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Effect of hardness of second phase particle on fatigue crack growth behavior of steels with hard second phase particle in soft ferrite matrix

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Abstract. ΔK-constant fatigue crack growth (FCG) tests were conducted on low carbon steels with uniformly distributed hard particle with different of pearlite, bainite and martensite in a soft ferrite matrix. The FCG tests by using a single edge cracked tension (SECT) type was performed inside a scanning electron microscope chamber equipped with a servo-hydraulic fatigue machine. During the test, in-situ crack path observation was carried out to identify the crack tip stress shielding phenomena. From the results, influence of hardness of second phase particle on the FCG behavior in Paris regime was systematically investigated. The results revealed that the ferrite-martensite (FM) steel showed significantly higher FCG resistance compared to that of ferrite-pearlite (FP) and ferrite-bainite (FB) steels. The harder second phase particle would be more difficult to be plastically deformed, which would induce higher plastic constrain. This higher plastic constrain may result in significant crack closure effect and stress shielding effect, thereby increasing higher FCG resistance.

Introduction

The extensive researches have been reported on effect of microstructure on FCG behavior in near threshold region [1-3]. Many microstructural factors, such as grain size [2], volume fraction of second phase [4] , morphology of second phase [5] and hardness [6] have been recognized. In contrast, a few research works on effect of microstructure on FCG behavior in Paris regime have been reported mainly for dual phase steels [3, 4].

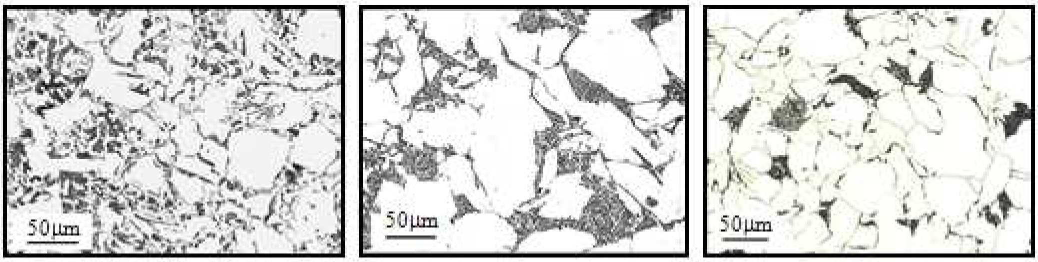
Mutoh and co-workers [3, 7] investigated the effect of morphology of second phase on fatigue crack growth behavior of ferrite-pearlite two phase steels and reported the microstructure with uniformly distributed pearlite particles in soft ferrite matrix (Steel D) showed the higher fatigue crack growth resistance compared to the microstructure with coarse networked pearlite phase with encapsulated ferrite phase (Steel N). They indicated based on the in-situ observations and fracture mechanical discussion that the crack path of Steel D was frequently deflected on micro scale due to distributed pearlite particles, which induced interlocking between crack surfaces and then crack tip stress shielding. They concluded that this significant crack tip stress shielding phenomena in Steel D contributed to higher fatigue crack growth resistance compared to Steel N. In the next step for more detailed understanding of effect of microstructure, the authors have investigated effect of size and spacing of pearlite particles on fatigue crack growth behavior of Steel D. They have concluded that the large size and spacing of the pearlite second phase would be beneficial for enhancing fatigue crack growth resistance [8]. However, the detailed effect of hardness of second phase on fatigue crack growth behavior and resistance in Steel D has not yet been clarified.

In the present study, the uniformly distributed particle microstructure steels with three different kinds of particles (pearlite/bainite/martensite) were prepared for further investigation on effect of second phase particle hardness on FCG behavior in the Paris regime.

Material and Experimental Procedures

Three different kinds of steels with different of uniformly distributed pearlite, bainite and martensite particles in ferrite matrix steels were prepared from the same starting steel by thermo-mechanical processing. The microstructure of the three different hard particle material were used in this study as shown in the Fig.1. The microstructural characteristics and mechanical properties of the three materials with different hardness, where FP, FB and FM indicated the ferrite-pearlite, ferrite-bainite and ferrite-martensite steels, respectively as indicated in Table 1.

FCG tests at ΔK-constant in Paris regime was mentioned in the previous work [9] . Also was explained the measurement and determining the crack closure were indicated. Mutoh et al. [7] described the determination of the effective crack tip stress intensity factor range, $\Delta K_{eff,tip}$.



