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Improvement of Fatigue Crack Propagation Property in Low Carbon Steel by Microstructural Control and an Investigation of its Practical Benefit

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The fatigue crack propagation properties of newly-developed SM490 grade steels were investigated in comparison with a conventional steel of the same grade. The fatigue crack propagation rate of the developed steel in Region II of the $da/dN-\Delta K$ relationship was suppressed to about 1/2 that of the conventional steel, and its ΔK_{th} value was more than twice as large as in the conventional steel. However, fatigue crack resistance for long crack propagation does not necessarily improve the fatigue life in a condition of increasing ΔK from a small defect, which is usually detected in practical fatigue damage in actual structures in service. The developed steels were subjected to surface crack propagation tests using specimens with artificial small defects to examine their potential under more practical conditions. The fatigue life of the developed steel was about three times longer than that of the conventional steel. A detailed analysis of the surface crack propagation revealed crack propagation below ΔK_{th} only in the developed steels, which suggested the so-called “short crack regime” in a fatigue crack. The crack propagation from a surface defect that deviated from long crack behavior was convincingly explained by the corrected threshold using the R-curve model of a short crack proposed in the previous literature. Based on the experimental fatigue life improvement and its analytical estimation of the propagation resistance in the short crack regime, the effect of the ΔK_{th} value for a long crack in the initial propagation stage just after fatigue crack initiation was discussed.

KEY WORDS: low carbon steel; fatigue crack propagation; crack closure; threshold stress intensity factor range; fatigue life; defect; short crack regime.

1. Introduction

Fatigue damage in welded steel structures, such as bridges and ships, which are subject to cyclic loading has been pointed out from an early date, and in some cases has become a serious social problem. It is difficult to completely prevent fatigue crack initiation because stress concentration is unavoidable under the current weld design and construction

conditions. Therefore, improvement of fatigue crack propagation life has been required in order to extend the fatigue life of welded structures. According to certain reported results, it is known that compressive residual stress, which is introduced by using a special weld consumable with a low transformation temperature¹⁾ and/or peening with various media,²⁻⁴⁾ is effective for reducing crack opening stress. While these techniques are effective for delaying local fatigue damage in the crack initiation and initial crack propagation stages, fatigue cracking in large-scale structures is occasionally detected

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only after propagating to a certain size through a weld and into the base material plate. Considering this situation, a combination of high resistance of the base plate steels and higher resistance against fatigue crack propagation, in addition to treatment near welds, such as improvement of the weld toe shape and/or introduction of compressive residual stress, could be effective for extending the service life of structures.

Fatigue damage is generally divided into the two stages of crack initiation and subsequent crack propagation. The former stage is strongly affected by the non-uniform resistance against crack propagation between the grain interior and grain boundary, and discontinuous crack behavior has been reported.⁵⁾ On the other hand, the latter crack propagation stage is dominated by the crack opening stress level, that is, mechanical factor control, and is uniquely evaluated as the relationship between the crack propagation rate da/dN and the stress intensity factor range ΔK . This da/dN - ΔK relationship can be divided into three regions: Centering on Region II, where steady crack propagation follows Paris' law, the lower ΔK side is Region I, which is the lower limit of crack propagation, and the higher ΔK side is Region III, where fast crack propagation occurs partially with a static fracture mode. The crack propagation in Regions I and II is little influenced by metallurgical factors, and differences in the crack propagation rate between materials have been understood as a secondary result reflecting different crack closure behaviors.⁶⁾

Several developments to induce the crack closure effect by microstructural control of steels have been reported.⁷⁻⁹⁾ Although all those efforts were intended to design a dual-phase microstructure which is expected to create a complicated crack path, various microstructures were targeted, including a ferrite/bainite microstructure,⁷⁾ ferrite/layered martensite microstructure⁸⁾ and ferrite/pearlite microstructure.⁹⁾ In all those developments, improvement of fatigue crack propagation properties was successfully achieved in Region II of the ΔK range from 15 to 30 MPa $m^{1/2}$.

To date, the authors have continued to search for the optimum microstructure with excellent resistance to fatigue crack propagation based on the microstructure control knowledge using online and off-line heat treatment processes. The fatigue damage which is often reported in actual structures occurs

under low stress amplitude and long fatigue life conditions. This means that the crack propagation life in Region I, where the propagation rate is slow, dominates the total fatigue life of the structure. Therefore, the authors focused not only on the properties in Region II, but also on the properties in the lower limit of crack propagation near the threshold ΔK_{th} . However, the crack propagation properties in Region I near a threshold such as the ΔK_{th} value are obtained experimentally from ΔK decreasing loading for a long crack, which is a different crack propagation history from ΔK increasing crack propagation after crack initiation. The relationship of the crack propagation properties near the threshold to the fatigue life in the initial propagation stage after crack initiation has not yet been clarified. It is well known that a short crack after crack initiation can propagate even at a ΔK value less than the threshold ΔK_{th} obtained for a long crack.¹¹⁾ Although the behavior of short cracks deviating from the propagation properties for a long crack has been studied as the “short crack issue,” this is mainly limited to phenomenological findings, and quantitative relationship between the short crack propagation rate and ΔK_{th} for a long crack is still not completely known.

In the present work, the fatigue crack behaviors of the newly-developed 490 MPa class steels, which are designed to improve resistance against fatigue crack propagation, were examined in comparison with a conventional steel. The developed steels were also subjected to fatigue crack propagation tests using specimens with an artificial small defect on the specimen surface to examine their potential under more practical conditions. The improvement of fatigue life of the developed steels in specimens with a small defect was investigated from the viewpoint of short crack behavior, and the relationship between the ΔK_{th} value for a long crack and the initial propagation life immediately after fatigue crack initiation was discussed.^{5,11)}

2. Materials and Procedures

The steel plates tested in the present work were three kinds of mill-produced steel plates with a thickness of 16 mm, whose chemical compositions and mechanical properties are listed in **Table 1**. All three plates satisfied the

Table 1. Chemical composition and mechanical properties of steels tested.

