Effect of grain size on crack growth resistance and notch sensitivity in fatigue of carbon steel

Norio KAWAGOISHI and Kohji KARIYA

Abstract   The effect of grain size on the crack growth resistance and the notch sensitivity in fatigue of commercial carbon steels with grain sizes of 6.5 and 20 μm was investigated using smooth specimen and V-groove notched specimens with various notch radii under rotating bending. A crack initiated at the early stage of stress repetitions and most of fatigue life was occupied by the growth life of a crack smaller than 1~2 mm. The crack growth rate was determined by the term $\sigma_a{}^n\ell$, uniquely in both steels, where σ_a and ℓ are the stress amplitude and the crack length and n is constant. The fine-grained steel has an excellent resistance to crack growth in comparison with many annealed carbon steels. This was explained by the barrier effect of grain boundary. Consequently, the notch sensitivity is higher in the fine-grained steel than in coarse-grained one not only for crack initiation but also crack propagation.

Keywords   Fatigue, Carbon steel, Grain size, Crack growth resistance, Small crack growth law, Notch sensitivity, Linear notch mechanics

1. Introduction

In general, the fatigue limit of a smooth specimen in carbon steel is increased by refining the grain size similar to the case of static strength, though the one for crack propagation in a sharply notched specimen is hardly influenced [1]. This is related to the phenomenon that there is no or little influence of grain size on the crack growth rate [2]. These results were obtained by steels with conventional grain size larger than about 10 μm. Recently, ultra-fine-grained steels with grain size smaller than a few μm have been developed and their mechanical properties were investigated. It was reported that the steels have not only higher fatigue strength but also an excellent crack growth resistance [3]. However, the mechanism of the increase in crack growth resistance is not fully clarified. Therefore, it is important to know the limiting grain size for getting an excellent crack growth resistance similarly the clarification of the mechanism of the increase in crack growth resistance.

In this study, in order to investigate the propagation behavior of a fatigue crack and the evaluation method of a fatigue crack growth rate for commercial carbon steels with different grain sizes, fatigue damage due to stress repetitions was observed at the specimen surface successively under rotating bending. In addition, notch sensitivities of the steels were investigated based on the results of smooth specimen through the linear notch mechanics.

2. Material and experimental procedures

Material used was a commercial rolled carbon steel with a mean grain size of 6.5 μm. The chemical composition is shown in Table 1. The material was annealed at 950°C for 2 h in order to get a different grain size of 20 μm.

Figure 1 shows microstructures of the as received steel and the annealed one. In the following, these materials are called as fine-grained steel and coarse-grained steel, respectively.

Table 2 shows their mechanical properties.

Figure 2 shows shape and dimensions of specimens. Fatigue tests were carried out using smooth specimens and V-groove notched specimens. In addition, specimens with a partial notch at the center of specimen were used to localize the crack initiation site and make easier the successive observation of surface damage. The fatigue strength reduction factor in a partially notched specimen

was smaller than 1.1. Therefore this specimen can be regarded as a smooth specimen. After machining, all of the specimens were annealed at 600˚C for 1 h in N_2 gas to release the residual stress and then electro-polished about 20μm from the specimen surface to remove the work affected layer. Crack initiation and propagation behavior was measured by using plastic replication method. The crack length ℓ was defined as the length of the circumferential direction along the specimen surface. Testing machine used was a rotating bending machine operated at 50 Hz in ambient air.
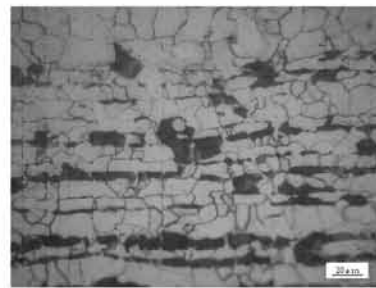
Table 1. Chemical composition

C	Si	Mn	P	S	Cu	Ni	Cr
0.16	0.35	1.4	0.014	0.002	0.02	0.01	0.02
Sn	T.Al	Ti	B	Nb	V	Mo	
0.001	0.018	0.002	1E-04	0.001	0.055	0.002	