(a) Ferrite-Pearlite (FP) (b) Ferrite-Bainite(FB) (c) Ferrite-Martensite (FM)

Figure 1: Microstructures of the three different hard particle materials used

Table 1 : Mechanical properties and microstructural characteristics of the three materials used

	FP	FB	FM
Yield strength (0.2%), MPa	224	321	275
Tensile strength, MPa	486	506	486
Ferrite grain size, μm	69	68	84
Hard phase volume fraction (%)	30	26	17
Spacing of hard particle, μm	80	53	57
Size of hard particle, μm	50	30	25
Hardness of ferrite (HV)	125	125	159
Hardness of hard particle (HV)	214	249	339

Results and discussion

Crack path and FCG behavior. Fig. 2 shows the fatigue crack path and crack growth rates for FM steel during the *ΔK*-constant FCG test. As seen from the figure, the crack was more straight at ferrite phase after the crack passed through the martensite particle and more tortuous when the crack tip nearest the martensite particle as shown in Figs. 3(a) and (b), respectively, which reveals the interlocking of crack surfaces (Δ) and the branching of crack (▲). Region A and B indicated the higher and lower FCG rate, pespectively. This fenomena was similar in the material FB where the crack tip approaches the hard particle, the crack was arrested for a while and then passed through the hard particle. This behavior was not observed in the material FP, while the crack path was deflected at the boundaries martensite particle as shown in Fig. 3(a). However, interlocking and branching in FM was more significantly observed compared to FP and FB, as seen from Fig. 3(b), which would result from hardness of martensite particle in FM. Figures crack path and crack growth rates for FP and FB steels were displayed and described in previous work [9].

Based on these in-situ crack path observations, it seemed that crack tip shielding phenomena, such as interlocking and branching were more significantly and frequently observed in FM, while they were less observed in FB and then in FP, which may be due to constrain of plastic deformation in ferrite phase where the present of the harder martensite particle in FM.

Effect of crack closure and stress shielding phenomena For the primary step to understand the reason for the difference in FCG resistance of the three microstructures, effect of crack closure, K_{cl} was investigated. The result showed that, the effective stress intensity factor range, ΔK_{eff} (= K_{max} - K_{cl}) was much significant in FM, it was less significant in FB and FP as shown in Fig. 4(a). The range of ΔK_{eff} was indicated the FM was higher than FB and FP, may be caused by the hardness of martensite. In addition, the FCG curves for the three materials by using ΔK_{eff}, it was found that the curves for FM, FB and FP did not coincide each other as seen from the figure da/dN- ΔK_{eff}.

This suggests that some mechanisms other than crack closure would influence on FCG resistance. Korda et al.[3] clearly indicated that the crack tip stress shielding due to interlocking and crack branching was the corresponding mechanism. That means the phenomena such as interlocking and crack branching elements were often observed on the crack wake for all three materials, FP, FB and FM.

To more clearly that the effect of the effect of crack tip stress shielding on FCG resistance was investigated. The effective crack tip stress intensity factor range, $\Delta K_{eff,tip}$ (= K_{tip}- K_{cl}), was evaluated according to the method where proposed by Mutoh et al. [7] as a new parameter. The both effects of the crack closure and crack tip stress shielding effects are taken into consideration.

The results showed that, when the FCG curves for FP, FB and FM were rearranged by using the new parameter $\Delta K_{eff,tip}$, the resultant FCG curves for three materials were merged to one curve, as shown in Fig. 4(b). The new parameter $\Delta K_{eff,tip}$, is suggested that would be the intrinsic controlling fracture mechanics parameter for the materials with crack tip stress shielding phenomena during FCG.

Effect of hardness. The presence of hard particle could enhance crack closure [5] and crack tip stress shielding [7]. From the foregoing results, the FCG behavior for three materials is summarized in Table 2. As seen from the table, harder uniformly distributed particles contributed to great crack closure effect and stress shielding effect. Therefore, FM with the hardness martensite particles showed the most significant crack closure and stress shielding effect, which improved FCG resistance. The harder second phase particle would be more difficult to be plastically deformed, which would induce higher plastic constrain. This higher plastic constrain may result in significant crack closure effect and stress shielding effect.

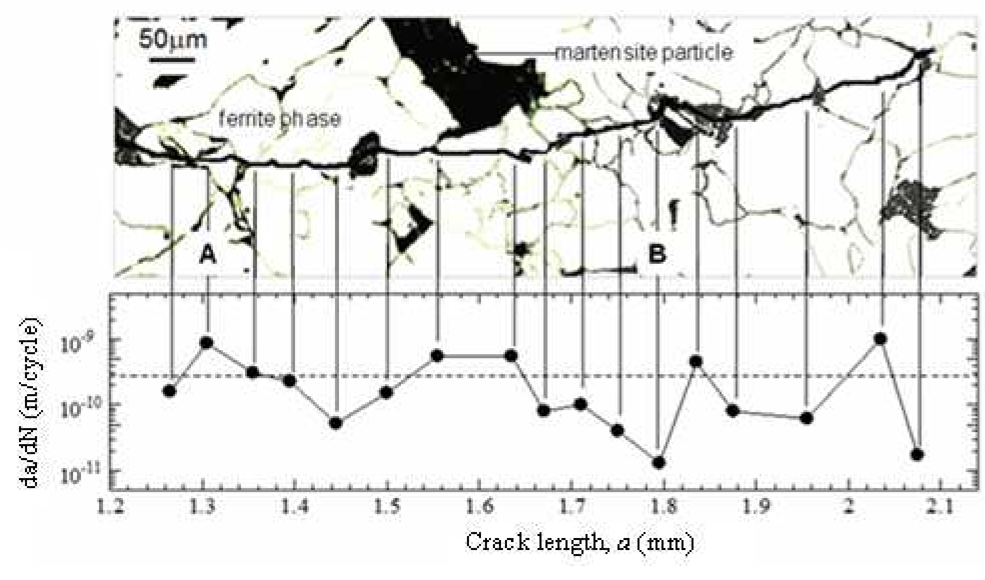


Figure 2: Crack path and crack growth for FM steel.

