THE PROPAGATION OF SHORT FATIGUE CRACKS IN 12% CHROMIUM STEELS

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ABSTRACT

The aim of the present investigation was a determination of the fatigue crack propagation behaviour of long and short fatigue cracks in two 12% Cr-steels. So as to eliminate effects caused by scatter in the material properties the same cracks were used for both the long crack (30-50 mm) and short crack (< 1 mm) experiments. It was shown that the crack length has no significant effect upon the growth rates or the threshold values for fatigue crack propagation. Correlation of the threshold values with the measured fatigue limit has shown that the latter is determined by the size of the inclusions in these steels.

KEYWORDS

12% chromium steels; fatigue crack propagation; fatigue crack threshold; short cracks; fatigue limit; inclusions.

INTRODUCTION

The interest in fatigue crack propagation in 12% Cr steels stems principally from their use in the fabrication of turbine components. Measurements of cracking rates have been made using long cracks since these are relatively easy to monitor with sufficient accuracy, the threshold value is found to be less sensitive to the crack length and the tests can be carried out at low stress amplitudes. However, it is the growth of small cracks from defects in the material which is of major interest in highly fatigue-loaded components. Therefore it is necessary to determine whether the data obtained for long cracks can be applied to the behaviour of shorter ones (typically < 1 mm long) particularly for very low propagation rates of less than one atomic spacing per loading cycle, ie. in the vicinity of the threshold, ΔK_o.

Conflicting data has appeared in the literature (Elsender, Gallimore and Poynton, 1977). Results have been presented indicating that in different materials short cracks may propagate faster (Chauhan and Roberts, 1979; Kitagawa and Takahashi, 1976; Pearson, 1975), at the same rate (Elsender, Gallimore and Poynton, 1977; Lankford 1977), or more slowly than longer cracks (Lankford, Cook and Sheldon, 1980). Quite different methods have been used in the previous investigations, namely:

(1) Loading of smooth specimens above the fatigue limit and optical monitoring of the fatigue cracks nucleated (Elsender, Gallimore and Poynton, 1977; Lankford, 1977; Pearson 1975)

(2) The use of notches to localise crack nucleation and analysis of the crack growth through the non-uniform stress field (Fisher and Sherratt, 1977)

(3) Crack initiation at weld spots in tests below the fatigue limit of defect-free material (Kitagawa and Takahashi, 1976)

(4) Further propagation of short cracks obtained by machining away part of a previously propagated longer fatigue crack (Chauhan and Roberts, 1979; Lankford, Cook and Sheldon, 1980)

The aim of the present investigation was to determine the propagation rates of clearly defined artificially introduced cracks of known length and geometry. Neither notches nor weld spots were used as nucleation points for the short cracks so as to avoid uncertainties arising from non-uniform stress fields and alteration of the metallurgical structure in the short crack regime. Loading levels were maintained below the fatigue limit to be representative of conditions which could arise in operating components.

PROCEDURE

The approach used in the present work was as follows:

1) Measure the propagation rate of long cracks (≃ 30 mm) using conventional double cantilever beam (DCB) specimens using small step reductions of the load to attain a valid threshold value below 10^{-11} m/cycle,

2) machine a new single edge notch (SEN) specimen containing only the tip (0.5 mm) of the previous crack. Anneal the specimen to relieve possible machining-induced local stresses at the crack tip,

3) recontinue the crack propagation experiment with the short crack at stress intensity amplitudes (ΔK) near the previous ΔK_o value.

In this way the effects of scatter in material properties and differences in crack front orientation between the specimens used to obtain the long crack and the short crack data have been effectively eliminated.

The experiments were carried out for two 12% Cr-steels (one of which contained 2% Ni) with microstructures consisting of tempered martensite. The chemical analyses and properties at room temperature are shown in Tables 1 and 2.

