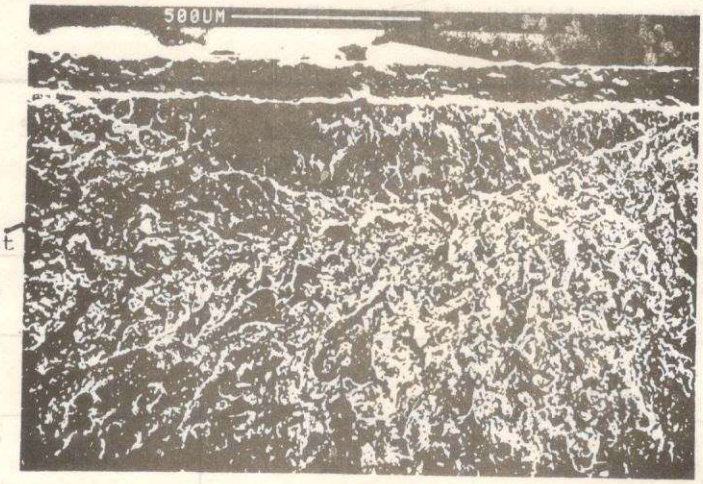
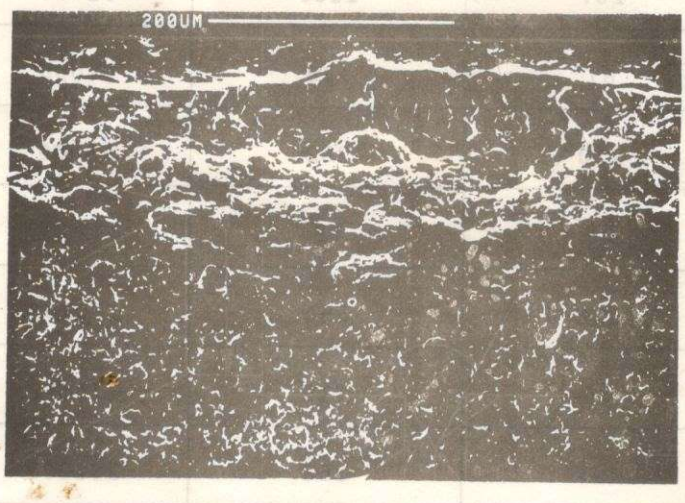


Fig. 1 Specimen dimensions and the positions of the potential probe near the notch



(a) Specimen A4



(b) Specimen B3

Figure 2: Typical Part-through Fatigue Cracks initiated from Irregularities along a through thickness notch surface.