Sample ID	Chemical composition (mass%)						Yield stress, σ_{ys} (MPa)	Tensile strength, σ_B (MPa)	Elongation, El (%)
	C	Si	Mn	P	S	Others			
Steel A	0.12	0.34	1.31	0.008	0.001	—	378	501	41
Steel B	0.05	0.17	1.60	0.013	0.003	Cr, Nb, Ti	510	585	30
Steel C	0.16	0.27	1.16	0.014	0.002	—	385	546	58

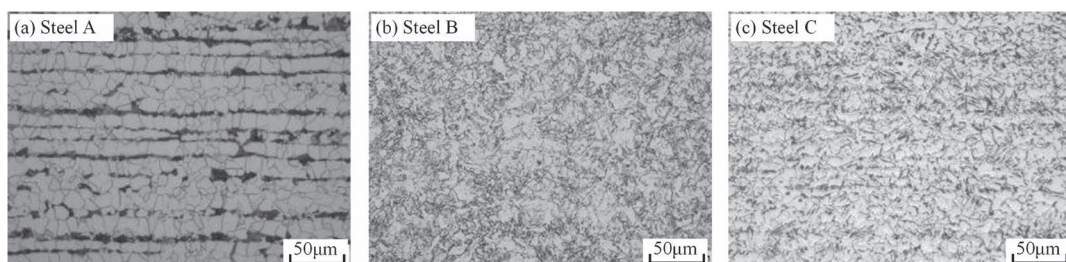


Fig. 1. Microstructures of steels tested.

SM490 grade as prescribed in Japanese Industrial Standards (JIS). **Figure 1** shows the microstructures on the cross section in the L-direction observed at a quarter thickness position with an optical microscope. Steel A is a conventional steel which was used as a basis for comparison and exhibits band-shaped pearlite on coarse ferrite microstructure, Steel B has a single-phase microstructure of mainly upper bainite, and Steel C displays a dual-phase microstructure of scattered fine pearlite in a ferrite matrix, which is intended to induce deflection of the crack path.

The fatigue crack propagation properties for a long crack were evaluated by two kinds of tests. One was a ΔK increasing test with a compact tension specimen (hereinafter, CT specimen), and the other was a ΔK decreasing test with a center crack tension specimen (hereinafter, CCT specimen).

For the ΔK increasing test, the CT specimen shown in **Fig. 2(a)** was machined out at the plate mid-thickness so that the loading direction would be along the L-direction. The specimen dimensions and test procedure were based on ASTM E647.¹²⁾ In the crack propagation test, a sinusoidal controlled cyclic load with a load ratio of 0.1 was applied with a frequency of 10 Hz at room temperature under the room atmosphere. A constant load amplitude was maintained during fatigue crack extension, which achieved a ΔK increasing test condition. The propagating crack length was estimated by the compliance change measured by a clip gauge mounted on the crack mouth. The measured crack length against the number of applied load cycles was approximated by a polynomial function for the selected neighboring three measurements before and after that number, and the crack propagation rate da/dN for the middle measurement of the seven was decided from the differential coefficient of the approximated function.¹³⁾ After the test, the specimens were ground to the mid-thickness and the crack path on the cross section was observed.

In order to evaluate the threshold properties for long fatigue crack propagation in the ΔK increasing test, a CCT specimen was used, as shown in **Fig. 2(b)**. Like the CT specimen, the CCT specimen was also machined out at the plate mid-thickness so that the loading direction was the L-direction. At both sides of the center machined notch,

seven strain gauges were mounted on the specimen surface on each side. The strain gauge mounted near the specimen edge was used to measure the unloading elastic compliance during crack propagation, and the crack extension was estimated from the compliance change based on a calibration curve obtained prior to the test. The other strain gauges were used to acquire the hysteresis loop of the crack tip deformation, and measurements by the gauge closest to the propagating crack tip were sequentially acquired. The crack closure load was identified from the measured hysteresis loop by the same procedure as previously reported.¹⁴⁾ This measurement procedure using the CCT specimen in **Fig. 2(b)** was established by one of the authors based on many investigations of crack closure behaviors.^{14–16)} In the crack propagation test, the sinusoidal controlled cyclic load with a load ratio of 0.1 was applied with a frequency of 10 Hz at room temperature under the room atmosphere. The load amplitude was selected so that the ΔK value at the test start was approximately 11 MPa $m^{1/2}$. The incremental ΔK decrease complied with ASTM E647. That is, the maximum load was incrementally reduced by 10% for every 0.5 mm of crack extension while maintaining the stress ratio of 0.1. The crack propagation rate da/dN was calculated by dividing the crack extension after a specified crack propagation by the number of load cycles. The incremental ΔK decrease was repeated until the measured crack propagation rate da/dN decreased to 10^{-11} m/cycle, and the final value was defined as ΔK_{th} .

In addition to the fatigue crack propagation test for the long crack, a surface crack propagation test was performed using a dumbbell-shaped specimen with a micro artificial defect, as shown in **Fig. 3(a)**, in order to reproduce short crack propagation. As with the other specimens, this specimen was also machined out at the plate mid-thickness so that the loading direction was the L-direction. At the center of the parallel part of the surface, a small artificial surface notch with the aimed size of 0.25 mm in depth and 0.5 mm in width was introduced by the picosecond laser technique. Figures 3(b-1), 3(b-2) and 3(b-3) show the appearance of the notch from the surface cross-section and photos of the fractured surface after the test, respectively. The notch shape on the surface shown in **Fig. 3(b-1)** has a blunt tip,

