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In-situ Observation of Fatigue Crack Growth Behavior of Microstructure Controlled Steel

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Abstract:

In the present study, fatigue crack growth (FCG) tests of structural pearlite-ferrite steels with two different ferrite grain sizes of 10μm and 50μm were performed. The results showed that the steel with coarse grained structure with large spacing and size of pearlite particle had a higher threshold value and better FCG resistance in both threshold and Paris regions. To understand clearly the effect of microstructure on FCG behavior, ΔK -constant FCG tests were performed (in Paris region) under a scanning electron microscope (SEM) equipped with a servo-hydraulic testing machine. From the crack path observations it was found that in the steel with coarse grained structure the crack path was more tortuous compared to the fine grained structure. These tortuous crack paths were more pronounced interlocking elements on the crack wake and then increased crack growth resistance.

Keywords: In-situ SEM observations, fatigue crack growth, grain size, interlocking

1. Introduction

It is well known that failure problems of structures and machines reported are mainly caused by fatigue. The improvement of fatigue strength and fatigue crack growth resistance of structural materials is strongly required for development of safety design and fabrication processes. Low carbon structural steels are used of structural applications, due to good weldability and toughness. In structural steel plates which produced by thermo-mechanical control processing, the microstructures obtained are highly refined as compared to those of conventional processed steels, resulting in a significant improvement in strength and toughness.

It is well known that fatigue crack growth near-threshold region is largely influenced by micro-structural factors, whereas in Paris region the microstructures have a less influence on fatigue crack growth behavior. These regions have received the most attentions since they dominate the crack propagation life. The effect of microstructure in low carbon steel has been reported in some reports [1-4,9]. However,

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only limited information is available on detailed influence of microstructure on fatigue crack growth resistance in Paris region [5,10].

The presence of hard phase was found to influence fatigue crack behavior in steel, which was known mainly in duplex steel with hard phase and ferrite matrix as soft phase. The effect of hard second phase for example, martensite was illustrated to contribute the superior fatigue strength and higher threshold value. It was reported that the presence of the second phase plays an important role to retard and deflect the crack path [6-8].

In the present study, the effect of grain size on fatigue crack growth behavior in micro structurally controlled structural steel plate with pearlite particle was investigated. To understand clearly the effect of microstructure on FCG behavior, ΔK - constant FCG test was performed inside scanning electron microscope (SEM) chamber equipped with a servo- hydraulic testing machine. During FCG test to understand the closure effect on FCG behavior crack closure were monitored. Crack path was also monitored during the test, for observing the crack tip stress shielding phenomenon, such as interlocking and crack branching.

2. Experimental Procedures and Materials

2.1 Materials

The materials used in this study were micro structurally controlled low carbon steels with pearlite particles of two different grain sizes. The chemical composition of the steel (in wt. %) used in the present study is C 0.2, Si 0.32, Mn 1.08, P 0.003 and S 0.00. The microstructures of the steels used in this study are shown in figure 1. The mechanical properties of steels is shown in table 2.

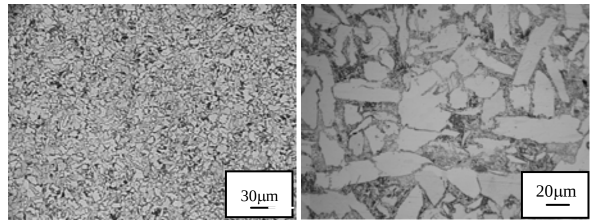

Figure 1. Microstructure (a) fine grained (FG) steel, (b) coarse grained (CG) steel

Table 2. Tensile properties and microstructural characteristics of the steels

Properties	Measured values	
	CG Steel	FG Steel
Ferrite grain size (μm)	50	10
Diameter of pearlite particle (μm)	73	12
0.2% Yield Strength (MPa)	236	310
Ultimate Tensile Strength (MPa)	475	492
Elongation (%)	38	38

2.2 Fatigue crack growth tests

ΔK decreasing / increasing fatigue crack growth tests of compact tension (CT) specimen in accordance with the ASTM Standards E 647 were performed, to obtain the threshold stress intensity factor range, ΔK_{th} and fatigue crack growth curve. The ΔK_{th} was determined as the ΔK at which no crack was observed for 10^6 cycles.