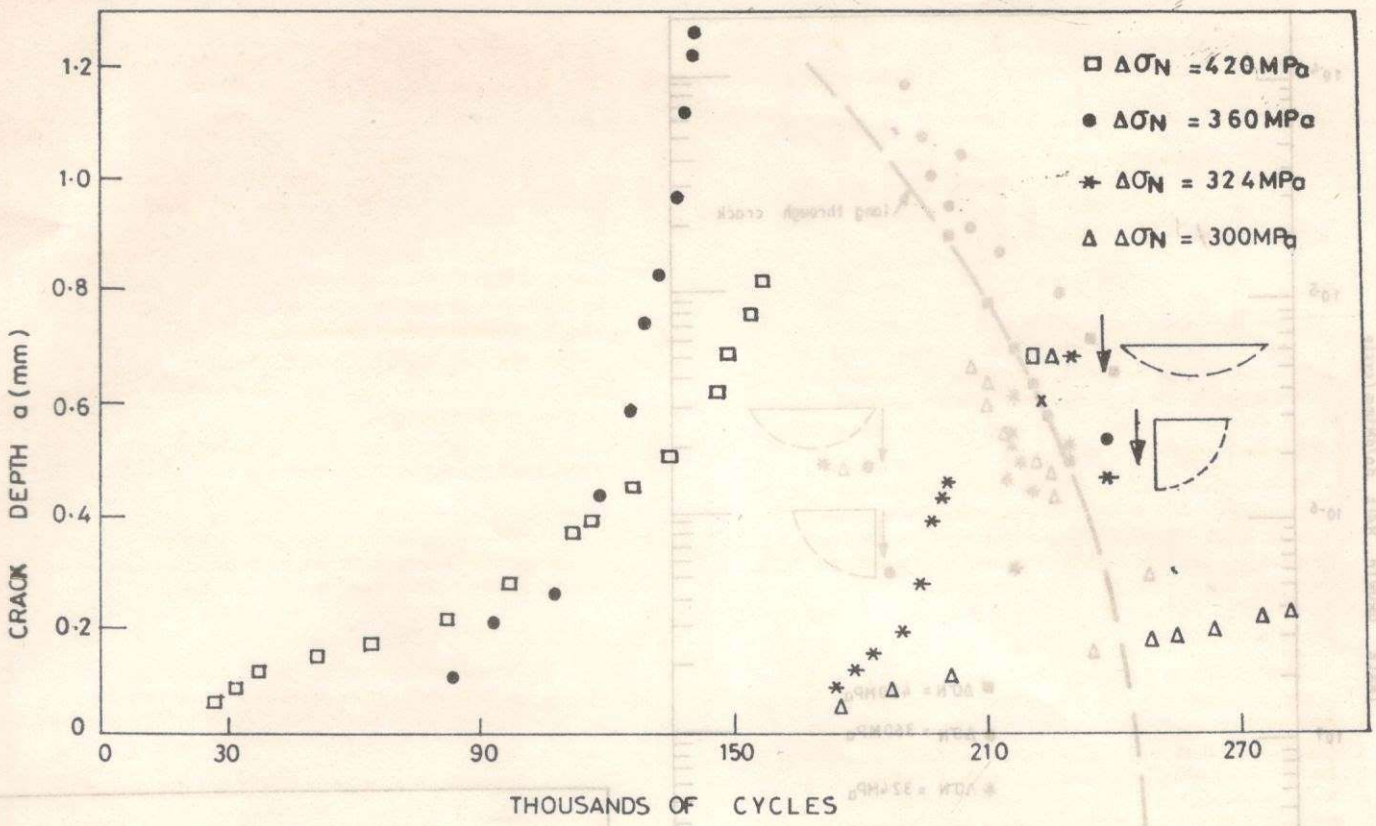


Fig. 3a Crack depth as a function of the number of cycles at different stress levels