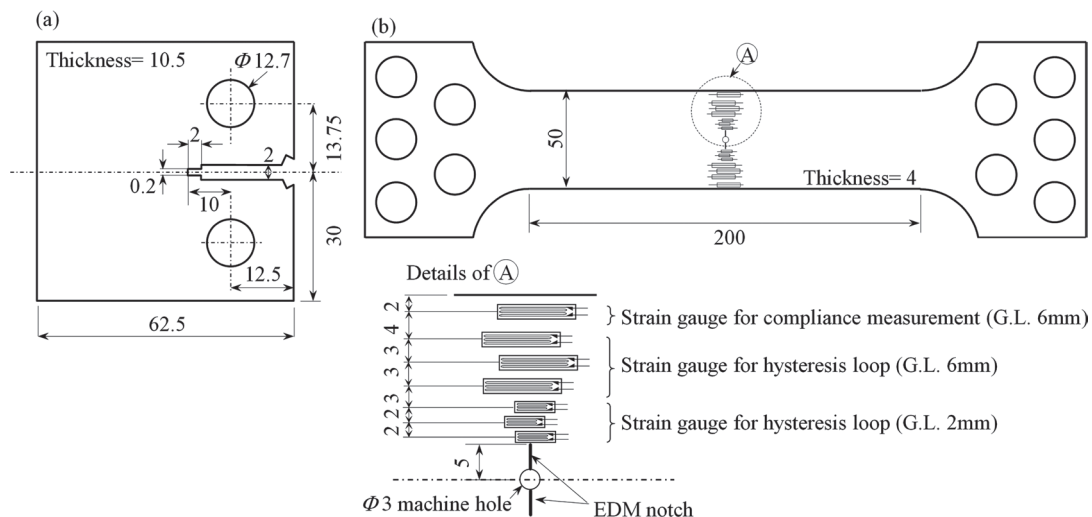


Fig. 2. Specimens used in crack propagation tests (unit: mm). (a) Compact tension (CT) type, (b) Center crack tension (CCT) type.

but the notch tip at the deepest position in Fig. 3(b-2) is quite sharp. The planar shape of the notch observed in Fig. 3(b-3) is approximately a rectangle of $0.25 \text{ mm} \times 0.5 \text{ mm}$, which was the target size, but the notch front in depth does not appear to be straight. In the crack propagation test, the sinusoidal controlled cyclic load with a load ratio of 0.1 was applied with a frequency of 6 Hz at room temperature under the room atmosphere. During the crack propagation test, the crack extension on the specimen surface was measured using crack gauges (KV-5C, Kyowa Co., Ltd.) in front of the artificial notch tips. Considering that fatigue cracks propagate from both tips of the notch, the crack gauges were mounted on both surface ligaments. Since the measuring limit of the crack gauge used here was short, at only 4 mm, two crack gauges were mounted side by side on each ligament to expand the measurable crack length range.

In addition of the surface crack propagation measurements described above, a beach mark test was also performed to examine the crack front shape of the propagating surface crack. The test procedure and conditions were the same as in the crack propagation tests, but a block cyclic load with the load ratio of 0.5 was applied for an appropriate number of cycles during the basic cyclic load with the load ratio of 0.1. This load ratio change was repeated seven times until

the specimen collapsed, and the aspect ratio of the semi-elliptical beach marks was measured on the fracture surface.

3. Results

3.1. Fatigue Crack Propagation Rate in Steels Tested

Figure 4 shows the relationship of the fatigue crack propagation rate da/dN in Region II to the stress intensity factor range ΔK for the three steels tested in the present work. Steels B and C similarly exhibit slower da/dN than Steel A, whereas there is no clear difference between Steel B and Steel C. The value of da/dN at ΔK of $15 \text{ MPa m}^{1/2}$ is about $1.1 \times 10^{-8} \text{ m/cycle}$, which is a similar crack propagation rate suppression to those of the developed steels previously reported in the literature.^{7,9)}

Figures 5(a), 5(b) and 5(c) show the da/dN - ΔK relationships in Region I obtained by the ΔK decreasing tests for each of the three steels. Each figure also includes the results for Region II shown in Fig. 4. Although different types of specimens were used for the ΔK increasing test and the ΔK decreasing test, on the notation scale in Fig. 5, the da/dN - ΔK relationship obtained in both tests appears to be generally continuous. The decided values of ΔK_{th} for each steel are also given in the figure. The fatigue crack propagation

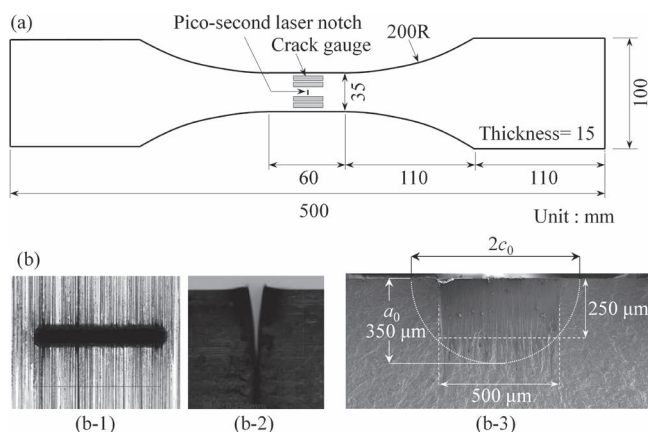


Fig. 3. Surface crack propagation specimen with pico-second laser notch and notch details. (a) Specimen with pico-second laser notch, (b) Pico-second laser notch details, (b-1) Surface appearance, (b-2) Center cross section, (b-3) Notch appearance on fracture surface.

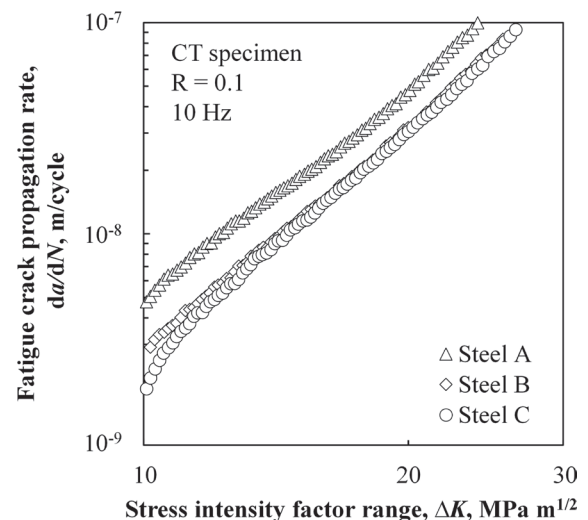


Fig. 4. da/dN - ΔK relations in region II of three steel plates obtained by ΔK increase test.

