ROLE OF MICROSTRUCTURE ON SHORT CRACK PROPAGATION AND ITS THRESHOLD

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ABSTRACT
The role of microstructure on short crack propagation in 0.003, 0.25 and 0.47% carbon steels has been studied. The influence of microstructure on the maximum threshold values of short cracks (ΔK_{mthsc}) has been examined with emphasis. The estimated critical crack lengths at ΔK_{mthsc} are found to be dependent, while the magnitude of ΔK_{mthsc} are found to be independent on the nature of short cracks. The magnitude of $\mathbf{\Delta K_{mthsc}}$ is found comparable to the fatigue threshold (ΔK_{th}) for long cracks. The interaction of short cracks with microstructure indicates that the former ones have an affinity to grow through ferrite-pearlite or ferrite-ferrite interfaces. The maximum short crack threshold values appear to increase with pearlite content of the ferrite-pearlite steels.

1 INTRODUCTION

That the initiation and propagation behaviour of small cracks may occupy a significant fraction of the fatigue life (Suresh [1], Zhixue [2]) of a material has led to an upsurge of interest to understand their behaviour in recent years. It is well recognized by now that under the same crack driving force, short crack growth rates usually exceed those of long cracks, and the short cracks grow at stress intensities below the long crack threshold. The main reasons for the anomalous behaviour of short cracks and their growth characteristics are compiled in a recent report (Ray [3]). The growth of these cracks below ΔK_{th} perturbs the basis of safe life design philosophy whereas the fatigue life time spent during the short crack growth regime may be dominating at times to bring in large deviations in the estimated results of fatigue life for fail safe design. The short cracks also exhibit single/multiple threshold values (ΔK_{thsc}) and the magnitude of ΔK_{thsc} is dependent on the length of short cracks unlike that for long cracks. For multiple short crack thresholds, the highest magnitude is termed here as ‘near long-crack fatigue threshold’ (NLFTH), and acquiring knowledge about this parameter is the primary focus of this report.

Several earlier investigations on short crack behaviour of steels (Taylor [4], Tokaji [5], Kaynak [6], Goto [7]) have focused on various facets of short crack problem except attempting to explore the possibility of determining the “near long-crack fatigue threshold” (NLFTH) through short crack studies. The primary purpose of this study is to generate small crack growth rate data in 0.003%, 0.25% and 0.47%C steels, in order to estimate the NLFTH and to the examining the role of microstructure on the characteristics of this parameter.

2 EXPERIMENTAL PROCEDURE

The materials used in this investigation are 0.003%, 0.25% and 0.47% carbon steels, referred henceforth as S00, S25 and S47 steels respectively, where the numeric in the codes indicate the carbon content of the steels. The composition of the steels is shown in Table 1. The S00 steel exhibits ferritic microstructure unlike a mixture of ferrite and pearlite by the S25 and S47 steels. The volume fraction of pearlite in S25 and S47 was found to be 27% and 63.0% respectively by areal analysis. The average ferrite grain size of S00 steel, determined by linear intercept method was found to be 64.4±1.3 μm. Tensile tests were carried out on cylindrical specimens of 6mm diameter and 25mm gauge length following ASTM standard E-8. The hardness of the material was determined by Vickers hardness test. The mechanical properties of the steels are summarized in Table 2.

Table 1. Chemical composition of the steels

Elements	**Composition (wt %)**		
	S00*	**S25**	**S47#**
C	0.003	0.25	0.47
Mn	0.13	0.73	0.77
Si	0.009	0.19	0.22
P	0.012	0.043	0.014
S	0.009	0.027	0.016

*0.052-Ti,0.001-Nb in S00; and #0.013-Cr in S47 steel.

Table 2. Mechanical properties of the steels

Steel	**YS (MPa)**	**UTS (MPa)**	**Elong. (%)**	**Hardness**
S00	93	238	45	94*
S25	333	543	33	157
S47	327	621	28	199

*Vickers hardness at 25 gmf, others are at 10 kgf.

Schematic configuration of a fatigue specimen is shown in Fig.1. The fatigue tests were performed on a 560N.m.s^{-1}(0.75hp) rotating bending machine operating at a frequency of 50Hz, details of which are reported elsewhere (Ray [3]). The initial imposed loads for crack initiation and the reduced loads at which the crack growth studies were conducted were different for the three steels. During the stage of crack growth, the tests were interrupted at each 15000 cycles or multiples of it, for recording the crack paths by an optical microscope and subsequently measuring their lengths using an image analyzer. After the fatigue test, the surface of each specimen was etched using 2%Nital and the entire traverse of the crack path together with its associated microstructure was recorded in several frames by using both optical and scanning electron microscopy.