Table 2. Mechanical properties

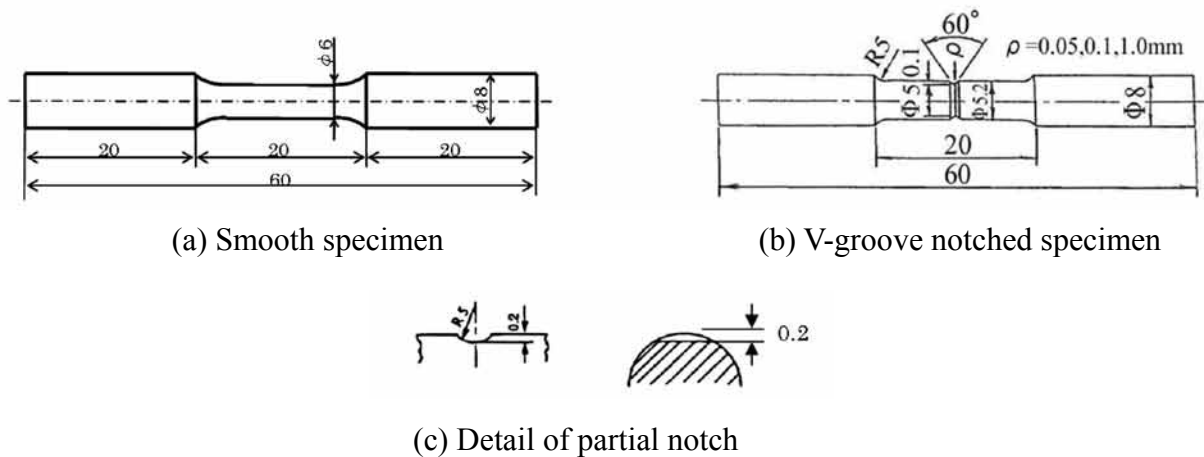|	σ_y (MPa)	σ_B (MPa)	ϕ (%)
Fine-grained steel	451	603	69.2
Coarse-grained steel	321	515	65.1
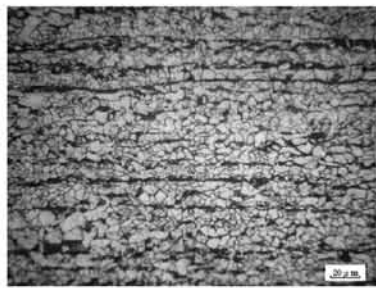
(a) Fine-grained steel

(b) Coarse-grained steel

Figure 1. Microstructures

(a) Smooth specimen

(b) V-groove notched specimen

(c) Detail of partial notch

Figure 2. Shape and dimensions of specimens

3. Experimental results and discussion

3.1 Crack initiation and propagation properties

Figure 3 shows *S-N* curves for partially notched specimens. In the figure, $N_{0.05}$ and N_f mean 0.05 mm crack initiation life and fatigue life, respectively. The fatigue strength and the resistance to crack initiation were increased by refining grain size. Endurance ratios σ_{w0}/σ_B (σ_{w0}: fatigue limit for the smooth specimen) were 0.51 for the fine-grained steel and 0.47 for the coarse-grained one, respectively.
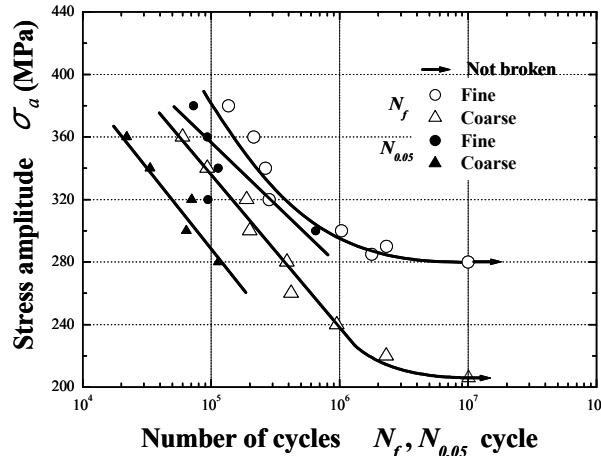
Figure 3. *S-N* curves of partially notched specimen

Figure 4 shows change in surface state of partially notched specimens at high stress level in both steels. The initiation size of a crack is nearly the same as grain size in both steels.

Figure 5 shows change in surface state of specimen in both steels at the fatigue limit. A crack initiates at the early stage of stress repetitions, and then the crack arrests finally. That is, the fatigue limit in each steel is also determined by the limit for crack propagation similar to many carbon steels.

Figure 6 shows crack growth curves in which the axis of abscissas is normalized by the number of cycles to failure. In the figure, arrow marks mean crack coalescence. In both steels, a crack initiated at the early stage of stress repetitions and most of fatigue life was occupied by the growth life of a crack smaller than 1~2 mm. Moreover, the relation between the logarithm of a crack length, $\log \ell$, and relative number of cycles, N/N_f, can be approximated by a straight line in wide range of crack growth process, meaning that the crack growth rate is proportional to the crack length.

In general, the stress for crack initiation in a smooth specimen becomes high; consequently the condition of small scale yielding is breakdown, especially in low strength steels. The stresses at fatigue limit σ_{w0} in the present steels were over $0.60\sigma_y$ (σ_y: yield stress), therefore the condition of small scale yielding is not satisfied, and stress intensity factor is not valid as a mechanical parameter controlling the crack growth. The following small crack growth law was proposed by H. Nisitani as the parameter evaluating crack growth rate under high stress levels [4, 5] and the validity of this law was confirmed in many ductile metals [6]:

$$\mathrm{d}\ell/\mathrm{d}N = C_1\sigma_a^n\ell, \tag{1}$$

where C_1 and n are constants.