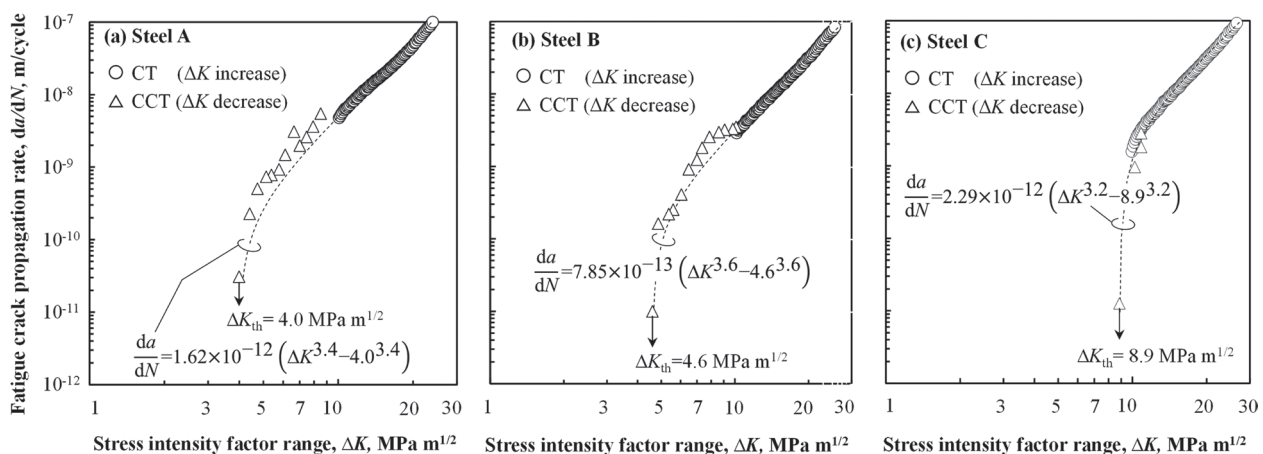


Fig. 5. da/dN - ΔK relations in region I of three steel plates obtained by ΔK decrease test overlapped on the relations in region II shown in Fig. 4 and regression curves by Paris's law.

resistance in Region II is similarly better in Steels B and C than that in Steel A, as shown in Fig. 4, whereas the ΔK_{th} value of Steel B is rather close to that of Steel A. That is, the resistance to crack propagation in Region II is not necessarily consistent with the resistance in Region I. On the other hand, the ΔK_{th} value of Steel C is about twice as large as that of Steels A and B. Steel C has a better crack propagation property not only in Region II but also in Region I.

Each figure in Fig. 5 includes the regression curve and formula which was approximated for both the results obtained by the ΔK increasing test and those obtained by the ΔK decreasing test. In the present work, the following type of equation was adopted in the approximation to express the crack propagation rate in Region I in addition to Region II.

$$da/dN = C(\Delta K^m - \Delta K_{th}^m) \dots\dots\dots (1)$$

where, C and m are material constants.

3.2. Results of Surface Crack Propagation Test

The surface crack propagation results against the number of applied load cycles are shown by the plots in Fig. 6. These results were obtained in the surface crack propagation tests using the specimens with a picosecond laser notch. The vertical axis of Fig. 6 is the half length of the surface crack length $2c$ measured by two crack gauges on the two sides of the small initial notch. The fatigue life of the three steels was in the range from 0.5×10^6 to 1.5×10^6 cycles. Since the purpose of this test was to compare the fatigue lives of the three test plates in the high cycle fatigue range, the selected stress condition appears to be appropriate. When

the fatigue lives are compared, Steel A shows the shortest life, Steel B shows a longer life approximately twice that of Steel A, and Steel C achieves the longest life of approximately three times that of Steel A. From the viewpoint of the order of superiority among the three test plates in fatigue crack propagation resistance, the fatigue lives shown in Fig. 6 are not consistent with the fatigue crack propagation behavior in Region II shown in Fig. 4, nor with the property in Region I, such as the value of ΔK_{th} .

Figure 7 shows the fracture surfaces of the dumbbell-shaped specimens with a picosecond laser notch after the crack propagation tests. These fracture surfaces were subjected to the same loading conditions as in the crack growth test in Fig. 6, but a block load with a suitably high stress ratio was applied and beach marks were intentionally formed on the fracture surfaces. Concentric beach marks originating from the picosecond laser notch are observed. The figure also shows the values of the aspect ratio a/c measured based on the clearly observed beach marks. As shown in Fig. 3(b-3), although the notch was a picosecond laser notch with a rectangular planar shape, the fatigue crack developed as a surface crack with a nearly semicircular shape.

4. Discussion

4.1. Characteristics and Factors of Fatigue Crack Growth Rate of Steels Tested

It is known that steel sheets produced by the thermo-mechanical controlled process (TMCP) can produce com-

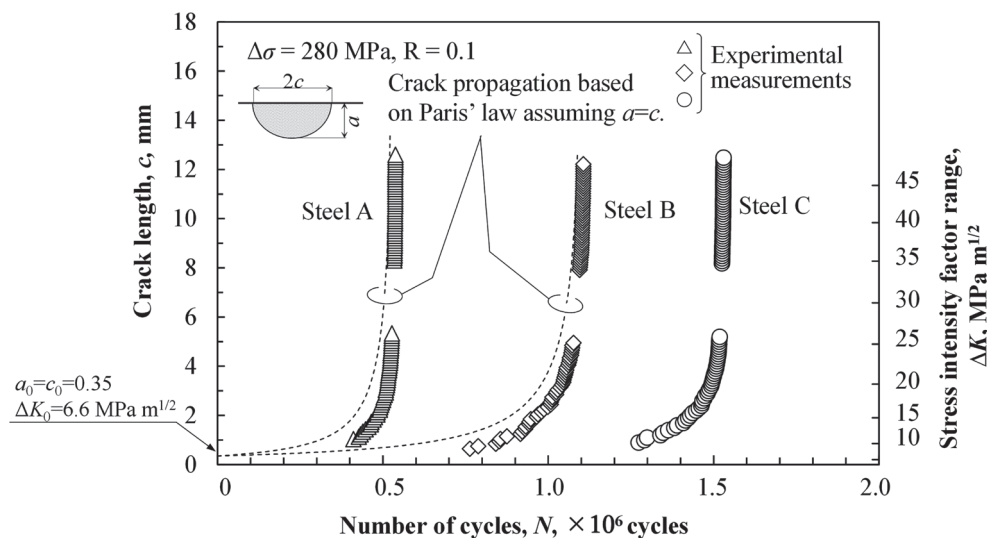


Fig. 6. Experimental c - N relationships in surface crack propagation test with pico-second laser notched specimen.