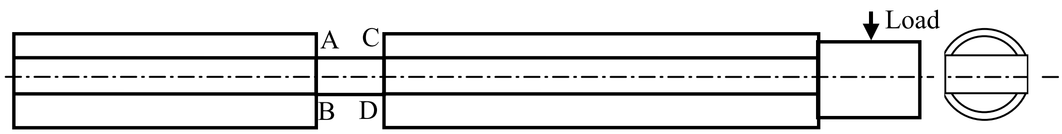

Fig.1 Configuration of the specimens used for short crack growth testing.

3 RESULTS AND DISCUSSION

3.1 Crack initiation

Crack initiation studies have been carried out on specimen configuration shown in Fig.1. The maximum (positive) and the minimum (negative) principal stress in bending occur at the points A or B (Fig.1) depending on their position at the top or the bottom surface of the specimen during its rotation. The fatigue cycling was interrupted at intervals of 10-15 kilocycles for locating possible initiation of cracks.

The first detected crack lengths in different specimens were found to vary between 75 and 974μm; but specimens having initial crack lengths < 650μm were only selected for short crack growth studies. The observed wide variation in the initial crack lengths could be due to (i) higher time interval between inspecting the specimen, (ii) uncertain non-uniformity in the machined micro-notch (iii) microstructural anomaly (e.g. abnormal ferrite-pearlite distribution) at the immediate vicinity of the micro-notch or (iv) combinations of the earlier mentioned facts.

The geometry of the micro-notch that led to the first observed crack in a specimen was recorded and its dimensions were measured to estimate the stress intensity factor (K_{ini}) for crack initiation. The micro-notches were considered as semi elliptical edge flaws, and K_{ini} was calculated as (Tada [8]):

$$K_{ini} = 1.12(3\sigma)\sqrt{\pi a/Q}\sqrt{\sec \pi a/2b} \qquad \ldots(1)$$

where; a= depth of elliptical flaw, c= half width of elliptical flaw, b= plate thickness=5mm, 1.12= surface flaw correction at A, 3 = stress concentration effect at A, Q=elliptical flaw correction = f (a/2c) obtained from standard graphs (Hertzberg [9]), $\sqrt{\sec(\pi a/2b)}$= finite width correction accounting for relatively large a/b ratio.

3.2 Variation of crack length with number of cycles

The crack growth studies were carried out by monitoring crack lengths at increasing number of cycles by interrupting the fatigue tests at pre-selected time intervals. The crack paths at interruption were recorded using an image analyzer and their lengths were measured. Typical obtained *a vs. N* data for the three investigated steels are shown in Fig.2. Commonly the shape of *a vs. N* curve is one of constant rising slope for long cracks. But the plots in Fig.2 exhibit some plateau regions, which are typical characteristic features of short crack growth behaviour. Such plateau regions have been observed in a few earlier investigations for medium carbon steel, high strength steel, austenitic stainless steel, ferrite-bainite steel and titanium alloys as reported by Ray et. al. (Ray [3]). The phenomenon of crack arrest at the plateau is usually attributed (Ray [3], Ravichandran [10]) to occur at microstructural barriers like grain boundaries.

The crack lengths at which their arrests occurred were found to vary in different specimens. The 'maximum' crack lengths, at which the event of crack arrest could be detected in various specimens were found to be in the range of 411 to 837, 1160 to 1180 and 679 to 898 μm for S25, S00 and S47 steels respectively. These crack lengths can be considered to represent the transition point between the short and the long cracks in a material. The existence of a plateau region and its considerable extent indicates either crack arrest phenomenon for short cracks at barriers or the emergence of fatigue threshold for a short or long crack. Short extents of the plateau usually imply crack arrest at barriers whereas long extents are indicative of short or near long crack fatigue threshold. Since the duration of crack arrest is significant for the observed plateaus, these may be considered to represent the threshold conditions. The wide variations in the 'maximum crack length' at which crack arrest occurred in different specimens can be attributed to the nature of the investigated cracks, and this aspect is an inherent characteristic of short crack growth behaviour. The occurrence of crack arrest at different lengths can originate from different possibilities like local microstructural environment, extent of crack deflection, plasticity associated with crack tip, crack closure and local residual stresses (Ray [3], Ravichandran [10]).