To understand clearly the effect of microstructure on FCG behavior in Paris region, ΔK -constant FCG test were performed using a single edge cracked tension (SENT) specimen inside the SEM equipped with a servo hydraulic testing machine with a sinusoidal load of frequency 20 Hz and load ratio R=0.1.The specimen geometry is shown figure 2. Prior to fatigue crack growth test, the specimen surface were polished and microstructure on the specimen surface were revealed by applying 3% nital for in-situ SEM observation of crack path.

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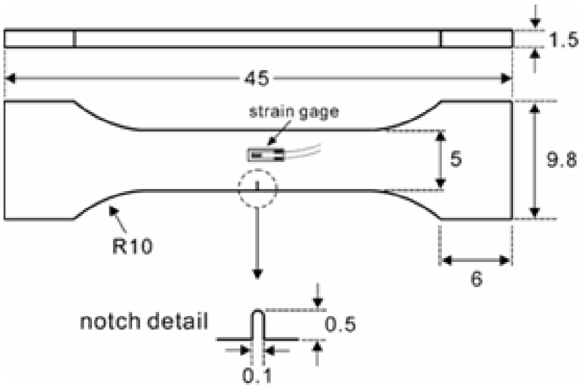

Figure 2. Specimen geometry for FCG test (unit in mm)

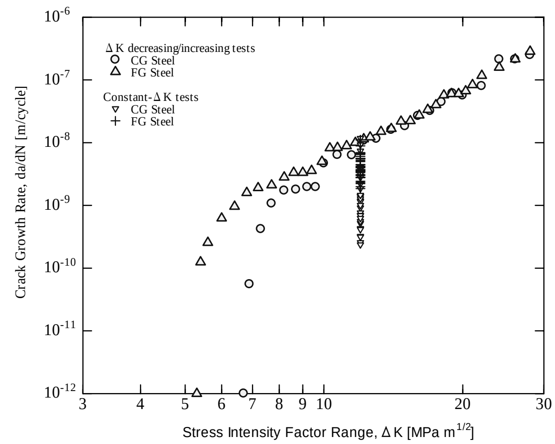

Figure 3. Relationship between da/dN and ΔK

Crack closure was monitored by using the unloading elastic compliance method with a resistance strain gauge attached in-front of the crack tip (Figure 2). Stress intensity factor range, ΔK, for SECT specimen was calculated according to the following equation[10]:

$$K_I = \sigma\sqrt{\pi a}\cdot F_I(\alpha), \quad \alpha = \frac{a}{W} \qquad (1)$$

where, F_I is a geometrical correction factor, which is defined as

$$F_I(\alpha) = 1.12 - 0.231\alpha + 10.55\alpha^2 - 21.72\alpha^3 + 30.39\alpha^4 \qquad (2)$$

4. Results and discussion

The fatigue crack growth curves for the steels investigated in this study are shown in figure 2. The threshold stress intensity factor range, ΔK_{th}, was higher in the steel with coarse grained (CG) structure (6.7 MPa$\sqrt{m}$) compared to that in the fine grained (FG) steel (5.3 MPa$\sqrt{m}$), similar influence of grain size on threshold stress intensity factor range has been reported [1,2,11].. From the figure, it can be found that, there is some difference in crack growth rate in the Paris region between two