Figure 7 is the results obtained by applying the above growth law to the present results. In both steels, the crack growth rates are determined by the term $\sigma_a^n\ell$, uniquely. This means that fatigue life can be estimated by the growth law, because most of fatigue life is occupied by the growth life of a small crack.

In comparing the resistance to crack growth among steels, following transformed small crack growth law in which is partially considered material properties is convenient, because constants C_1 and n are different depending on the strength and cyclic properties of the material:

$$\mathrm{d}\ell/\mathrm{d}N = C_1\sigma_a^n\ell = C_2(\sigma_a/\sigma_{SC})^n\ell = C_3(\sigma_a/\sigma_B)^n\ell, \tag{2}$$

where C_2 and C_3 are constants and σ_{SC} is cyclic yield stress which has a good correlation with tensile strength (i.e. $\sigma_{SC} \propto \sigma_B$). In this equation, a reciprocal of C_3 represents the resistance to crack growth, because the constant C_3 is the crack growth rate when $\sigma_a = \sigma_B$, $\ell = 1$. Moreover, $(\sigma_a/\sigma_B)^n\ell$ corresponds to the crack tip opening displacement $\Delta CTOD$, because crack growth rate is nearly proportional to $\Delta CTOD$ [7]. However, tensile strength is used to consider the mechanical properties in Eq.(1) for convenience. Therefore, it is difficult to evaluate the microstructural or environmental
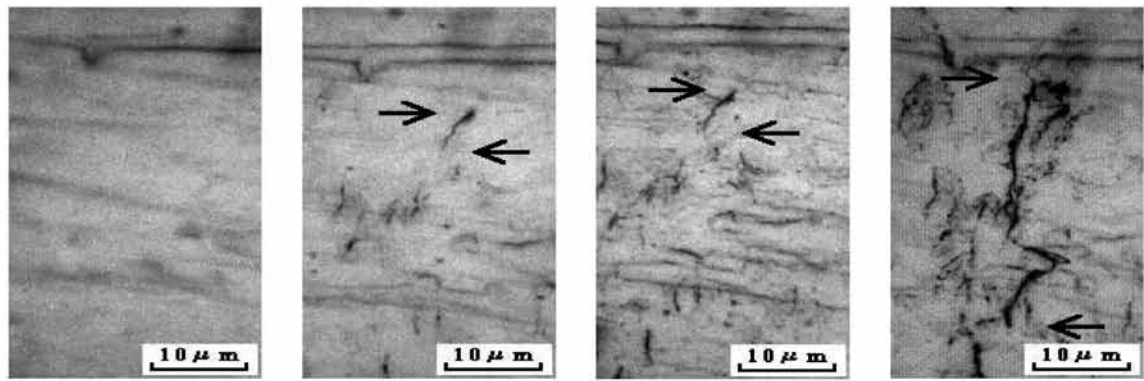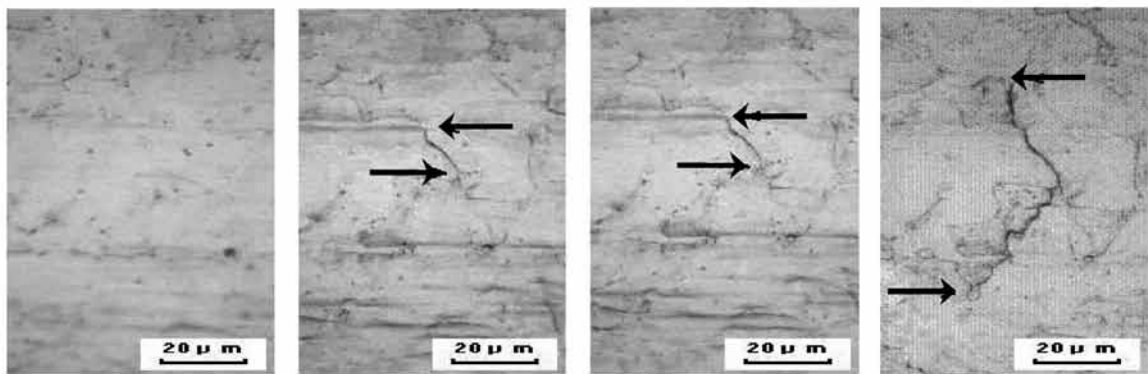
$N = 0$ (cycle)　　　　$N = 5.0 \times 10^3$　　　　$N = 4.0 \times 10^4$　　　　$N = 1.0 \times 10^5$

(a) Fine-grained steel (σ_a=360MPa, N_f=2.15×10⁵cycles)