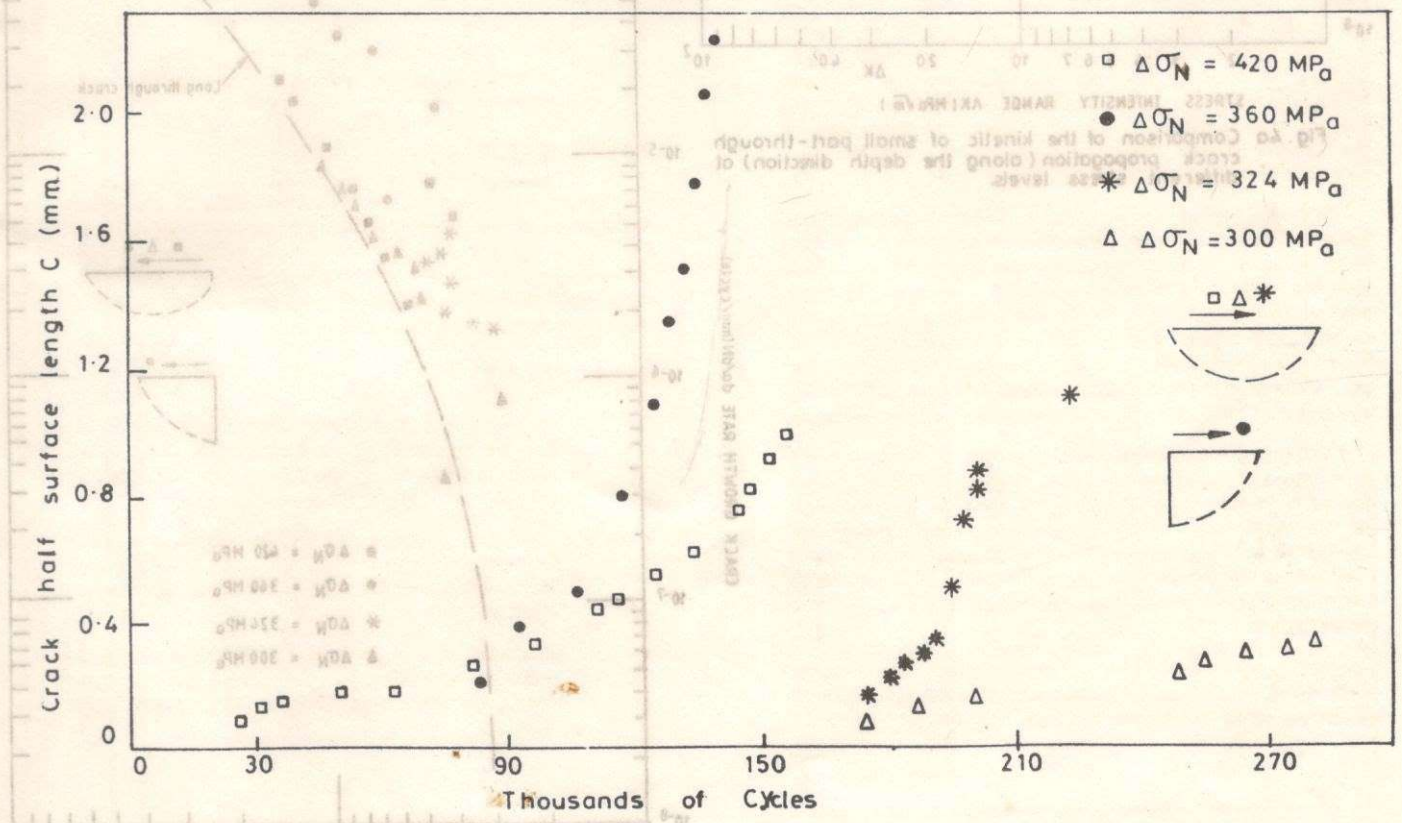


Fig. 3b Crack half surface length as a function of the number of Cycles at different stress levels