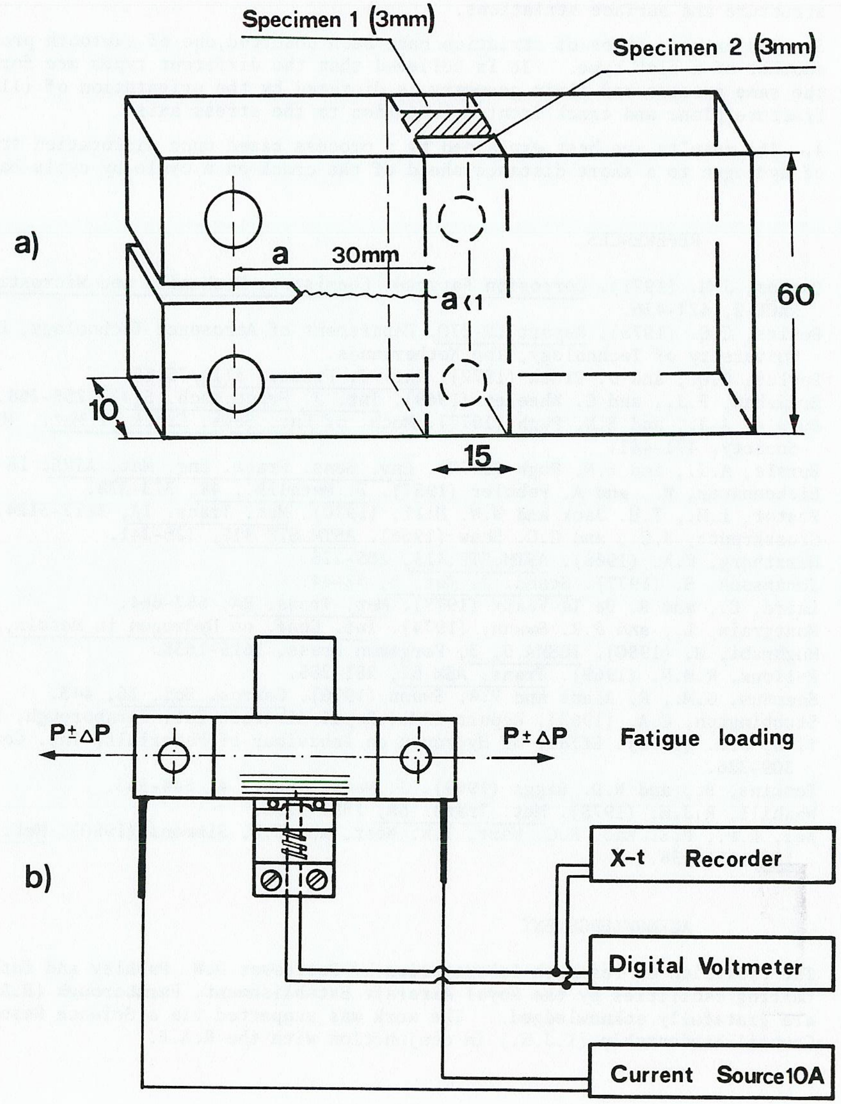

Fig. 1. Schematic representations of (a) machining of the short crack (SEN) specimens from a long crack (DCB) specimen and (b) the testing arrangement employed.

TABLE 1 Chemical Analysis (wt%)

	C	Si	Mn	Cr	Ni	Mo	V
Steel A	0.19	0.27	0.48	11.7	0.48	0.95	0.30
Steel B	0.11	0.19	0.67	12.3	2.55	1.83	0.41

TABLE 2 Mechanical Properties at Room Temperature

	0.2% Proof Strength (N/mm^2)	Ultimate Tensile Strength	Elongation to Fracture (%)	Reduction of Area (%)	Charpy impact energy (J)
Steel A	691	847	23	64	85
Steel B	886	993	20	61	102

The testing was performed at room temperature with sinusoidal loading at a frequency of 250 Hz. Load ratios, R(= P_{min}/P_{max}) of 0.1 and 0.5 were used. In the first stage of the investigation the growth rates of fatigue cracks were determined in 10 mm thick DCB specimens machined from bar with the propagation direction parallel to the major rolling direction. The use of small step reductions of load (≤ 5%) and continuous crack length monitoring using the DC electrical potential method (Scarlin, 1975) allowed crack growth rates to be measured accurately down to very low values in the region of ΔK_o.