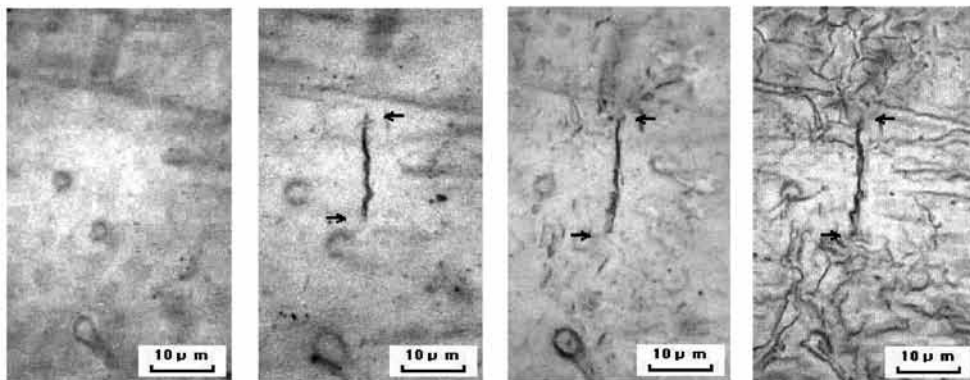$N = 0$ (cycle)　　　　$N = 2.0 \times 10^4$　　　　$N = 6.5 \times 10^4$　　　　$N = 2.5 \times 10^5$

(b) Coarse-grained steel (σ_a=280MPa, N_f=3.91×10⁵cycles)

Figure 4. Change in surface state of partially notched specimen due to stress repetitions at high stress (⟶ : crack tip)

$N = 0$ (cycle)　　　　$N = 6.0 \times 10^4$　　　　$N = 1.0 \times 10^6$　　　　$N = 1.0 \times 10^7$
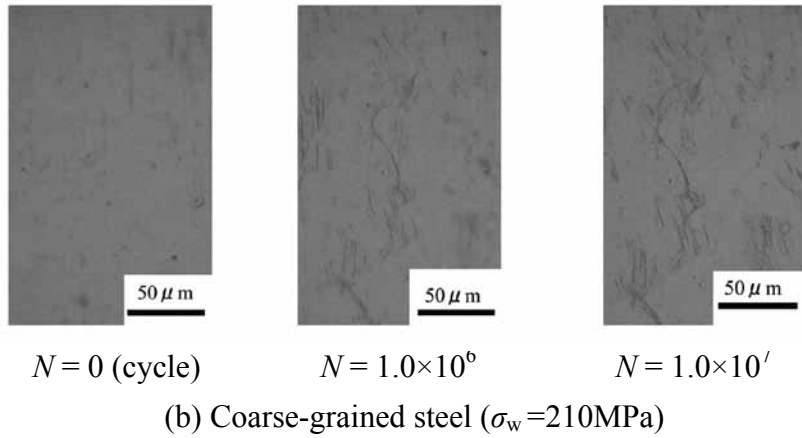
(a) Fine-grained steel (σ_w=280MPa)

$N = 0$ (cycle) $N = 1.0 \times 10^6$ $N = 1.0 \times 10^7$

(b) Coarse-grained steel (σ_w =210MPa)

Figure 5. Change in surface state of partially notched specimen due to stress repetitions at fatigue limit

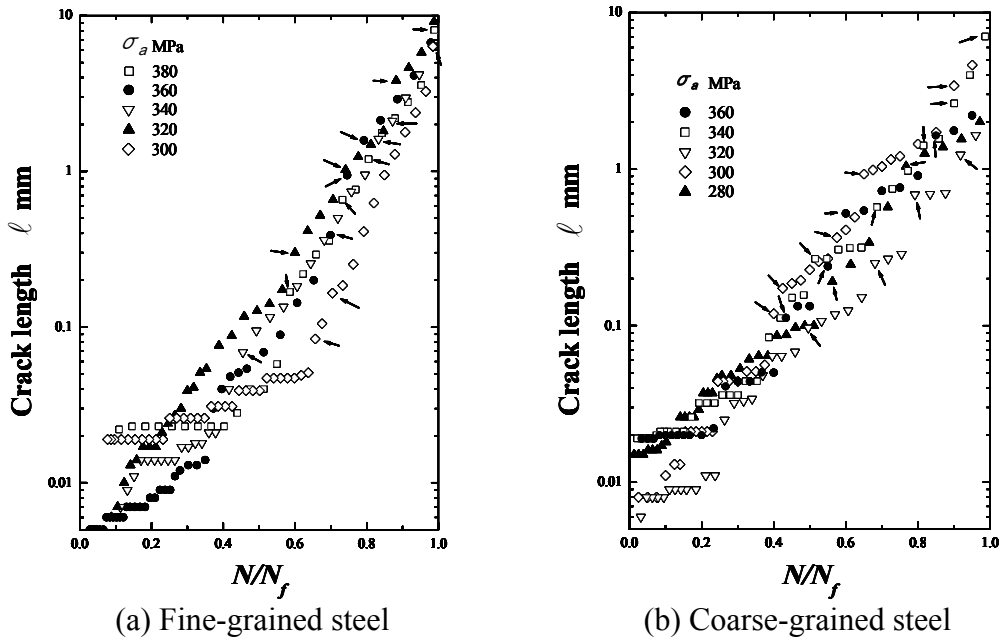(a) Fine-grained steel   (b) Coarse-grained steel