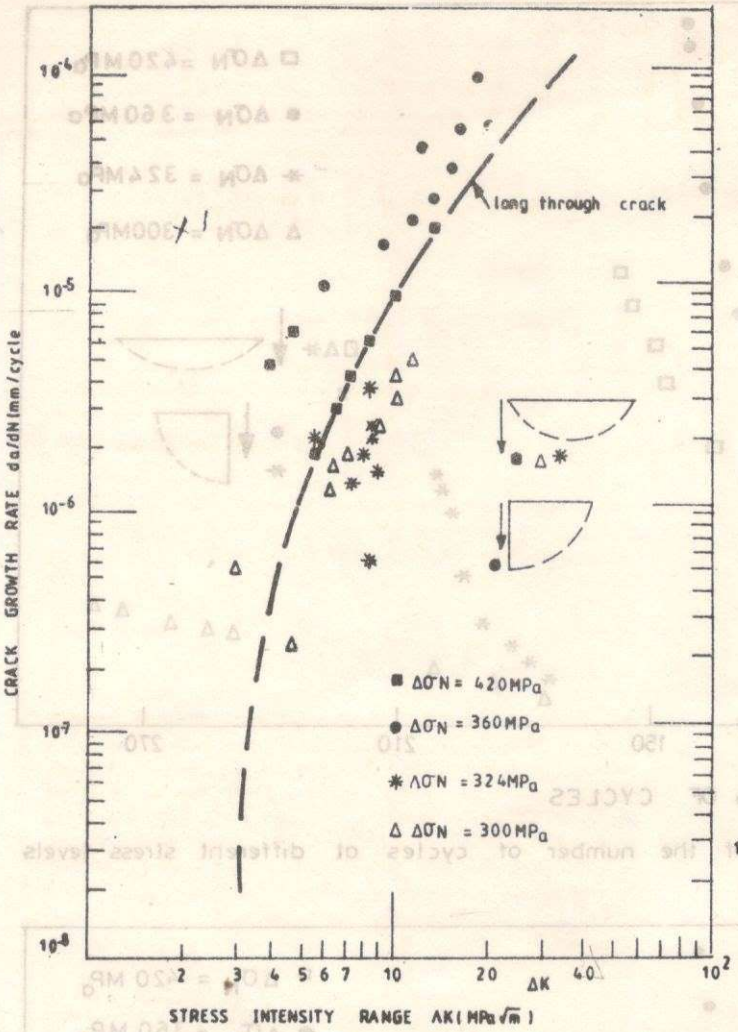


Fig. 4a Comparison of the kinetic of small part-through crack propagation (along the depth direction) at different stress levels.

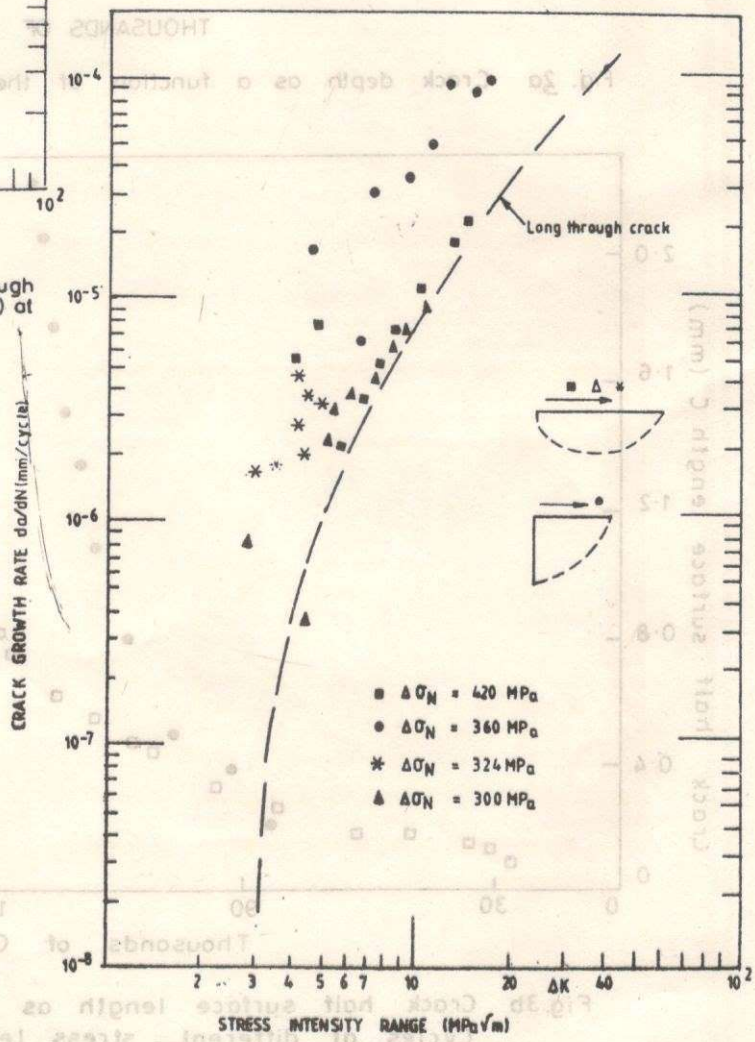


Fig. 4b Comparison of the kinetic of small part-through crack propagation (along the surface direction) at different stress levels.