Minimum Fatigue Crack Length for the Application of Small-Crack Growth Law*

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In the present study, the influence of the microstructure of materials on the characteristics of small-crack growth was investigated, and the minimum crack length to which the small-crack growth law \( \frac{dl}{dN} \propto l \) is applicable was evaluated in the cases of ferrite-pearlite steel, ferrite-martensite steel and quenched and tempered carbon steel. Initial crack growth is influenced markedly by the grain boundary, pearlite structure and martensite structure, and these influences decrease with increase in crack length. However, even in the process in which crack growth is influenced by the microstructure, the mean crack growth rate is estimated by extrapolating the crack growth rate in the region where it is mainly controlled by the mechanical parameter alone.

Key Words: Fatigue, Rotating Bending, Microstructure, Ferrite-Martensite Steel, Ferrite-Pearlite Steel, Quenched and Tempered Steel, Crack Growth Law, Small Crack

1. Introduction

The fatigue process is mainly composed of crack initiation and propagation processes. The latter process is more significant in practical application, because most of the fatigue life is spent in the propagation of the crack, especially in the case of a small crack. Therefore, it is very important in the prediction of fatigue life to evaluate the growth life of small cracks.

From this standpoint, the authors have investigated the growth behaviour of small cracks using many kinds of materials, and have reported that the growth rate of the small crack cannot be evaluated by linear elastic fracture mechanics, but is controlled uniquely by \( \sigma_{f}^{V} \). Furthermore, we proposed a prediction method for the fatigue life based on the growth law, \( \frac{dl}{dN} \propto \sigma_{f}^{V} \), and confirmed its validity\(^{(4),(6)}\).

When the crack length is small and comparable to the size of microstructures, i.e., grain size, the growth behaviour of cracks is irregular because of the influence of microstructures, and it is difficult to quantitatively evaluate the growth rate using only a mechanical parameter, e.g., \( \Delta K \), \( \Delta J \) or \( \sigma_{f}^{V} \).

In the case of materials whose total life is consumed mainly by the growth life of small cracks influenced by microstructures, it is especially important in the prediction of fatigue life to evaluate the growth rate of the small crack.

The authors have previously clarified that the minimum crack length for the application of the growth law stated above is 1~3 grains.\(^{(1),(2),(6)}\). However, we did not focus on the growth behaviour relating to microstructures.

In the present paper, detailed observations were performed successively on the surface of plain specimens in order to investigate the effect of microstructures on the growth behaviour of small cracks, and the minimum fatigue crack length for the application of the small-crack growth law was discussed in the cases of several materials which have different
microstructures, i.e., ferrite-pearlite steel, quenched and tempered steel and ferrite-martensite steel.

Many studies have been conducted on the effect of microstructure on the growth behaviour of small crack; for example, Tokaji et al. investigated the limitation for the application of linear elastic fracture mechanics and microstructurally small cracks in many materials from the standpoints of the size of the microstructures, the crack opening behaviour and the fracture mechanism.

The main purpose of the present paper is to clarify the relation between the small-crack growth law which is proposed by one of authors and the microstructure of materials.

2. Materials, Specimens and Experimental Procedure

Materials used are rolled round bars of 0.15% and 0.42% carbon steel (diameter: \( \phi 19 \) mm).

Table 1 shows the chemical compositions. The 0.15% carbon steel was used as materials of annealed steel (S15C F.P.) which have a ferrite-pearlite structure, and materials of dual-phase steel (S15C F.M.), which have a ferrite-martensite structure. The 0.42% carbon steel was used in the quenched and tempered state (S45C Q.T.). These steels show different effects of microstructure on crack growth.

The procedure of heat treatment and the microstructure of each material are shown in Figs.1 and 2. The mean ferrite grain size in the ferrite-pearlite steel is about 67 \( \mu m \), and the mean ferrite and martensite grain sizes and the volume fraction of martensite in the dual-phase steel are about 35 \( \mu m \), 38 \( \mu m \) and 40%, respectively.

Table 2 shows the mechanical properties after heat treatment of each material.

Figure 3 shows the shape and dimensions of the specimens. Although all the specimens have a fine shallow partial notch to localize the crack initiation site, their strength reduction factors are close to 1.