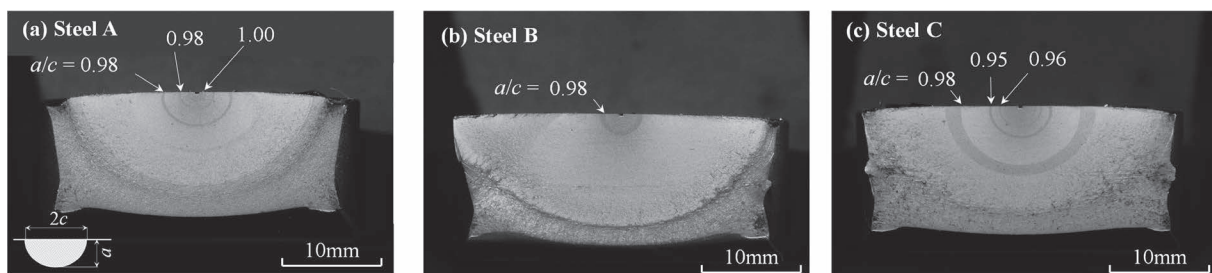


Fig. 7. Fracture appearances with beach marks in pico-second laser notch specimens after crack propagation test.

pressive residual stress in the surface and anisotropy in properties.¹⁷⁾ Since the specimens used in this study were taken from the center of the steel plate thickness, even if compressive residual stress existed on the steel plate surface, it could not affect the fatigue test results. Therefore, it can be judged that the excellent fatigue crack growth characteristics of Steel C shown in Figs. 4 to 6 are attributable to its microstructure. On the other hand, the fatigue crack propagation characteristics shown in Figs. 4 and 5 are the result for a through-thickness crack propagating in the thickness direction, and the characteristic anisotropy of fatigue crack propagation is unknown, especially in the thickness direction. However, the results in Fig. 7, in which the surface crack propagation test was reproduced by using specimens with an artificial defect, suggested that the surface crack propagation maintained its nearly semicircular shape. It is well known that the stress intensity factor K is different in the deepest region and at the surface in the case of a semi-elliptical crack; *i.e.*, the K value is higher at the surface when $a/c > 1$, and conversely, the K value is higher in the deepest region when $a/c < 1$.¹⁸⁾ When there is no anisotropy in the fatigue crack growth characteristics, the shape of the surface crack converges to a semicircular shape with growth. Based on these considerations, it can be analogized that the fatigue crack growth characteristics of the three specimens evaluated here were not so strongly anisotropic as to change the shape of the surface crack, and that the fatigue crack growth characteristics shown in Figs. 4 and 5 were roughly equivalent to those in the plate thickness direction.

As mentioned in the Introduction, it is generally thought that metallurgical factors have little intrinsic influence on fatigue crack growth characteristics, and the characteristic differences among materials reflect the differences in crack closure behavior. In this study, the crack closure load during fatigue crack propagation was also measured by the unloading elastic compliance method. **Figure 8** shows the crack opening ratio U , which means the ratio of the effective stress intensity factor range ΔK_{eff} to the stress intensity factor range ΔK against applied ΔK . Both the results of the ΔK increasing test using the CT specimens and the ΔK decreasing test using the CCT specimens are arranged in terms of the value of ΔK at the time the crack closure load level was measured. With regard to Steel B, the level of crack closure

load in the ΔK decreasing test was not measured and will therefore be omitted from the following discussion. Figure 8 shows that a small crack opening ratio is obtained for both Steel A and Steel C when the value of ΔK is small. However, both Steel A and Steel C are not assumed to be continuous with the results of the ΔK increasing test when the results of the ΔK decreasing test are extrapolated. This seems to be due to the difference in the shape of the crack opening behind the crack tip caused by the use of a different type of load from that of the CT specimen in the ΔK increasing test and the CCT specimen in the ΔK decreasing test. The reason why the continuity of the results between the ΔK increasing test and the ΔK decreasing test appears different in Fig. 8 from that in Fig. 5 is a factor of the notation in Fig. 5 using a double logarithmic axis. Although the aperture ratio of Steel C is generally smaller than that of Steel A, the differences between the materials are significant in the low ΔK range obtained in the ΔK tapering test, such that at $\Delta K = 9 \text{ MPa m}^{1/2}$, that is, the aperture ratio of Steel C is less than half that of Steel A. It is considered that this strong suppression of the crack opening driving force in Steel C resulted in the low da/dN and high ΔK_{th} values in Region I, which appeared in the results for Steel C shown in Fig. 5.

Although several causes of crack closure behavior have been pointed out in the past,¹⁹⁾ it is unlikely that the difference in the opening ratio between Steel A and Steel C shown in Fig. 8 was caused by a difference in plastically-induced crack closure because the σ_{ys} of Steel A and Steel C shown in Table 1 are generally equal and the size of the plastic zone of the crack tip is assumed to be similar under equal K values. **Figure 9** shows the results of observation of the mid-section thickness of the CT specimen after the tests of Steel A and Steel C, where the path of crack growth is traced with white lines. In both Steel A and Steel C, the fatigue cracks mainly developed in the ferrite phase, whereas in Steel A, the cracks propagated linearly, and in Steel C, propagation displayed many branches and bends, and the branched cracks were long. In addition to reducing the K_I component that opens the tip, crack branching and bending also induce fracture surface roughness-induced crack closure.^{20,21)} Although this is not a qualitative analogy, the low opening ratio of Steel C shown in Fig. 8 suggests that the main cause was fracture surface roughness-induced crack closure by tissue control.