Figure 6. Crack growth curves (⟶ : crack coalescence)

(a) Fine-grained steel   (b) Coarse-grained steel
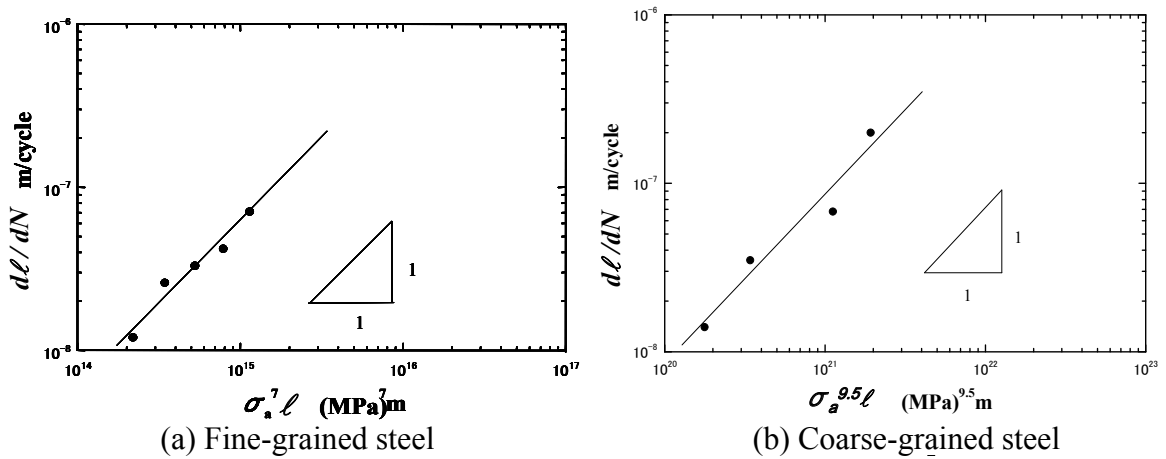
Figure 7. Relation between crack growth rate and $\sigma_a^n \ell$

effect like an effect of roughness or oxide induced crack closure by this equation.

Figure 8 shows relation between $d\ell/dN$ and $(\sigma_a/\sigma_B)^n\ell$. At the same mechanical severity, the crack growth rate in the fine-grained steel is lower than in the coarse-grained steel.

Figure 9 shows relation between C_3 and σ_B. In the figure, the results in many carbon steels were also plotted [6]. As seen from the figure, the fine-grained steel has an excellent resistance to the crack growth, though the growth resistance in the coarse-grained steel is equivalent to the ones in many steels.

It is reported that ultra-fine grained materials have an excellent resistance to crack growth and it is explained from the points of view of bifurcating or branching of crack and the roughness induced crack closure effect [3, 8].

Figures 10 and 11 show morphology of cracks in both steels observed on specimen surface by an optical microscope and SEM, respectively. Crack propagates straightly in the fine-grained steel and zigzag manner in the coarse-grained one reflecting the grain size and mainly propagates as a transgranular crack in both steels.

Figure 12 shows fracture surfaces. We can observe striations and the plateau size is larger in the coarse-grained steel than in the fine-grained steel corresponding to the grain size.

From the results mentioned above (see Figs. 10, 11, 12), it is difficult to explain the reason for the excellent resistance to crack growth of the fine-grained steel by the roughness induced crack closure effect, because the roughness corresponds to the grain size.

Figure 13 shows relation crack growth rate and crack length in which the deviation of crack growth rate in the growth process is indicated in detail. In both steels, marked decrease in the crack growth rate is confirmed. It was confirmed that cracks arrested at grain boundaries, meaning that the arresting was caused by a barrier effect of grain boundary. The decrease is very often in the fine-grained steel and the affected region is wide till longer crack length, meaning that the barrier effect of grain boundary is larger in the fine-grained steel than in the coarse-grained one. This may be a main reason for the high resistance to crack growth of the fine-grained steel.
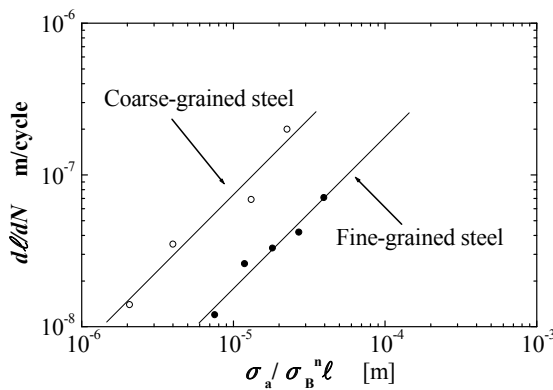