After attaining satisfactory data at sufficiently low growth rates SEN specimens containing the crack tip (approx. 0.5 mm) were machined as shown in Fig. 1. These specimens have a reduced specimen thickness of 3 mm which is still sufficient to maintain plane strain conditions at the stress intensity levels employed.

The extension of the short crack was also monitored by the DC electrical potential technique whereby the current was transmitted to the specimen through welded wires and the increase in microvolt signal accompanying crack growth was registered using thin wires spring-loaded against the specimen on either side of the crack (see Fig.1b). In the measurement range employed (0.5 to 1.5 mm crack length) a signal increase of approx. 400 µV was obtained. When allowance is made for known sources of error such as variations in room temperature this provides an accuracy in determination of crack length of approx. 0.01 mm, so that a considerable number of measurements could be made in the short crack range for each specimen.

Measurements were made by loading the short crack at ΔK values close to or slightly above the previously measured ΔK_o. Plotting of the crack length on an X-t recorder permitted transients after increasing or decreasing the loading to be recognised

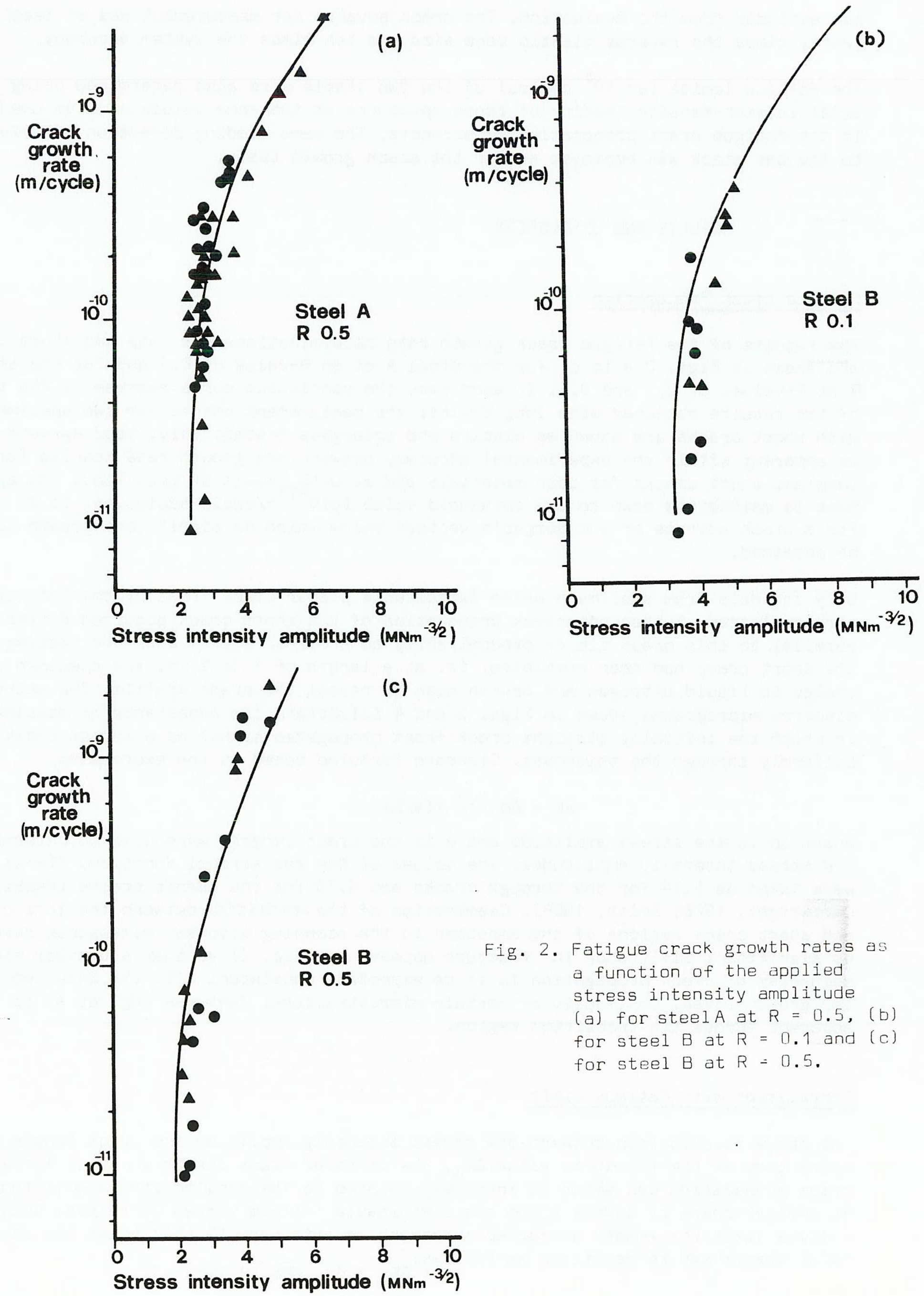

Fig. 2. Fatigue crack growth rates as a function of the applied stress intensity amplitude (a) for steel A at R = 0.5, (b) for steel B at R = 0.1 and (c) for steel B at R = 0.5.

and excluded from the evaluation. The crack advance per measurement was at least twenty times the reverse plastic zone size and ten times the system accuracy.

The fatigue limits (at 10^8 cycles) of the two steels were also determined using axial tension-tension loading of round specimens at the same values of R as used in the fatigue crack propagation experiments. The same loading direction relative to the bar stock was employed as for the crack growth tests.

RESULTS AND DISCUSSION

Fatigue crack Propagation