3.3 Variation of crack growth rate with the crack length

The crack growth rate (*da/dN*) was calculated by measuring the increment in crack length (d*a*) in a specific interval and dividing it by the connecting number of fatigue cycles (dN). These data were next examined by plotting da/dN (in log scale) *vs. a*. At each plateau (Fig.2), the magnitude of da/dN tends to zero and is not measurable; so in order to incorporate these points in the plots, da/dN is arbitrarily kept at a very low value equal to 10^{-8} μm/cycle. All crack length measurements were done in the primary direction of crack growth i.e. normal to the edge of the specimen containing the micro-notch. It may be noted here that the resolution for measuring the length of a crack by the image analyzer is 0.5 μm.

A compilation of the plots of d*a*/dN *vs.* *a* for different specimens is presented in Fig.3. These plots, in general, indicate considerable fluctuations in crack growth rate; but the average growth rate exhibits a decreasing trend upto a certain crack length followed by an increasing trend with or without repetition of similar cycles for each specimen. The crack lengths at which large deviations in growth rate occur (Fig.3) correspond to microstructural barriers like grain boundary or ferrite pearlite interface. One or more minima can be observed in the d*a*/dN *vs.* *a* plots. The maximum crack length at which a minimum in d*a*/dN is noted in Fig.3 is termed here as the critical or the transition crack length. Beyond the transition length, the fluctuations in crack growth rate decrease and d*a*/dN gradually increases with *a* exhibiting lower magnitudes of scatter.

3.4. Crack growth rate *vs.* stress intensity factor range

The stress intensity factor ahead of a crack tip depends on the geometry of the crack-specimen configuration and the nature of the loading. The examination of a few fracture surfaces after short crack growth studies indicated that there is considerable amount of crack depth and cracks may be treated as quarter elliptical corner cracks. For convenience of ΔK-calculations, it was assumed that the nature of the cracks to be quarter penny edge cracks. The stress intensity factor for this type of crack is given as (Tada [8]):

$$\Delta K = (1.12)^2 (2/\pi) \sigma \sqrt{\pi a} \qquad \ldots(2)$$

where $(1.12)^2$ represents two surface flaw corrections and $2/\pi$ represents the correction for a quarter penny edge crack. The stress (σ) ahead of a crack under bend load (P) is given as,

$$\sigma = (6P \times L)/WB^2 \qquad \ldots(3)$$

where L is the distance between the point of application of load and the location of crack in the specimen, and W and B are the dimensions of the reduced section of the specimen (Fig.1). Using equation (3), one finds that the magnitude of stress linearly varies from point C to A in Fig.1.

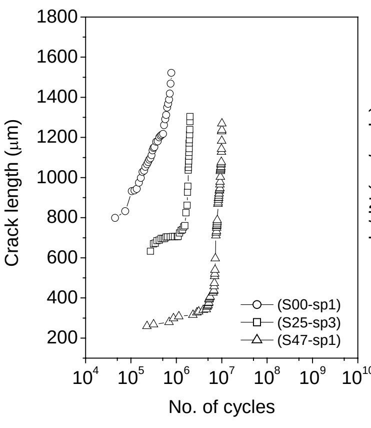

Fig.2 variation of crack length with number of cycles in different materials.

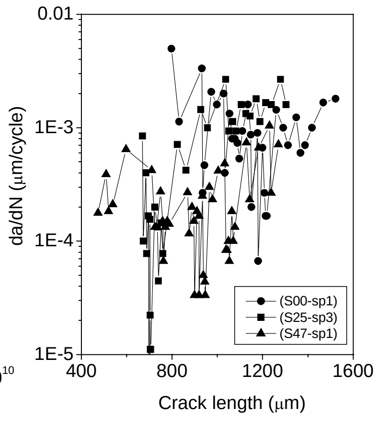

Fig.3 Variation of crack growth rate with crack length in the investigated specimens.

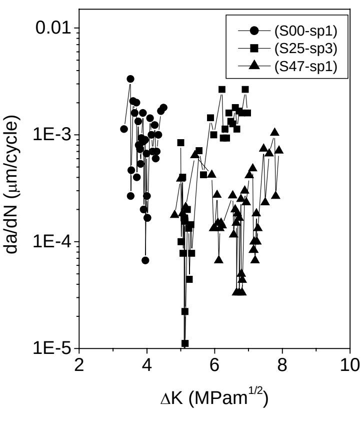

Fig.4 crack growth rate against stress intensity factor range for different specimens.