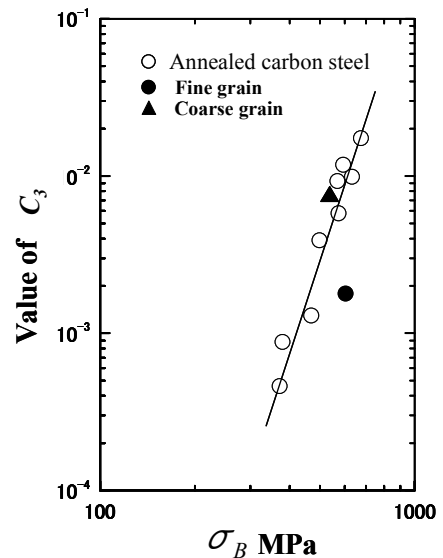Figure 8. Relation between crack growth rate and $(\sigma_a/\sigma_B)^n\ell$

Figure 9. Relation between constant C_3 and tensile strength σ_B

Fine grained steel
(σ_a=300MPa, N_f=1.02×10⁶)

Coarse grained steel
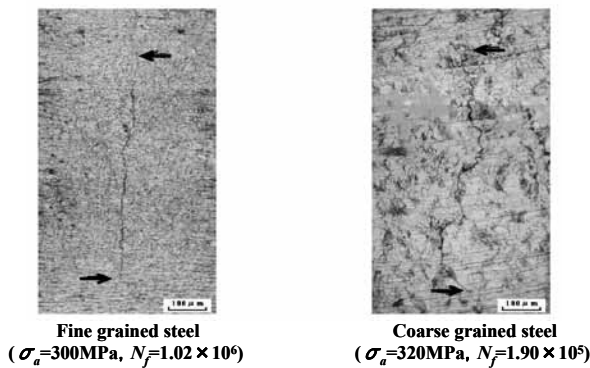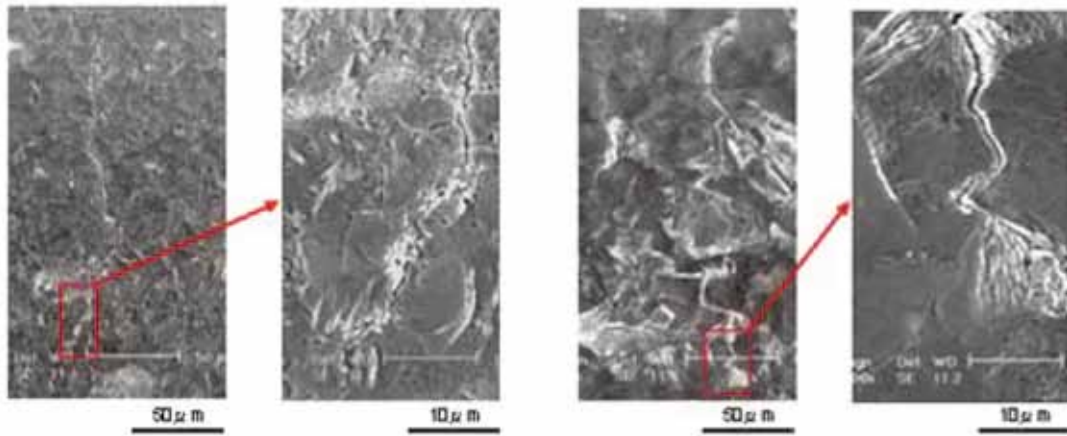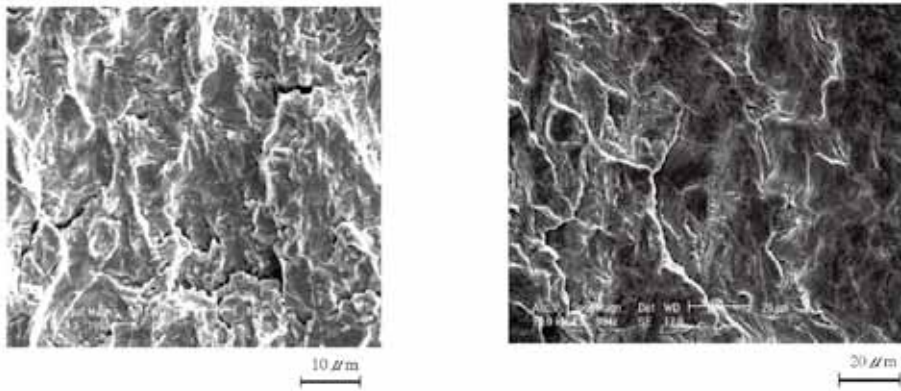(σ_a=320MPa, N_f=1.90×10⁵)

