AN ESTIMATION METHOD OF FATIGUE CRACK PROPAGATION RATE UNDER VARYING LOADING CONDITIONS OF LOW STRESS INTENSITY LEVEL

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ABSTRACT

Fatigue crack propagation tests were carried out on a carbon steel, JIS S35C, and an aluminum alloy, JIS A5083-O, using repeated two- and three-step loadings which were composed of above and below the threshold condition, and crack propagation rates and crack closure behavior were investigated.

By means of electron fractography, striations corresponding to the block loadings of high and low levels were found on the fractured surface, which confirmed that crack propagation occured even below the threshold level under varying loading conditions. And it was found that the crack propagation rate could be estimated by the modified Miner's rule of crack propagation based on the effective stress intensity range, ΔK_{eff}, which was measured by the unloading elastic compliance method. On the other hand, the crack opening point, K_{op}, under repeated two- or three-step loadings was found to be constant and nearly equal to that of high level loading obtained by the constant amplitude test. An estimation method of fatigue crack propagation rate under varying loading conditions from the constant amplitude test was proposed by combination of above mentioned testing results.

KEYWORDS

Fatigue crack propagation; repeated two-step test; repeated three-step test; crack closure; threshold condition; effective stress intensity factor.

INTRODUCTION

Since Elber's suggestion (Elber, 1971) crack closure phenomenon is well known to play an important role for fatigue crack propagation, retardation and arrest (Wheeler, 1972; von Euw, Hertzberg and Roberts, 1972; Schijve, 1976). The authors have proposed a technique, called as "unloading elastic compliance method", to detect the crack opening point and propagated crack length at the interior of the specimen by using a strain gage (Kikukawa, Jono and Tanaka, 1976). And by using this method it was found that the fatigue crack propagation rates plotted against the effective stress intensity range, ΔK_{eff}, fell within a fairly narrow band on many kinds of steels and another narrow band on aluminum alloys irrespective of the stress ratio, R, in the region above propagation rate of 10^{-5} mm/cycle. On the other hand, in the region below 10^{-5} mm/cycle crack propagation and closure behavior were found to be different depending on materials even on the plot to ΔK_{eff}, and the threshold conditions existed to ΔK_{eff} for most steels investigated. Under varying loading conditions, however, it was pointed out that the fatigue crack could propagate under the stress below fatigue limit (Koterazawa and Shimo, 1976) and also below the threshold condition (Kikukawa and others, 1977). In this study, therefore, fatigue crack propagation behaviors under varying loading conditions of relatively low stress intensity level were investigated and an estimation method of fatigue crack propagation rate under varying loading conditions was proposed by considering crack closure phenomena.

EXPERIMENTAL PROCEDURE

The materials used are a normalized 0.38 % carbon steel, JIS S35C (880°C × 1.2 hr, cooled in air), and an aluminum alloy, JIS A5083-O. Chemical composition and mechanical properties of them are listed in Tables 1 and 2.

Fatigue crack propagation tests of R = 0 under repeated two- and three-step loadings as well as constant amplitude loadings were carried out on a SEN specimen with an electro-magnetic type in-plane bending testing machine at frequency of 40 Hz. The configuration of the specimen is shown in Fig. 1. Side grooves of proper shape were put on the specimen in order to make crack front so straight that the difference of crack propagation and opening behavior between the specimen surface and the interior were negligible (Kikukawa and others, 1980). Although crack length and crack opening point were measured by the unloading elastic compliance method, in order to detect the crack opening point of each cycle separately, a mini-computer, MELCOM 70/25 (64 kW) was used for measurement.

Figure 2 shows the patterns of test loadings. K_H, K_M and K_L are stress intensity factor of high, medium and low level loading, respectively, and number of cycles in one block are represented by N_H, N_M and N_L for high, medium and low level loading, respectively. Unit of K, if omitted in the figure, is MPa·$\sqrt{m}$, hereafter.