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<th>Table 1 Chemical composition</th>
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![Fig. 1 Procedure of heat treatment (F.C.: furnace cooling, W.Q.: water quenching, value in ( ) : diameter of material in heat treatment) (a) ferrite-pearlite steel (b) quenched and tempered steel (c) ferrite-martensite steel]

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<th>Table 2 Mechanical properties</th>
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<td>( \sigma_{ob} )</td>
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![Fig. 2 Microstructure (a) ferrite-pearlite steel (b) quenched and tempered steel (c) ferrite-martensite steel]
Therefore, the specimens can be considered as plain specimens. After machining, the ferrite–pearlite steel was annealed for 1 h at 600°C. Prior to testing, all the specimens were electropolished to about 40 μm in diameter. Furthermore, the ferrite–pearlite and ferrite–martensite steels were etched slightly by 3% nital to allow observation of the relation between the crack growth behaviour and the microstructure.

The observation of the surface state and the measurement of crack length were conducted using the plastic replica method under an optical microscope. Crack length is defined as the length of the
circumferential direction along the specimen surface.

The machine used is the Ono-type rotating bending fatigue testing machine (capacity 15 N·m, frequency about 50 Hz).

3. Results and Discussion

3.1 Crack initiation and early propagation processes

Figure 4 shows the change in surface state due to stress repetitions. In the ferrite-pearlite and the quenched and tempered steels, the fatigue process is divided into the crack initiation process and crack propagation process as reported in previous papers. That is, in the former process, fatigue damage is accumulated gradually at the region relating to the grain size without an increase in size, and then the region develops into a crack. However, in ferrite-martensite steel, slip bands are observed in the ferrite grains at an early stage of stress repetitions, and the number of slipped grains increases with an increase in stress cycles. The morphology of the slip, however, is a planar type, similar to the one which is observed in prestrained or aged materials, and it is different from the wide slip bands usually observed in annealed materials. It is difficult in this material to distinguish the slipped region from a crack. Therefore, hereafter, crack initiation is said to occur when the length of a slip band or crack exceeds the size of one grain. Furthermore, some differences between ferrite-pearlite steel and ferrite-martensite steel are recognized in the crack propagation process. That is, in ferrite-martensite steel, as many slip bands are initiated, as mentioned above, cracks coalesce frequently and propagate, threading through ferrite grains. Therefore, the crack growth is a zigzag type reflecting the influence of microstructures. On the other hand, in ferrite-pearlite steel, though many slip bands are initiated, relatively few develop into cracks, hence the coalescences of cracks are few. The fatigue process in the quenched and tempered steel is similar to that in the ferrite-pearlite steel.

Figure 5 shows the relationship between the logarithm of crack length, log L, and the relative number of cycles, N/Nf (Nf: number of cycles to failure). In all the materials tested, cracks begin to form at the early stage of stress cycling, and most of the total life is occupied by the growth of a crack smaller than 1~2 mm. In ferrite-martensite steel, especially, roughly 100 % of the total life is occupied by crack propagation. In Fig. 5, arrow marks indicate the coalescence of cracks. The frequency of coalescence is much higher in ferrite-martensite steel than in ferrite-pearlite steel and quenched and tempered steel. Although the growth behaviour in quenched and tempered steels is monotonous, in ferrite-pearlite steels and ferrite-martensite steels, a substantial scatter in crack growth is observed, reflecting the influence of microstructures in the range of crack lengths smaller than about 0.3 mm. However, there is little stress dependency in the relation between log L and N/Nf, and the relation is approximated by a single straight line when the crack is small in each material.

3.2 Influence of microstructure on the crack growth behaviour

As mentioned in the previous section, most of the fatigue life is consumed by the propagation life of a small crack. Therefore, it is essential to evaluate the growth rate of a small crack in the prediction of fatigue life. However, the retardation and acceleration of crack growth yield remarkably to the influence

![Fig. 5 Crack growth curves](image-url)
of microstructure in the range of early crack propagation.

In this section, the influence of microstructure on crack growth is investigated by examining the early growth behaviour of small cracks.

Figure 6 shows the detailed change in crack growth rate corresponding to the microstructures in ferrite-pearlite steel and ferrite-martensite steel. That is, in Fig. 6, the crack growth rates are those obtained separately from each growth of both crack tips, and the microstructures and the crack path are sketched corresponding to the variation in crack growth rate. The characters A, B, . . . A', B' . . ., indicate the positions where a marked retardation of crack growth is recognized. As seen from Fig. 4, a crack begins as a length related to the grain size, not from a small point. Therefore, the origin in Fig. 6 is plotted on the middle point of the initiated crack. As seen from the figure, a blocking effect on the crack growth is observed at the grain boundary and the hard phase, in the pearlite structure in the ferrite-pearlite steel and the martensite structure in the ferrite-martensite steel. In the ferrite-martensite steel, even if the blocking effect of the ferrite grain boundary on the crack growth decreases, the crack growth rate decreases markedly when a crack reaches the martensite structure (process from D to E in Fig. 6 (b)). This indicates that the blocking effect of the martensite structure is very large. This effect of the microstructure, however, disappears with the increase in crack length. The critical lengths \( l_c \), at which the marked effect of microstructure is recognized, are about 300 \( \mu \)m in ferrite-pearlite steel and about 400 \( \mu \)m in ferrite-martensite steel, and these lengths correspond to 4\( d_f \) and 11\( d_f \), respectively, where \( d_f \) is the mean size of the ferrite grain. These results indicate that the range of crack length affected by microstructures is larger in the ferrite-martensite steel than in the ferrite-pearlite steel. The life of crack growth from crack initiation to critical length \( l_c \) is about 50 \% of the total fatigue life in both steels; thus, the evaluation of the crack growth rate in these ranges is very important.