The results of the fatigue crack growth rate determinations for long and short cracks are shown in Figs. 2 a to c. for the steel A at an R-value of 0.5 and for the steel B at R-values of 0.1 and 0.5. In each case the continuous curve represents the trend of the results obtained with long cracks; the measurement points for two specimens with short cracks are shown as circles and triangles respectively. Good agreement is apparent within the experimental accuracy between the growth rate results for long and short cracks for both materials and at both levels of mean load. The agreement is maintained down to the threshold value ($\sim 10^{-11}$ m/cycle-equivalent to 20 cycles for a crack advance of one Burger's vector) below which no significant growth could be obtained.

Only the data from specimens which exhibited a planar crack front of the long crack were evaluated. Subsequent crack propagation of the short crack occurred either parallel to this crack tip or predominantly as a corner crack. When the testing of the short crack had been completed, ie. at a length of 1 to 2 mm, the specimen was cooled in liquid nitrogen and broken open to reveal the crack profile. The scanning electron micrographs shown in Figs. 3 and 4 illustrate the appearance of specimens in which the initially straight crack front propagated either as a corner crack or uniformly through the thickness. Standard formulae based on the expression

$$\Delta K = \Delta\sigma \sqrt{\pi a}\ f(a/W)$$

where $\Delta\sigma$ is the stress amplitude and a is the crack length, were used to determine the stress intensity amplitudes. The values of the geometrical function, f(a/w), were taken as 1.14 for the through cracks and 0.75 for the corner cracks (Rooke and Cartwright, 1976; Smith, 1966). Examination of the transition between the long crack and short crack regions of the specimen in the scanning electron microscope revealed no significant difference in fracture appearance (Fig. 5) so that a similar micromechanism of crack propagation is to be expected, consistent with the observed similar growth rates. Continuity of certain microstructural features (eg. at A) is apparent across the transition region.

Correlation with Fatigue Limit

The above relationship between the stress intensity amplitude and crack length indicates that at the threshold value, ΔK_o, the critical crack length at which fatigue crack propagation can occur is inversely related to the applied stress amplitude. At smaller crack or defect sizes the sustainable fatigue stress increases, until the fatigue limit for smooth uncracked specimens is attained. At this point the above relationship may be rewritten as follows:

$$\Delta K_o = \Delta\sigma_o \sqrt{\pi a_c}\ f\ (a/W).$$

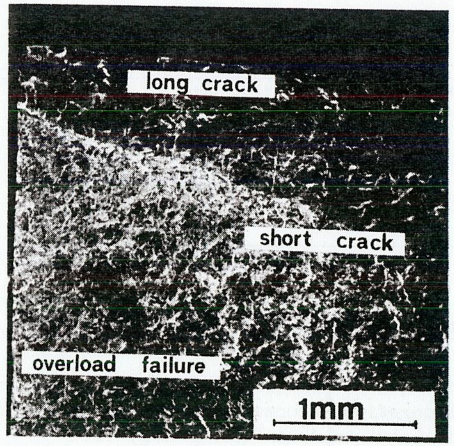

Fig. 3. Scanning electron micrograph showing propagation of a short crack as a corner crack.

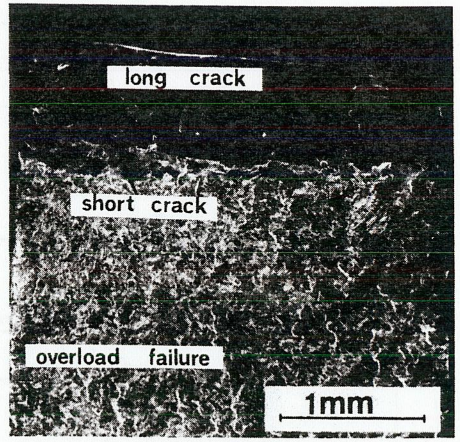

Fig. 4. Scanning electron micrograph showing uniform propagation of a short crack.

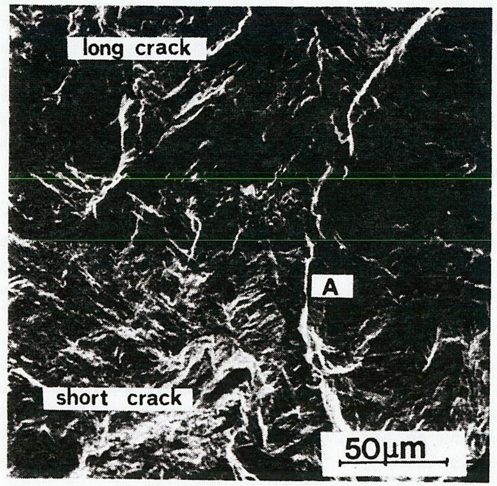

Fig. 5. Scanning electron micrograph of the transition region between the long crack and the short crack.

where $\Delta\sigma_D$ is the fatigue limit determined for the same value of R, thereby permitting the evaluation of a_c, the radius of the characteristic defect present in the nominally crack-free cylindrical fatigue specimen. The growth of defects or cracks of larger size than a_c may be predicted using fracture mechanics principles whereas features below this size will only nucleate cracks if loading is carried out above the fatigue limit.

The results for steel A are shown in Fig. 6a. In this case the geometrical function f(a/w) for semicircular surface cracks has been used to determine the critical defects sizes at various load levels along the ΔK_o line. The regions in which ΔK_o measurements with long cracks and short cracks were obtained are indicated. Extrapolation to the measured fatigue limit of 410N/mm^2 shows that a semicircular surface flaw of depth ~ 20 µm will propagate at this loading amplitude and lead to failure of the specimen. Metallographic sections transverse to the loading direction show that approximately spherical manganese sulphide inclusions of radius upto 25 µm are present throughout the material (identified using crystal-dispersive X-ray analysis in the scanning electron microscope).

A similar examination of the steel B shows that in this case the inclusions are considerably elongated parallel to the rolling direction (normal to the direction of fatigue loading) with sizes upto ~ 80 µm in length and 5 µm in thickness. The relationship between the applied stress amplitude and the critical crack depth above which fatigue crack propagation occurs is shown for steel B in Fig. 6b. In this case the relationship has been determined for elongated elliptical surface cracks with the same length to depth ratio (16:1) as is observed for the inclusions. Extrapolation to the measured fatigue limit shows that an elliptical flaw of depth 4.8 or 3.5 µm will propagate to cause fatigue failure at load ratios R of 0.1 and 0.5 respectively. These values are also in good agreement with the measured inclusion size. Moreover examination in the scanning electron microscope of cylindrical fatigue specimens which had failed just above the fatigue limit shows that the crack is initiated at elongated inclusions which are longitudinally intersected by the specimen surface.