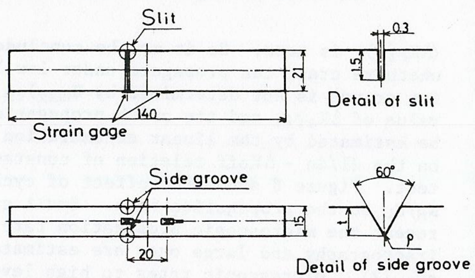
TABLE 1 Chemical Composition of Materials Investigated (%)

Material	C	Mn	Si	P	S	Cu	Ni	Cr
S35C	0.38	0.72	0.25	0.010	0.015	0.04	0.02	0.13

Material	Mg	Mn	Si	Ti	Fe	Cr
A5083-O	4.46	0.63	0.18	0.017	0.19	0.12

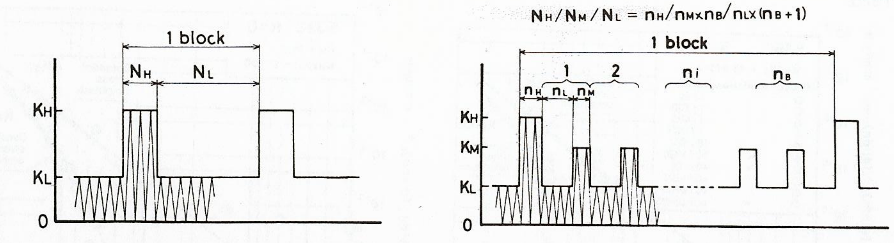
TABLE 2 Mechanical Properties of Materials Investigated

Material	Yield point (0.2 % proof stress) MPa	Tensile strength MPa	Elongation %	Reduction of area φ %	Fracture ductility ε_f %
S35C	372	612	23.7	58.5	88.0
A5083-O	131	301	23.5	42.1	54.7



	t (mm)	ρ (mm)
A5083-O	1.5	0.1
S35C	0.7	1.0

Fig. 1. Configuration of test specimen.



(a) repeated two-step loading (b) repeated three-step loading

Fig. 2. Pattern of test loadings.

TEST RESULTS

Crack Propagation Rate Under Constant Amplitude Test

As a reference, crack propagation rates under constant amplitude loadings were examined by a K-decreasing method. Decreasing rates of K were chosen as dK/dl = -3 and -1 MPa·$\sqrt{m}$/mm for S35C and A5083-O, respectively. The results are shown against both K_{max} and ΔK_{eff} by small solid circles in Figs. 5 and 7. The threshold conditions in terms of K_{max} were 9.6 and 4.3 MPa·$\sqrt{m}$ for S35C and A5083-O, respectively. The one in terms of ΔK_{eff}, $\Delta K_{eff})_{th}$, existed for S35C and was found to be 3.6 MPa·$\sqrt{m}$. However, it was found almost zero for A5083-O.

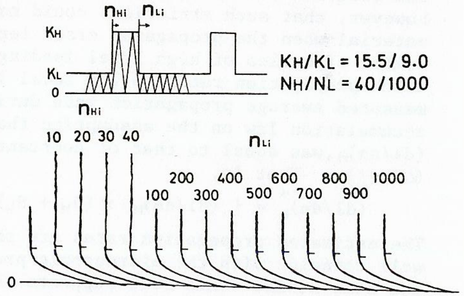


Fig. 3. Load-displacement curves measured by mini-computer.

Crack Propagation Rate Under Repeated Two- and Three- Step Tests

Firstly repeated two-step tests were carried out on S35C on the condition that the load level of K_H/K_L was hold to be 15.5 MPa·$\sqrt{m}$/ 9.0 MPa·$\sqrt{m}$, which were above and below the threshold condition, and the cycle ratios of N_H/N_L were changed widely. Figure 3 shows an example of automatically measured load-displacement hysteresis in the unloading elastic compliance method during one block loading of repeated two-step test where short horizontal bars represent the crack opening points. As can be seen in the figure, crack opening points are almost constant during loading cycles. So the crack opening point $(K_{op})_H$ and $(K_{op})_L$ for high and low level loading, respectively, were defined as average of the crack opening point for each loading level, and ΔK_{eff} was calucurated by the following equations.

$$\left.\begin{aligned}(\Delta K_{eff})_H &= K_H - (K_{op})_H \\ (\Delta K_{eff})_L &= K_L - (K_{op})_L\end{aligned}\right\} \quad (1)$$

On the other hand, by means of electron fractography striations corresponding to high and low level loadings were often found on the fractured surface as shown an

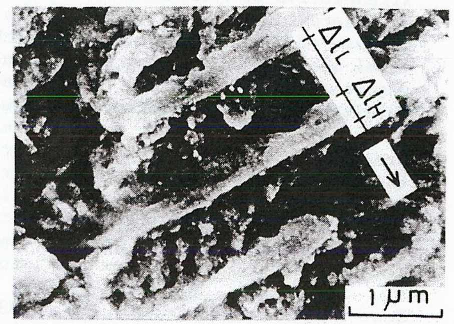


Fig. 4. Fractograph under repeated two-step test on S35C. (Δl_H and Δl_L correspond to propagated length under K_H and K_L of one block loading, respectively. K_H/K_L =15.5/9.0, N_H/N_L=40/1000)