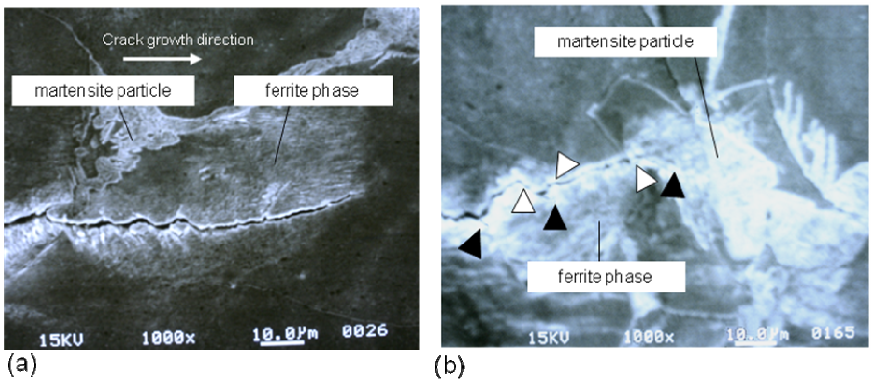


Figure 3: Crack path at higher magnification for FM steel: (a) crack path at A, (b) crack path at B. (▲: crack branching, Δ: crack interlocking).

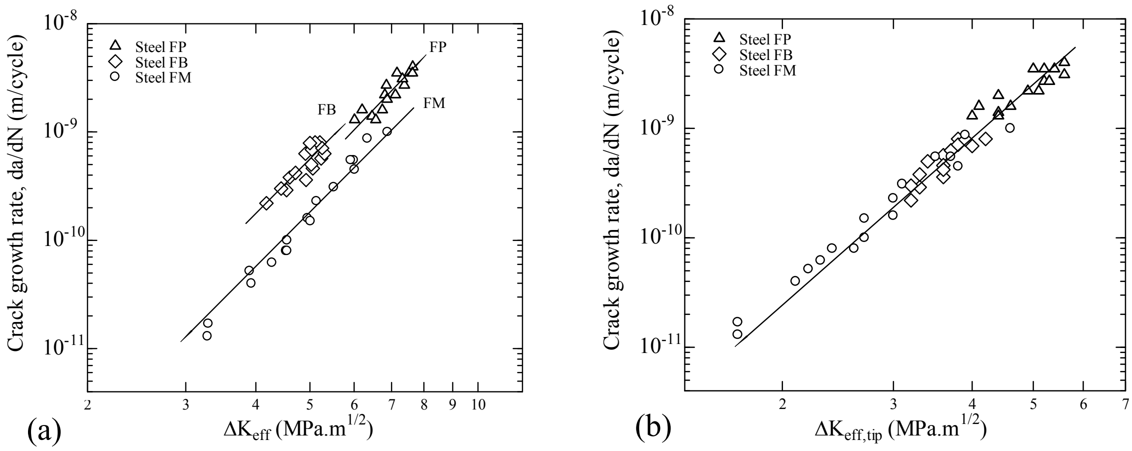


Figure 4: Relationships between crack growth rate, da/dN and (a) stress intensity factor range, ΔK_{eff} (b) $\Delta K_{eff,tip}$

Table 2: FCG behavior of the three materials

	Particle spacing	Particle size	Hardness of particle (HV)	Crack deflection at lower FCG	Closure	Interlocking/ branching	Stress shielding	FCG Resistance
FP	largest (70 μm)	largest (70μm)	201	less	less	less	less	Lower
FB	smallest (53 μm)	medium (30μm)	249	medium	medium	medium	medium	Medium
FM	medium (57 μm)	smallest (25μm)	339	more	more	more	more	Higher

Conclusions

Fatigue crack growth behavior of three kinds of steels with three kinds of uniformly distributed second phase particles (pearlite, bainite and martensite particles) in ferrite matrix was investigated to understand effect of hardness of second phase particle. Harder second phase particle enhanced both crack closure effect and crack tip stress shielding effect and then significantly improved fatigue crack growth resistance. Main reason for this will be more significant constrain of plastic deformation around the particle for harder particle, which will result in more significant crack closure and interlocking due to crack deflection and crack branching for significant stress shielding effect.

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