For the materials investigated in the present work it appears that long and short cracks propagate at the same rates and that the propagation of cracks from their initiation sites at inclusions can be predicted using linear elastic fracture mechanics. The much higher propagation rates reported for short cracks in aluminium alloys (Pearson, 1975) and a 3.5% Ni steel (Chauhan and Roberts, 1979) may be attributed to the use of an inappropriate formula for the calculation of ΔK. Similarly the use of a spot weld as a crack starter (Kitagawa and Takahashi, 1976) in a high-strength ferritic steel may have influenced the observed higher growth rates which were only observed in the first 0.2 mm of growth. The observed slower propagation of short cracks (Lankford, Cook and Sheldon, 1980) in a nickel alloy which was attributed to the difficulty in propagating the short crack front length into the adjoining grain was not observed in the present work where the crack front lengths of the short and long cracks were both very much larger than the grain size so that no increased obstruction of the crack is to be expected for the tests with short cracks.

Lankford (1980) has shown recently that the size of defect which can propagate, when loading at the fatigue limit, is strongly influenced by the yield strength of the steel. A high strength steel (Lankford, 1977) shows a value similar to those determined in the present work (similar to the inclusion size) whereas for a mild steel (Nakai and Tanaka, 1980) only a defect of ≥ 1 mm in size can propagate on loading below the fatigue limit. Cracks below this critical size can not impair the fatigue strength of this mild steel so that crack nucleation sites of a similar size must be developed during fatigue testing of smooth specimens. It is not stated whether