Figure 10 shows the data collected from the previous

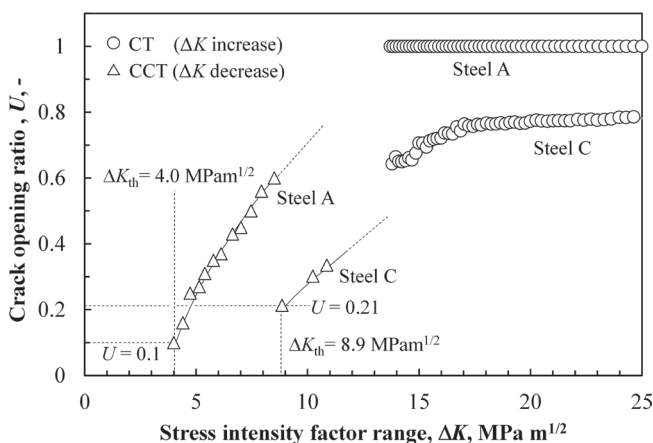


Fig. 8. Variation of crack opening ratio $U (= \Delta K_{\text{eff}}/\Delta K)$ against apparent ΔK .

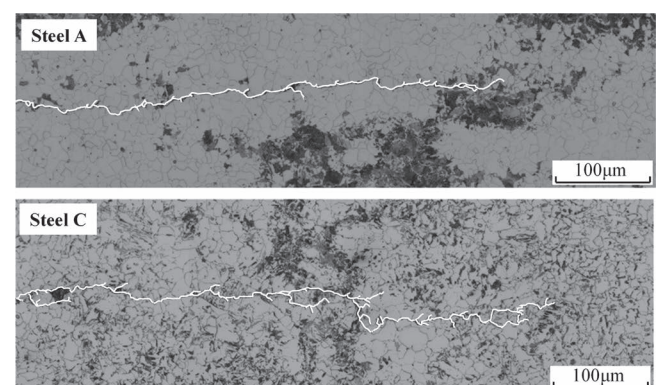


Fig. 9. Fatigue crack propagation path of steel A and C near $\Delta K = 25 \text{ MPa m}^{1/2}$.

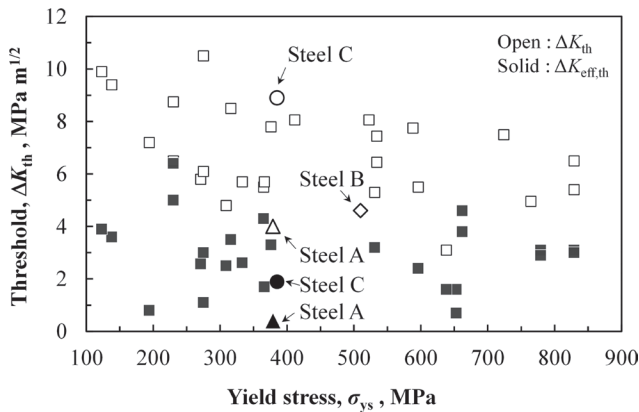


Fig. 10. Distribution of ΔK_{th} and $\Delta K_{eff,th}$ in literatures.

literature^{7,10,22–30)} and their effective values, $\Delta K_{eff,th}$, arranged against the σ_{ys} of the materials. Among the test results evaluated with the CT or CCT specimens in the stress ratio range of $R = 0$ to 0.1 , only those judged to be retained at $da/dN = 10^{-10}$ to 10^{-11} m/cycle are shown. Figure 10 also shows the ΔK_{th} of this material and the $\Delta K_{eff,th}$ calculated from U at the time of crack arrest. Although the variation is large, according to Fig. 10, there is a trend toward a gradual decrease in ΔK_{th} in response to the increase in σ_{ys} , which is consistent with previous reports.^{31,32)} On the other hand, σ_{ys} dependence is less pronounced in $\Delta K_{eff,th}$ than in ΔK_{th} . Because of the wide variation, it is also impossible to make a general judgment, but it is understandable that σ_{ys} dependence becomes weaker if the value of $\Delta K_{eff,th}$ is interpreted as a material specific value that does not include crack closure.³²⁾ Figure 8 showed that ΔK_{th} is σ_{ys} dependent with a considerable range, in which the values of the ΔK_{th} of Steel A and Steel B are at the lower end of the variability, while the ΔK_{th} of Steel C is at the higher end of the variability. On the other hand, the value of $\Delta K_{eff,th}$ for Steel A and Steel C is at the low end of the variation in the values reported in the past. However, since the value of $\Delta K_{eff,th}$ strongly depends on the method of measuring the crack closure load level, it is not possible to judge the position of this specimen from these results alone.

4.2. Relationship between Long and Short Crack Growth Characteristics

According to the results of the crack propagation tests for the specimens with artificial defects shown in Fig. 6, while most of the fracture life is occupied by the initial crack propagation life in the range of $\Delta K < 15$ MPa m^{1/2}, a relatively small proportion is occupied by the crack propagation life in the range of $\Delta K = 15$ to 30 MPa m^{1/2}, which has been a focus of attempts to improve the fatigue crack propagation characteristics. Although the balance of these types of crack propagation in fracture life cannot be judged uniformly because it also depends on the degree of stress concentration in the target structure, considering the fact that fatigue cracks often initiate from latent defects in real structures, the crack propagation characteristics in the low ΔK region, i.e., the Region I, can be dominant in fatigue life in real problems.