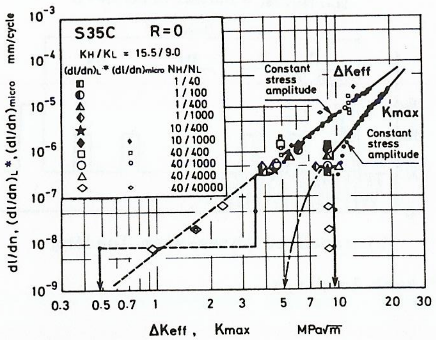


Fig. 5. K_{max}, ΔK_{eff} - dl/dn relation for repeated two-step test on S35C.

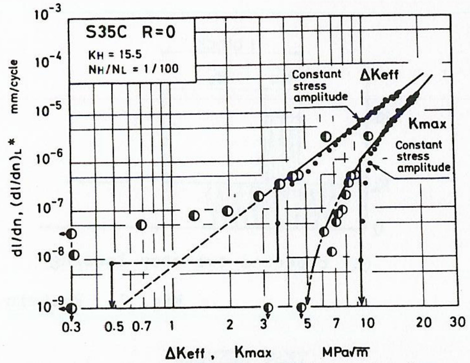


Fig. 6. K_{max}, ΔK_{eff} - dl/dn relation for repeated two-step test on S35C.

example in Fig. 4 which confirmed that crack propagation occured even below the threshold level under varying loading conditions. And microscopic propagation rates calculated by the striation spacing, $(dl/dn)_{micro}$, were plotted against ΔK_{eff} in Fig. 5 by small symbols. Thus obtained rates were found to give good agreement with the relation between dl/dn and ΔK_{eff} for the constant amplitude test. It was found, however, that such striations could not always be observed on the surface with this material when the propagated crack length in one block loading was small or the number of cycles of high level loading were very small. In that case, therefore, crack propagation rates to low level loading, $(dl/dn)_L^*$, were estimated from the measured average propagation rate during two-step loading, $(dl/dn)_{HL}$, by linear accumulation law on the assumption that the propagation rate to high level loading, $(dl/dn)_H$, was equal to that of constant amplitude test at the same level of K_H or $(\Delta K_{eff})_H$. That is,

$$(dl/dn)_L^* = [\ (dl/dn)_{HL} \times (N_H + N_L) - (dl/dn)_H \times N_H\ ]\ /\ N_L \qquad (2)$$

The estimated propagation rates are shown in Fig. 5 by large symbols, and found to well coincide with the microscopic propagation rates shown by the small symbols of the same kinds. This fact supports the assumption of eq. (2). Although crack propagation rates to K_{max} show a fairly large scatter depending on the cycle ratios of N_H/N_L, those to ΔK_{eff} show good agreement with the constant amplitude test result irrespective of cycle ratios, and the decrease of propagation rates as increase of N_L (represented by symbols of ◇) can be explained by the decrease of ΔK_{eff}, probably because of dynamic strain aging which occured during large number of cycles of low level loading. Furthermore, it should be noticed that the fatigue crack could propagate at the effective stress intensity level even below $\Delta K_{eff})_{th}$ under varying loading conditions. Thus the fatigue crack propagation rates under varying loading conditions are necessary to be estimated by the modified Miner's rule of crack propagation based on the effective stress intensity range, ΔK_{eff}.
Figure 6 shows the results of repeated two-step tests on the same material where K_L were stepwisely changed on the condition that K_H and cycle ratio were hold constant. It was confirmed that crack propagation occured below the threshold condition as to K_{max}, but the rate of it could be approximately estimated by the modified Miner's rule based on ΔK_{eff} in this case, too.