Figure 10. Morphologies of cracks observed by optical microscope

(a) Fine-grained steel   (b) Coarse-grained steel
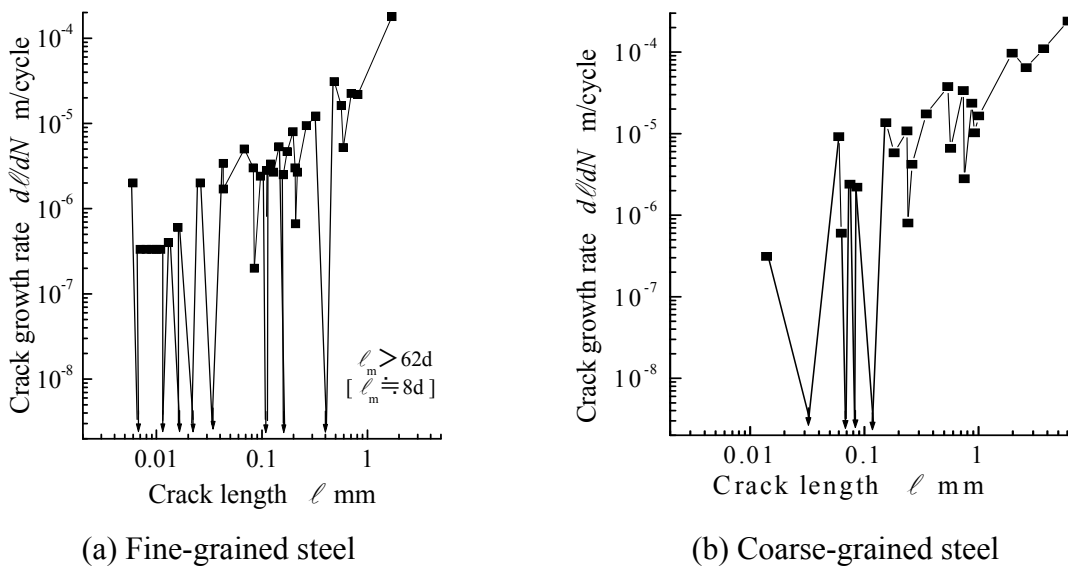
Figure 11. Feature of crack tip observed by SEM

(a) Fine-grained steel   (b) Coarse-grained steel

Figure 12. Fracture surfaces

(a) Fine-grained steel   (b) Coarse-grained steel

Figure 13. Relation between crack growth rate and crack length

3.2 Notch sensitivity

Table 3 shows fatigue limits defined as fatigue strength at 10^7 cycles in smooth specimens and notched ones. Figure 14 shows examples of non-propagating cracks in sharply notched specimens in both steels. Figure 15 shows relation between fatigue limit and stress concentration factor. Fatigue limits in the fine-grained steel are higher not only for crack initiation but also for crack propagation than those in the coarse-grained one. Higher fatigue limit for crack initiation may be explained from that the area related to crack initiation is narrower in the fine-grained steel. Moreover, the reason for higher fatigue limit for crack propagation is due to the excellent resistance to crack propagation as mentioned before.

Figure 16 shows relation between the maximum stress at the notch root normalized by the fatigue limit of the smooth specimen and a reciprocal of notch radius based on linear notch mechanics [9]. As seen from Fig.16, notch sensitivities are increased for both of crack initiation and its propagation by refining grain size. Branch points are about 0.1 mm and 0.2 mm in the fine-grained steel and the coarse-grained one, respectively.

Table 3. Fatigue limits for crack initiation and its propagation

Material	dg (μm)	ρ (mm)	K_t	σ_{w0} (MPa)	σ_{w1} (MPa)	σ_{w2} (MPa)
Fine-grained steel	6.5	∞	1	320	-	-
		1	1.41	-	270	-
		0.1	2.72	-	165	180
		0.05	3.54	-	130	180
Coarse-grained steel	20	∞	1	240	-	-
		1	1.41	-	200	-
		0.1	2.72	-	135	165
		0.05	3.54	-	110	165

dg: grain size, ρ: notch radius, K_t: stress concentration factor, σ_{w0}: fatigue limit of smooth specimen,
σ_{w1}: fatigue limit for crack initiation of notched specimen, σ_{w2}: fatigue limit for crack propagation of notched specimen
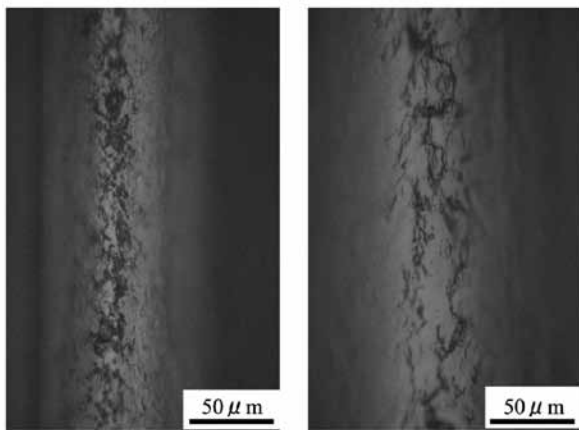
(a) Fine-grained steel
(σ_{w2}=130MPa)