A crack propagation analysis was performed for the results of surface crack propagation tests using specimens with artificial defects as plotted in Fig. 6 using the crack

propagation characteristics obtained for long cracks, as shown in Fig. 5. Although the initial shape dimensions of the artificial defect were rectangular, as shown in Fig. 3(b-3), a semicircular surface crack ($a_0 = c_0 = 350$ μm) with a radius of 350 μm containing the rectangular defect was assumed here. In the crack growth analysis, the value of ΔK calculated from the applied stress variation and the crack size was substituted into the Paris law for each specimen determined by the experimental results in Fig. 5 on the basis of Raju-Newman's equation,³³⁾ and the obtained crack growth rate da/dN was used to integrate the crack propagation for 2 000 cycle increments. The results of the surface crack propagation analysis calculated based on the long crack propagation characteristics are shown in Fig. 6 by the dashed lines. The initial value of ΔK assuming a semicircular shaped initial crack with a radius of 350 μm was 6.6 MPa m^{1/2}, which was analyzable for Steel A and Steel B, but not for Steel C because the initial value of ΔK_0 was less than the value of ΔK_{th} . In Steel A and Steel B, where crack growth analysis was possible, the crack growth prediction based on the Paris law is generally consistent with the experimental results, such as the stress cycle level at which crack growth rapidly accelerates. Although the analysis was based on several assumptions, such as the assumption that the artificial defect has no crack initiation life and the assumption that it is a semicircular crack containing an indistinct rectangular defect of the deepest shape, the results of the analysis generally agree with the experimental measurement results. Therefore, the assumptions made here are considered to be valid.

On the other hand, in the Steel C specimen with an artificial defect, although the initial value of the loaded ΔK , i.e., ΔK_0 , was smaller than the value of ΔK_{th} , the specimen actually cracked and fractured. The propagation behavior of a short crack diverges from that of a long crack, and the phenomenon that a short crack propagates even at ΔK below the lower limit of crack propagation for a long crack has long been known as the microcrack problem.⁵⁾ Chapetti *et al.* developed an R curve model (hereinafter referred to as the MDC model), as shown schematically in Fig. 11, from Kitagawa's idea on the lower limit of microcrack growth¹¹⁾ and formulated the microcrack growth resistance.^{34,35)} In the MDC model, only the material specific crack growth resistance, ΔK_{dR} , acts on the crack corresponding to the grain size immediately after the crack is generated, but the crack growth resistance increases with crack progress and is considered to be asymptotic to the value of ΔK_{th} for long cracks. The following equation was proposed for the microcrack growth resistance, ΔK_{dR} , as a function of the crack length, a .

$$\begin{aligned} \Delta K_{thR}(a) &= \Delta K_{dR} + \Delta K_{ExR}(a) \\ &= \Delta K_{dR} + (\Delta K_{th} - \Delta K_{dR})\{1 - e^{k(a-d)}\} \quad \dots\dots (2) \end{aligned}$$

where, k is given by

$$k = \frac{1}{4d} \frac{\Delta K_{dR}}{\Delta K_{th} - \Delta K_{dR}}$$

and d is the grain size and ΔK_{ExR} is the incremental term of growth resistance with crack growth.

The following discusses the possibility of predicting the crack propagation from the artificial defect of Steel C shown

in Fig. 6 by using the lower limit of microcrack propagation, ΔK_{ExR} , based on the MDC model, for ΔK_{th} of the Paris law determined in Fig. 5. In the MDC model, the first barrier that Stage I cracks meet is the internal grain boundary, where the stress intensity factor range, ΔK , calculated by the fatigue limit, $\Delta \sigma_w$, and the grain size, d , which are controlled by crack arrest, is considered to be ΔK_{dR} . In this study, the stationary crack size corresponding to the fatigue limit and the fatigue limit of a smooth specimen of the test material were not measured. Therefore, the value of $\Delta K_{\text{eff, th}}$, which is analogized from Fig. 8, was used as the value of ΔK_{dR} . Although the crack length of interest is very different from that of ΔK_{dR} , it seems to be a logical assumption to use the value of $\Delta K_{\text{eff, th}}$, which has a similar physical meaning, considering the physical meaning that ΔK_{dR} is crack propagation resistance without the effect of the crack wake, in other words, the crack closure effect. Although the grain size d is required in order to calculate ΔK_{dR} by Eq. (2), since the MCD model preferentially considers the grain size to be a potential fatigue crack initiation point, the grain sizes used here were $24 \mu\text{m}$ for Steel A and $22 \mu\text{m}$ for Steel C, as the grain sizes with a cumulative frequency of 98% in the calculation of ΔK_{thR} based on the structural observation photograph in Fig. 1. These constants for Steel A and Steel C are applied to Eq. (2), and the obtained ΔK_{thR} is shown in Fig. 12. The dashed

lines also show the change in the value of ΔK when the initial crack is a semicircular crack with a radius of $350 \mu\text{m}$ and the test stress fluctuation width is the same as in the experiment, i.e., $\Delta \sigma = 280 \text{ MPa}$. According to the estimation results in Fig. 12, the ΔK value of $6.6 \text{ MPa m}^{1/2}$ for the initial defect lies just above the change curve of the ΔK_{thR} of Steel C, indicating that the crack can propagate even in Steel C.

Therefore, the same crack propagation analysis as at the beginning of this section was carried out by substituting the function of the crack length a of Steel A and Steel C, ΔK_{thR} shown in Fig. 12, into the ΔK_{th} of both materials shown in Fig. 5. The results are shown as dashed lines in Fig. 13. Compared with the results of the crack growth analysis of Steel A shown in Figs. 13 and 6, the analytical result of Fig. 13 considering the R curve behavior in the microcrack growth area predicts a slightly shorter life, but there is no significant difference between the two, and the experimental results are generally described in both cases. On the other hand, as mentioned above, an analysis of the crack evolution from the assumed initial crack was not possible for Steel C from the long crack growth characteristics, but considering the propagation resistance change in the microcrack region, the results can roughly describe the crack growth from the artificial defect of Steel C, as shown in Fig. 13. This suggests that the propagation characteristics of the long crack

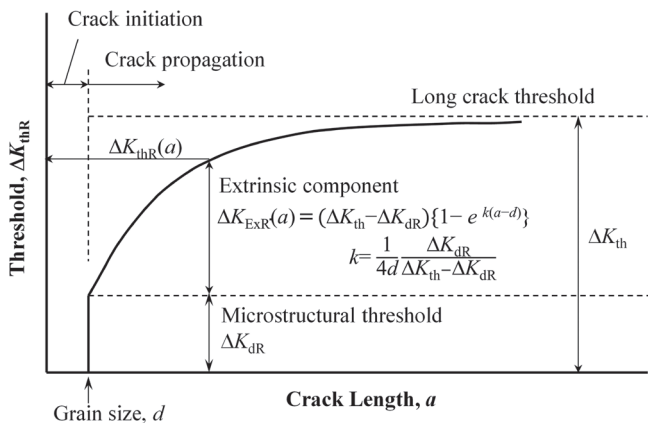


Fig. 11. Defined fatigue crack propagation threshold as a function of crack length in small crack regime.³⁴⁾