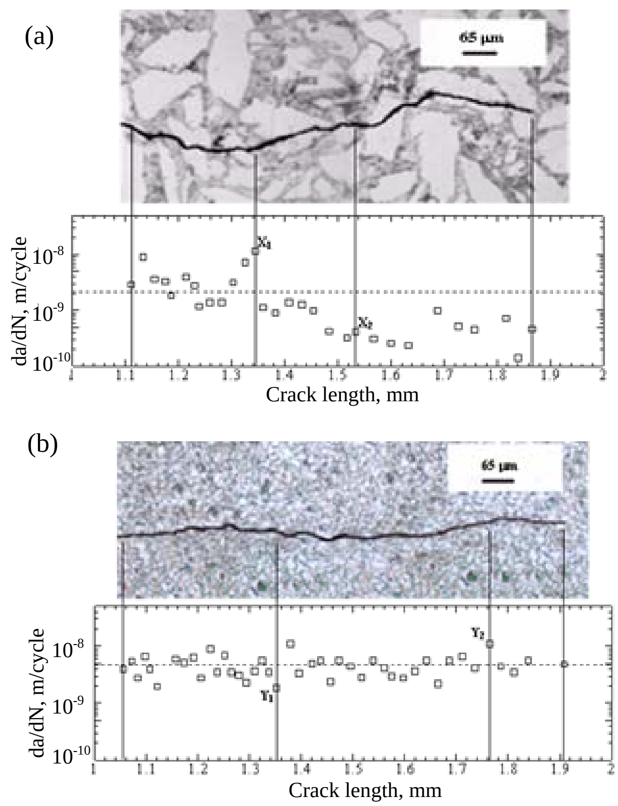

Figure 4. Relationship between crack lebgth and da/dN in constant-ΔK (a) CG steel (b) FG steel

microstructures. In the Paris region, fatigue crack growth resistance of the CG steel was higher compared to that of the FG steel. The results of ΔK - constant fatigue crack growth

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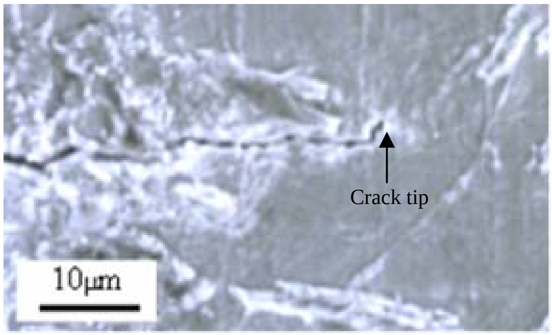
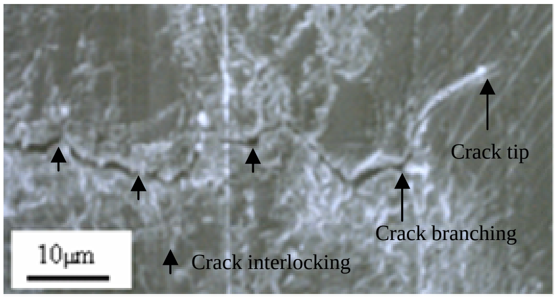
(figure 3) also showed that the steel with CG microstructure had a higher crack growth resistance.

Figures 4(a) and (b), show the crack growth rates and the crack paths under ΔK-constant tests, for the CG and FG steels, respectively. The average crack growth rates of the CG steel was 2.0 x 10^{-9} m/cycles, which was lower than that of the FG steel (4.7 x 10^{-9} m/cycle). It was found from the figure that, the crack path in the CG steel was more tortuous compared to the FG steel. It was also observed that the hard second phase (pearlite particle) disturb crack propagation, the degree of which may depend on the spacing and size grain of the hard phase. The high magnification of SEM micrographs of crack path are shown in figure 5. From the figure it was observed that when the crack tip approaches hard pearlite particle, the crack path tended to deflected. The angle of deflection was more significant in the coarse grained steel compared to the fine grained steel. Due to this, the crack path was more tortuous in the CG steel compared to the FG steel. Figures 5(a) and (b) show crack paths in the CG steel, corresponding to the points X_1 and X_2 in figure 4(a). At the point X_1 it was observed that crack growth rate was higher as the crack almost open completely (figure 5a). On the other hand, lower crack growth rate was observed at point X_2, where the crack interlocking occurs and also that crack tip was closed even at maximum load. The similar phenomenon was also observed in the FG steel as shown in figure 5(c) and (d), corresponding to the point Y_1 and Y_2 in figure 4(b), respectively.