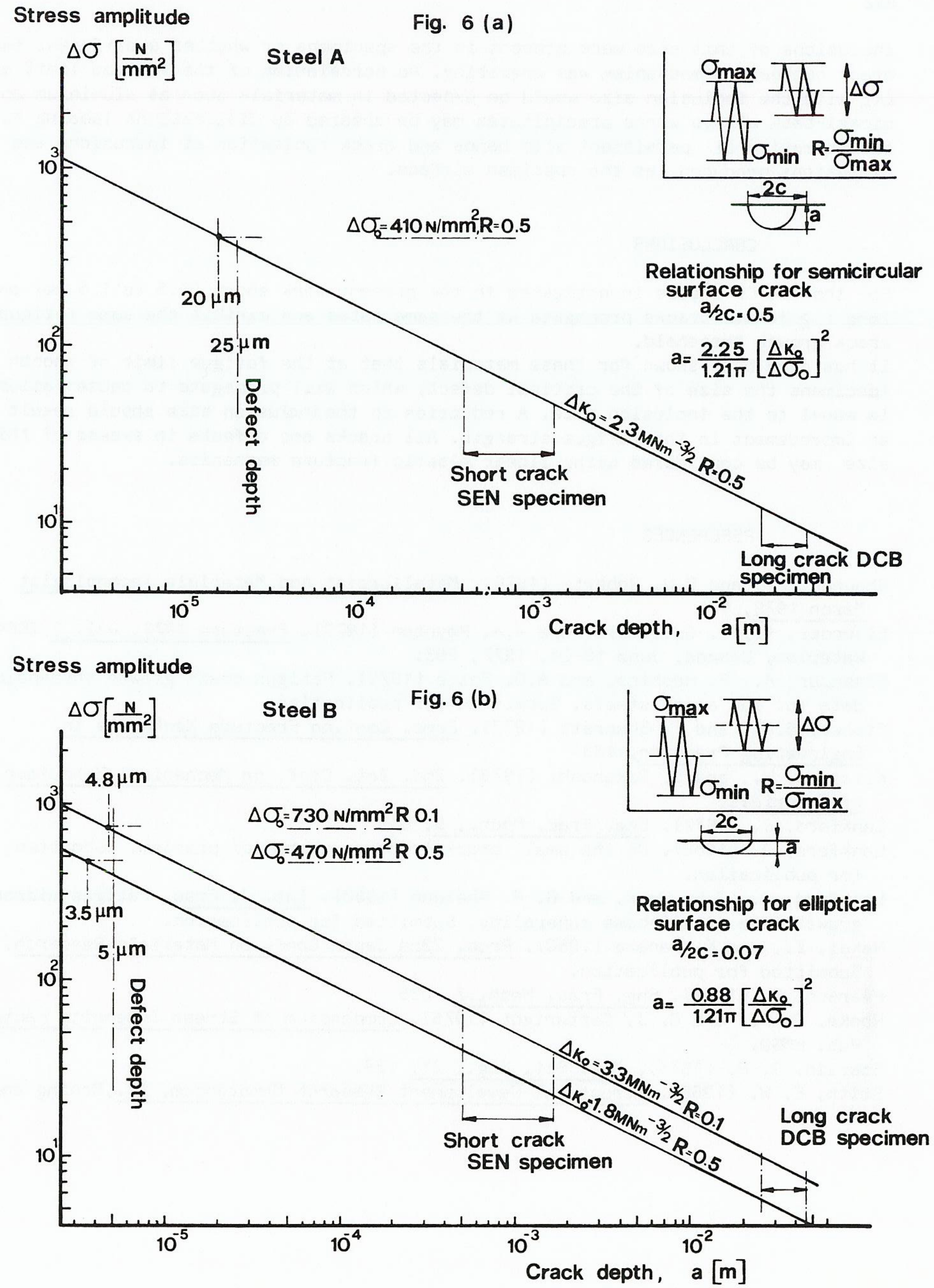

Fig. 6. The relationship between the applied stress amplitude and the crack depth (a) for steel A and (b) for steel B

inclusions of this size were present in the specimens or whether a different fatigue crack nucleation mechanism was operating. No correlation of the fatigue limit and ΔK_0 with the inclusion size would be expected in materials such as aluminium and nickel-base alloys where precipitates may be sheared by dislocations leading to the formation of persistent slip bands and crack nucleation at intrusions and extrusions produced at the specimen surface.

CONCLUSIONS

For the 12% Cr steels investigated in the present work short (0.5 to 1.5 mm) and long ($\gtrsim$ 30 mm) cracks propagate at the same rates and exhibit the same fatigue crack growth threshold.

It has also been shown for these materials that at the fatigue limit of smooth specimens the size of the critical defect, which will propagate to cause failure, is equal to the inclusion size. A reduction in the inclusion size should result in an improvement in the fatigue strength. All cracks and defects in excess of this size may be considered using linear elastic fracture mechanics.

REFERENCES

Chauhan, P., and B.W. Roberts (1979). Metallurgist and Materials Technologist March 1979, 131

Elsender, A., R. Gallimore, and W.A. Poynton (1977). Fracture 1977, vol. 2,ICF4, Waterloo, Canada, June 19-24, 1977, 953.

Elsender, A., P. Hopkins, and A.D. Batte (1979). Fatigue crack growth threshold data for low alloy steels. Submitted for publication.

Fisher, B.C., and F. Sherratt (1977). Proc. Conf.on Fracture Mechanics in Engineering Practice, 183

Kitagawa, H., and S. Takahashi (1976). 2nd. Int. Conf. on Mechanical Behaviour of Materials.

Lankford, J. (1977). Eng. Frac. Mech., 9, 617

Lankford, J. (1980). On the small crack fracture mechanics problem. Submitted for publication.

Lankford, J., T.S. Cook, and G. P. Sheldon (1980). Int. J. Frac. Fatigue microcrack growth in a nickel-base superalloy. Submitted for publication.

Nakai, Z., and K. Tanaka (1980). Proc. 23rd Japan Conf. on Materials Research. Submitted for publication.

Pearson, S. (1975). Eng. Frac. Mech..7, 235

Rooke, D. P., and D. J. Cartwright (1976). Compendium of Stress Intensity Factors. Pub. HMSO.

Scarlin, R. B. (1975). Mat. Sci. Eng., 21, 139.

Smith, E. W. (1966). Structural Development Research Memorandum, 17.,Boeing and Co.