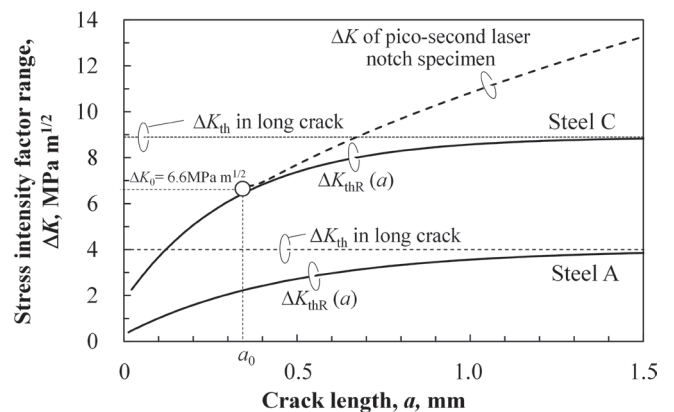


Fig. 12. Comparison of fatigue crack propagation threshold and ΔK of pico-second laser specimen.

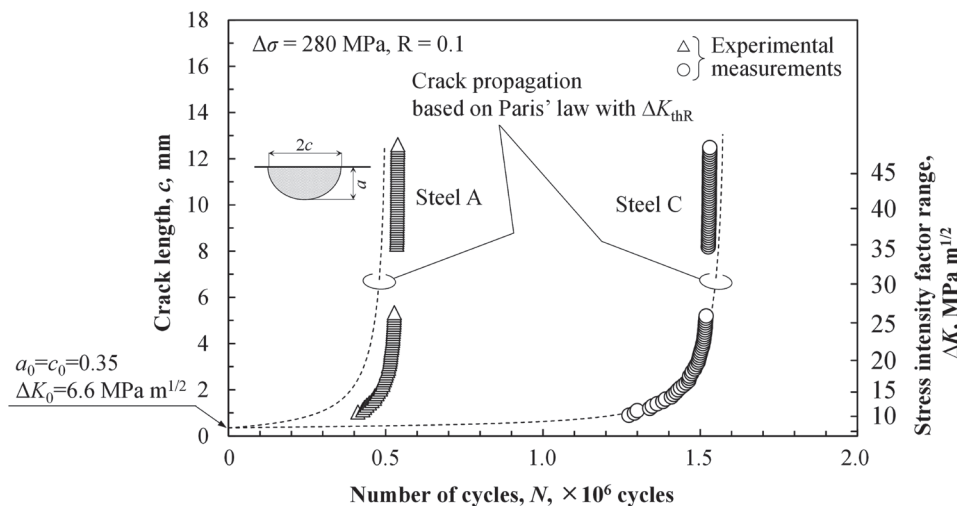


Fig. 13. Crack propagation based on Paris' law with fatigue crack propagation threshold as a function of crack length.

in Steel A and the short crack in Steel C became dominant even for the same assumed initial crack.

In the MDC model shown in Fig. 11, the grain boundary is considered to be a barrier against the propagation of fatigue cracks initiated on the material surface, and the increase in crack progress resistance with the progress of cracks is modeled. However, the specimens Steel A and Steel C, which were the objects of the MDC model in Fig. 13, have a multiphase structure, so it is expected that the barrier effect of the grain boundaries assumed in the model is actually heterogeneous. That is, the MDC model cannot take microstructural heterogeneity into account. In addition, considering the fact that the MDC model makes several assumptions, the results in Figs. 12 and 13 should be regarded as one estimation. Nevertheless, the fact that the MDC model was able to roughly explain the crack growth behavior of Steel C from an artificial defect, which could not be explained by the lower limit characteristics of long crack growth, suggests that the effect of the multiphase structure is not large, which is an important finding in linking the crack growth characteristics of long cracks with those of short cracks. That is to say, this study has verified experimentally and theoretically that Steel C, in which tissue control was attempted with the aim of improving the lower limit characteristics of the growth of long cracks, especially ΔK_{th} , had the effect of increasing crack growth resistance not only in the characteristics of long cracks but also in the initial growth process of fatigue cracks that initiate on the surface, and thereby had the effect of greatly improving the growth life of short cracks.

5. Conclusion

In this study, we investigated the fatigue crack propagation characteristics of steel plates (SM 490 compatible) developed with the aim of improving fatigue crack growth characteristics. Furthermore, the relationship between the initial propagation life of fatigue cracks generated from artificial defects and the propagation characteristics of long cracks was examined from the viewpoint of microcracks, and the following findings were obtained.

(1) The fatigue crack growth rate in Region II of the developed steel was suppressed to about 1/2 that of the conventional steel and showed a crack growth suppression effect comparable to that of the fatigue resistant steel reported in the previous literature. The properties of the crack growth lower limit, especially the value of ΔK_{th} , which was the aim of the development, were more than twice as large in the developed steel as in the conventional steel.

(2) The fatigue life of the developed steel was extended to about three times that of the conventional steel in surface crack propagation tests using specimens with a micro artificial defect.

(3) The surface cracks arising from microdefects were areas of microcracks that occurred in the developed steels at a ΔK_{th} below the lower limit for the development of long cracks. The experimental results of the surface crack growth in the developed steels were convincingly explained by correcting the microcrack growth resistance using the R curve model of microcracks proposed in the previous literature.

(4) From the results described in (3) above, it can be verified that the lower limit characteristics of long crack

growth, especially ΔK_{th} , have the effect of increasing the crack growth resistance even in the initial growth process of fatigue cracks that initiate on the surface, and have the effect of greatly improving the growth life of short cracks.

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