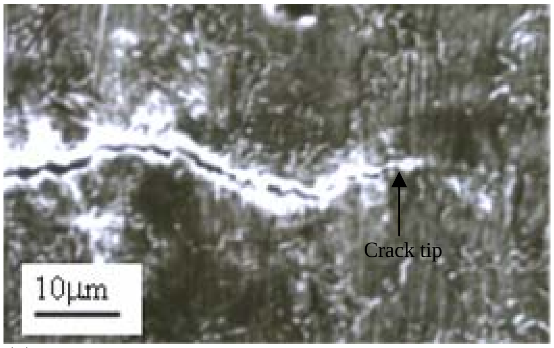
Relationships between effective stress intensity factor range, ΔK_{eff} and da/dN for the two steels are shown in figure 6. The threshold effective stress intensity factor ranges, $\Delta K_{eff,th}$ still indicated some difference between the two steels. The crack



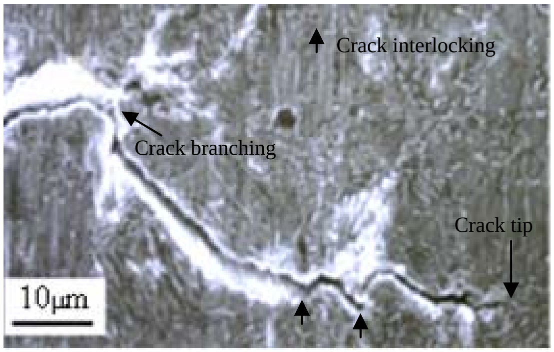
(a) Point X_1



(b) Point X_2



(c) Point Y_1



(d) Point Y_2

Figure 5. High magnification in-situ SEM observation (a), (b) CG steel and (c),(d) FG steel at the maximum load point

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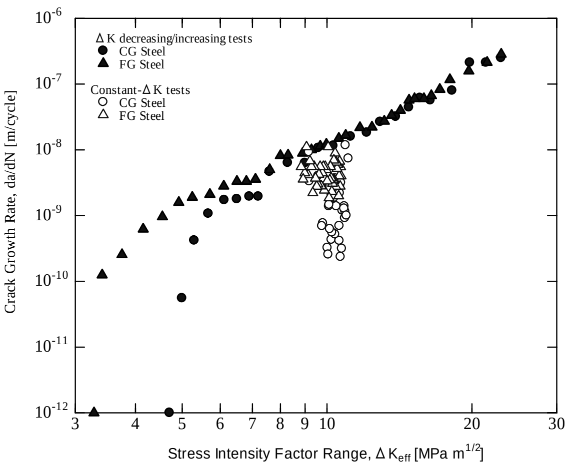

Figure 6. Relationship between da/dN and ΔK_{eff}

growth curves for both the steels in the higher ΔK_{eff} region also show some difference, which means another mechanism also played a role. As seen from figure 5, interlocking between crack surfaces and crack branching are possible mechanisms influencing crack growth resistance. These mechanisms contribute to crack tip stress shielding. Therefore, it is considered that higher fatigue crack growth resistance of CG microstructure will be due to significant crack closure phenomenon and crack tip stress sheiding.

4. Conclusions

The main conclusions are summarized as follows:

1. Microstructure have a significant effects on FCG behavior in both threshold and Paris region.
2. The crack path the FG steel was more straight compared to the CG steel.
3. The crack growth resistance of CG steel was higher compared to that of FG steel.
4. Crack closure behavior and crack tip stress shielding in the CG steel were more significant compared to those in FG steel.

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