Figure 7 shows the relationship between the crack growth rate and the crack length in the entire range of crack growth. Dotted lines in the figure indicate the mean values of the growth rate obtained by approx-

(a) ferrite-pearlite steel \((\sigma_t = 280 \text{ MPa}, N_r = 6.0 \times 10^4 \text{ cycles})\)

(b) ferrite-martensite steel \((\sigma_t = 440 \text{ MPa}, N_r = 6.9 \times 10^4 \text{ cycles})\)

Fig. 6 Influence of microstructure on crack growth behaviour

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imating the crack growth data of smooth specimens with a smooth curve. Moreover, in the case of ferrite-martensite steel, the results of specimens with a small blind hole (diameter and depth, 0.3 mm) are also indicated by a solid line, because they are evaluated approximately by a mechanical parameter and the fluctuation of crack growth is small. The range of crack length smaller than 0.3 mm in this case was extrapolated from the results of larger crack growth. Although the crack growth behaviours are highly irregular in the early propagation stage, the crack growth rates increase monotonously when the crack length is larger than the critical length. In this range, the crack growth rate is mainly controlled by a mechanical parameter, i.e., it is proportional to the crack length, \( \frac{dl}{dN} \propto l \), in all materials. Furthermore, in ferrite-martensite steel, the results of smooth specimens are nearly equal to those of specimens with a hole. Moreover, even in the range where the crack growth rate is strongly influenced by microstructures, the average values of the crack growth rate are nearly equal to the extrapolated crack growth rates of the specimens with a hole. Therefore, it can be said that the minimum crack length for the application of the relation, \( \frac{dl}{dN} \propto l \), is nearly equal to the initial crack size, namely, the mean size of the ferrite grain. It is clear that the relation, \( \frac{dl}{dN} \propto l \), also holds in the quenched and tempered steel from Fig. 7 (b), though the relation between the critical length \( l_c \) and the microstructural size is not investigated.

The results of Figs. 6 and 7 show that the relation, \( \frac{dl}{dN} \propto l \), holds in most of the range of crack growth, though the influence of microstructures and coalescence of cracks in the crack growth process result in the fluctuation of the crack growth rate.

The results in the present paper indicate that the small-crack growth law proposed by us is more conventional and has a wider range of application than other mechanical parameters.

4. Conclusions

Rotating bending fatigue tests were performed on specimens of ferrite-pearlite steel, quenched and tempered steel and ferrite-martensite steel in order to investigate the influence of microstructures on the behaviours of small-crack growth, the minimum fatigue crack length for application of the small-crack growth law and the prediction method for fatigue life.

The following conclusions were obtained.

(1) Two types of effects of microstructures on crack growth were observed: (a) that due to the presence of microstructures which have different resistances to crack growth and (b) that due to the coalescence of cracks due to the presence of proceeding cracks, in the path of crack growth. The former is substantial when a crack is small and there is little dependency on the crack length in the latter.

(2) Although a crack is initiated in the ferrite grain in both ferrite-pearlite steel and ferrite-martensite steel, the critical crack lengths \( l_c \), for which crack growth rates are greatly affected by microstructures, are about 300 \( \mu m \) (\( \approx 4d_r \), \( d_r \): mean size of ferrite grain) in the former and 400 \( \mu m \) (\( \approx 11d_r \)) in the latter. This difference is caused by the larger blocking effect in martensite than in pearlite on crack growth. In quenched and tempered steel, the effect of microstructures on the crack growth is negligible.
(3) In most of the crack growth process, including the process in which crack length is smaller than \( l_0 \), the mean values of crack growth rate can be approximately determined by the small-crack growth law. That is, the minimum crack length, to which small-crack growth law is practically applicable, is much smaller than \( l_0 \) and nearly equal to the length of the crack under the current definition.

References