(b) Coarse-grained steel
(σ_{w2}=110MPa)

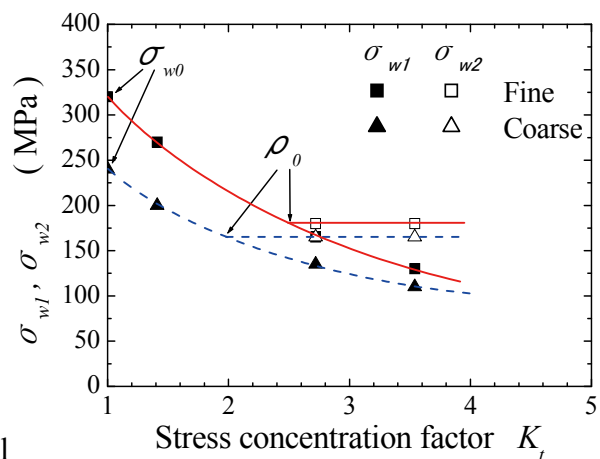Figure 14. Non-propagating cracks at fatigue limits (ρ=0.05mm)

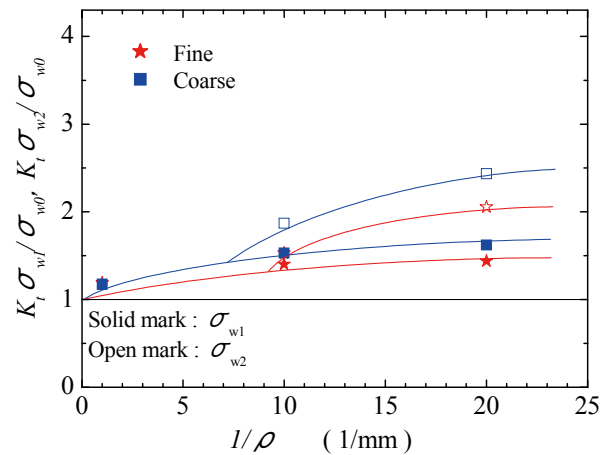Figure 15. Relation between fatigue limit and stress concentration factor

Figure 16. Relation between $K_t\sigma_{w1}/\sigma_{w0}$, $K_t\sigma_{w2}/\sigma_{w0}$ and $1/\rho$

4. Conclusions

The resistance to crack growth and the notch sensitivity for commercial carbon steels with grain sizes of about 6.5 and 20 μm were evaluated based on the small crack growth law considering the static strength and linear notch mechanics. Main results were summarized as follows:
(1) Most of fatigue life was occupied by the growth life of a crack smaller than 1-2 mm.
(2) Crack growth rate was determined by the term $\sigma_a{}^n\ell$, uniquely.
(3) The steel with a grain size of 6.5 μm showed an excellent crack growth resistance, though the one with 20 μm showed nearly the same as the one for many commercial carbon steels. This was caused by the barrier effect of grain boundary.
(4) Notch sensitivities are increased by refining grain size for both of crack initiation and its propagation.

REFERENCES
[1] H. Nakazawa, H. Kobayashi, A. Morita, S. Iikura, K. Miyauchi and Y. Ishii, Transaction of the Journal of Society of Mechanical Engineers, Japan, 40-329 (1974), pp. 9-22.
[2] M. Kage and H. Nisitani, Transaction of the Journal of Society of Mechanical Engineers, Japan, 51-461 (1985), pp. 3-9.
[3] H. Kimura, Y. Akiniwa, K. Tanaka, J. Kondo and T. Ishikawa, Journal of Society of Material Science, Japan, 51-7 (2002), pp. 795-800.
[4] H. Nisitani, Mechanics of Fatigue, ASME AMD (edited by T. Mura), 47(1981), pp.151-166.
[5] H. Nisitani and N. Kawagoishi, Transaction of the Journal of Society of Mechanical Engineers, Japan, 50-450 (1984), pp. 277-282.
[6] H. Nisitani, N. Kawagoishi and M. Goto, Handbook of fatigue crack propagation in metallic structure, Elsevier Science Ltd. (1994), pp.733-778.
[7] P. Neumann, Acta Metallurgica, 22(1974), pp.1155-1162.
[8] A. Sugeta, Y. Uematsu, T. Kumegawa and M. Jono, Journal of Society of Material Science, Japan, 54-7 (2005), pp. 754-760.
[9] H. Nisitani, Transaction of the Journal of Society of Mechanical Engineers, Japan, 48-447 (1983), pp. 1353-1359.