234 Effect of Microstructure on Fatigue Crack Growth Behavior of Structural steel

O M. Jayaprakash^a, M. Sukri Mustapa^a, Y. Mutoh^{a*} and T. Sadasue

^aDepartment of Mechanical Engineering, Nagaoka University of Technology,
1603-1 Kamitomioka, Nagaoka, Niigata 940-2188, Japan

^bSteel Research Lab, JFE Steel Corporation, 1, Kawasaki-cho, Chuo-ku, Chiba, Japan

The fatigue crack growth tests were performed on low carbon structural steel with five different microstructures, i.e. steel with pearlite particle (15 and 50 μm grain size), with bainite particle (15 and 50 μm grain size) and with martensite particle. The results showed that microstructure influence fatigue crack growth behavior in both threshold region and Paris region and the presence of hard phase enhances fatigue crack growth resistance. The results were discussed based on the crack path observation and crack closure behavior

Key words: Structural steel, Fatigue crack growth, microstructure, second phase particle, Crack Closure

1. Introduction

Increasing applications of structural steels necessitate more precise characterization of its mechanical properties so that designer can better ensure fail safe behavior in service. The fatigue and fracture process of a component includes crack initiation and crack propagation. In the fatigue crack growth, it is well known that near-threshold region is largely influenced by micro-structural factors where as in Paris region the microstructures have less influence on fatigue crack growth behavior [1]. 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 [2]. However, only limited information is available on detailed influence of microstructure on fatigue crack growth resistance in Paris region.

In the present study, the effect of microstructure (effect of grain size and second phase particles) on fatigue crack growth behavior was investigated. Attention has been paid to the fatigue crack growth mechanisms both near threshold region and Paris region. Crack paths were observed and crack closure behavior during tests were also monitored to understand the effect of microstructure on fatigue crack growth behavior.

2. Experimental Procedures

In the present study low carbon structural steels with five different microstructures, i.e. steels with, (1). Fine grain (FG) pearlite particle (10 μm Grain size), (2). Coarse grain (CG) pearlite particle (50 μm Grain size), (3). Fine grain (FG) bainite particle (10 μm Grain size), (4). Coarse grain (CG) bainite particle (50 μm Grain size) and (5). martensite particle were investigated.

ΔK decreasing / increasing fatigue crack growth tests in accordance with the ASTM Standards E 647 were performed on MTS servo-hydraulic testing machine. Compact tension specimens with thickness of 12 mm and width of 50 mm were used. A sinusoidal load with frequency 20 Hz and load ratio $R=0.1$ was applied throughout the test. Crack closure was monitored by using unloading elastic compliance method with a resistance strain gauge attached in-front of the crack tip. Stress intensity factor, ΔK , for CT specimens were calculated according to the equation,

$$\Delta K = \frac{\Delta P}{B W^{1/2}} \cdot F(\alpha)$$

$$F(\alpha) = \frac{(2+\alpha)(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4)}{(1-\alpha)^{3/2}}$$

$\alpha = a/w$, a - crack length, W - width, B - thickness of the specimen. The crack paths (in the Paris region) were observed using optical microscope.

3. Results and Discussions

Fig. 1 shows the fatigue crack growth curves for the steels investigated in this study. Among the steels tested, the steel

with martensite particle shows higher threshold value and lower fatigue crack growth rates. The crack path for this steel is

Fig. 1 Relationship between da/dN and ΔK

shown in the Fig. 2. It was observed that when the crack tip approaches the hard martensite phase the crack path deflected and changed the direction. Due to this the crack path was more tortuous which would induce crack interlocking and so the crack growth rates were reduced. Next to the steel with martensite particle, the steel with CG pearlite particle exhibited higher threshold value and lower crack growth rates. From the Fig. 3 it was observed that the crack path for the steel with CG coarse grain pearlite particle was more tortuous compared to the steels with FG pearlite particle, FG bainite particle and CG bainite particle.

Next to the steel with martensite particle and the steel with CG pearlite particle, the steel with CG bainite particle showed higher threshold value and lower crack growth rates. From Fig. 5 (a) it was observed that the crack path of steel with CG bainite particle steel is more tortuous than FG bainite steel and FG pearlite steel. Next to the steel with coarse grained

Fig. 2 Crack path in martensite steel

bainite particle, the steel with FG fine grained bainite showed higher threshold value and lower crack growth rates (crack path shown in Fig. 6). From the Fig.5 (b), it was observed that in the steel with bainite particle when the crack tip approaches the hard bainite phase the crack stopped for a while and then

propagates through the hard bainite phase. This behavior was not observed in the steel with pearlite particle. In the steel with FG pearlite particle it was observed that the crack path was more straight (shown in Fig. 4) and when the crack tip approaches pearlite phase the crack easily propagates through it.

Fig. 3 Crack path in CG pearlite steel.

Fig. 4 Crack path in FG pearlite steel.

Fig. 5 (a) Crack path in CG bainite steel, (b) Crack path in bainite steel, (inside the white circle) showing crack stopped for a while, when it approaches bainite particle.

Fig. 6 Crack path in FG bainite steel

Fig. 7 Relationship between closure ratio and ΔK

The relationship between crack closure ratio, $U (= \Delta K_{cl} / \Delta K)$ and ΔK for the steels investigated in the present study are shown in Fig. 7, where $\Delta K_{eff} (= K_{max} - K_{cl})$ is effective stress intensity factor range, K_{max} is maximum stress intensity factor

and K_{cl} is the stress intensity factor at closure. It was apparent from the figure that crack closure behavior was more pronounced near the threshold region for all the steels. It was observed that crack closure was more in steel with martensite particle. High closure in steel with martensite particle could be promoted by roughness induced crack closure because of lots of crack deflections on the crack path compared to steels with pearlite and bainite particle. Next higher closure was observed in steel with CG pearlite particle, this also due to roughness induced crack closure because of more tortuous crack path in steel with CG pearlite particle. It was observed in steel with bainite particle the crack closure is less pronounced than in steel with pearlite particle. The relationship between da/dN and ΔK_{eff} is shown in Fig. 8. The threshold effective stress intensity factor ranges, $\Delta K_{eff, th}$ still indicated some difference between the steels. The steel with martensite particle had the lower threshold value compared to other steels, which is different from the result observed in the crack growth curves arranged by ΔK .

Fig. 8 Relationship between da/dN and ΔK_{eff}

4. Conclusions

The main conclusions from the present investigation are summarized as follows.

1. Both threshold region and Paris region have significant effects on microstructure and the presence of hard phase have a significant effect on fatigue crack growth rate.
2. Steel with martensite particle exhibited higher threshold value and lower crack growth rates, due to more crack deflections by hard martensite particle.
3. Steel with CG pearlite particle and CG bainite particle exhibited higher threshold value and lower crack growth rates than steel with FG pearlite particle and FG bainite particle respectively.
4. Steel with CG pearlite particle exhibited higher threshold value and lower crack growth rates than steels with CG bainite particle and FG bainite particle, because of more tortuous crack path observed in steel with CG pearlite particle.
5. In steel with bainite particle when the crack tip approaches the hard bainite phase the crack stopped for a while and propagates through the hard bainite phase. This behavior was not observed in steel with pearlite particle.
6. In steel with FG pearlite particle the crack path was more straight compared to other steels in present investigation, so it exhibited lower threshold value and higher crack growth rates.

References

1. S. Taira K. Tanaka, M. Hoshina, ASTM STP 675 (1979) 135.
2. G.E. Dieter, Mechanical Metallurgy, McGraw-Hill, London, 1988.