The recorded data of da/dN *vs.* a were converted to da/dN *vs.* ΔK using the afore-mentioned procedure for estimating ΔK; ΔK was taken as K_{max} following ASTM standard E647. The plots of da/dN *vs.* ΔK for a few tested specimens are shown in Fig.4. The nature of these plots is similar to those of da/dN *vs.* a. The plots of da/dN *vs.* ΔK for different specimens reveal several minimum values which correspond to the plateau regions in Fig.2. The magnitude of ΔK corresponding to the maximum crack length for a specimen at which a plateau in a *vs.* N plot is observed, is considered the transition between the short to long crack. These values are referred here as ΔK_{nlfth} for the material, which take into account the implicit assumption that there is negligible difference between ΔK_{th}, estimated by standard long crack growth studies and that at the transition between a short and its long crack form. Some of the earlier studies like that of Kaynak et al. (Kaynak [6]) indicate that there exists some difference between fatigue threshold values determined by short and long crack growth studies. But the maximum value of fatigue threshold determined by short crack growth is usually lower than that obtained by long crack growth experiments. Hence the obtained values of $\Delta K_{nlfth}/\Delta K_{th}$ for the investigated steels can be considered as conservative estimates. The average threshold value of S00 steel can be expressed as 4.2±0.3MPam$^{1/2}$ and that of S25 and S47 steels can be expressed as 5.1 ± 1.0 and 6.9±0.3 MPam$^{1/2}$ respectively. The transition crack length and the short crack fatigue threshold have been discussed elaborately in a recent communication (Ray [3]).

3.5. Effect of pearlite on threshold

Typical microstructural feature that are associated with the transition of short to long crack in S25steel is shown in Fig.5. The crack in Fig.5 is observed to take deflection almost of the order of 90^o along the ferrite-pearlite interface prior to passing through the pearlite colony. The combined phenomena of large crack deflection and its passage through ferrite-pearlite interface prior to its further movement through pearlite colony can be ascribed as the reason for crack arrest.

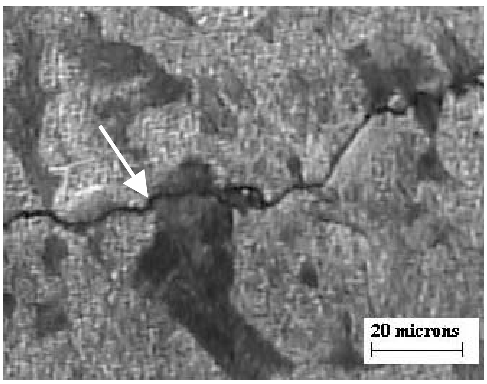

Fig.5 Transition points of short to long crack in specimen 1 of S25 steel (Ray [3]).

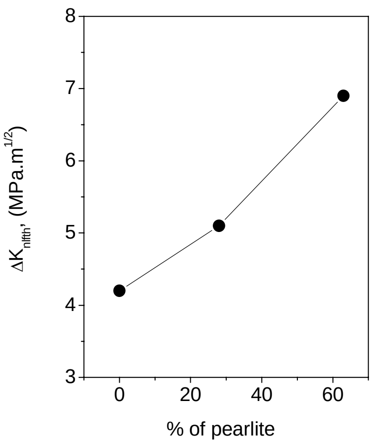

Fig.6 variation of short crack fatigue threshold .with change in pearlite percentage

It is noted that the ΔK_{nlfth} value for the investigated steels increases with increase in carbon content or amount pearlite or strength of the steels. Taylor (Taylor [4]] has reported that fatigue threshold of large cracks exhibit an increasing trend with increase in strength level of the steels. The estimated magnitudes of ΔK_{nlfth} for the three steels are thus found to show a trend of variation similar to that for long crack threshold and strength as reported by Taylor. Figure 6 shows the variation of short crack fatigue threshold with change in pearlite percentage of the investigated steels. The results in Fig.6 indicate that fatigue threshold increases with increasing pearlite percentage or carbon content in ferrite-pearlite steels.

4 CONCLUSIONS

The following major conclusions can be drawn from the investigation:

♦ The applied stress to initiate a short crack varies with the nature of the material but the number cycles to initiate a short crack is of the order of 10^5 for the investigated steels.

♦ The defined transition crack lengths are dependent on the nature of the investigated short crack and the microstructure of the materials.

♦ The magnitudes of NLFTH for S00, S25 and S47 steels were found to be 4.2±0.3, 5.1 ± 1.0 and 6.9±0.3 $MPam^{1/2}$ respectively.

♦ The NLFTH obtained from short crack growth studies at R = -1 for plain carbon steels increases with increasing carbon content or with increasing pearlite content.

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