Test results on aluminum alloy, A5083-O, are shown in Figs. 7 to 11. In Fig. 7 the effect of K_H level on propagation rate under low level loading was examined. Concerning the crack propagation rate to K_{max}, ◆ and ▼ show the finite propagation rates whereas propagation rates are zero for ■ and ▲ at the same values of K_L. However, if they are plotted against ΔK_{eff}, finite values are found for the test condition of (⬬ ▼ ◆ ●) where $(\Delta K_{eff})_L$ exist and zero for the condition of (▲ ■) where

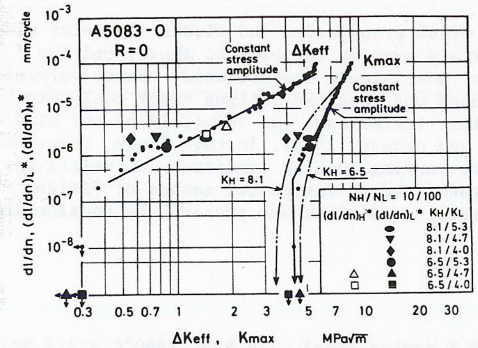


Fig. 7. K_{max}, ΔK_{eff} - dl/dn relation for repeated two-step test on A5083-O.

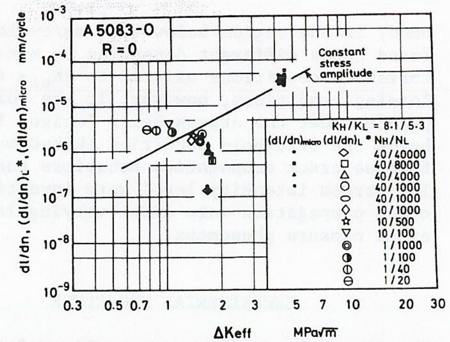


Fig. 8. ΔK_{eff} - dl/dn relation for repeated two-step test on A5083-O.

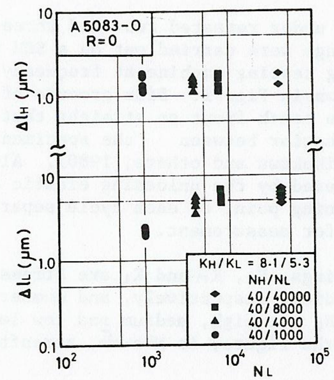


Fig. 9. Effect of number of cycles of N_L on crack propagation length Δl_H and Δl_L.

$(\Delta K_{eff})_L$ is zero. So it may be concluded that whethere crack can propagate under low level loading or not is not determined by $K_{max})_{th}$ but by the value of ΔK_{eff}, and the crack propagation rate can be estimated by the linear accumulation law based on the dl/dn - ΔK_{eff} relation of constant amplitude test. Figure 8 shows the effect of cycle ratios of N_H/N_L on the propagation rate. Small symbols represent the microscopic propagation rate obtained by fractography and large ones are estimated values by eq. (2). Microscopic rates to high level loadings when they are evaluated by ΔK_{eff} are almost same independent of cycle ratios and well coincide with constant amplitude test. However, propagation rates to low level loadings were found to be affected by the number of cycles of N_L even in the dl/dn - ΔK_{eff} plot and showed the decrease with increase of N_L in the range more than 10^3 cycles. These behaviors may be interpreted by Fig. 9 where the propagation length under K_H and K_L of one block

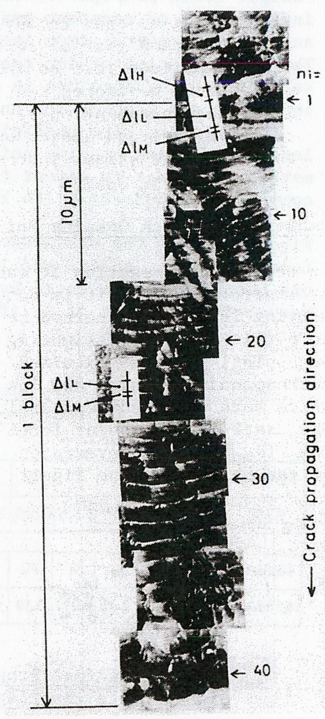


Fig. 10. Fractograph under repeated three-step test on A5083-O. ($K_H/K_M/K_L$ = 8.1/6.5/5.3, $N_H/N_M/N_L$ = 40/40×39/1000×40)

loading is plotted against N_L. Propagation length under low level loading, Δl_L, increased with N_L but saturated at the length of about 6 µm, which resulted in the decrease of the averaged propagation rates as shown in Fig. 8. Such saturation, however, can be easily broken if proper medium level loadings are mixed in the two-step loadings (Kikukawa, Jono and Kondo, 1979). Figure 10 shows the fractograph of the fractured surface under repeated three-step loadings. Δl_H, Δl_M and Δl_L correspond to the propagated length under K_H, K_M and K_L of one sub-block loading, respectively. It was found that Δl_L was large at n_i = 1, and decreased with n_i to show the minimum spacing at about 10 µm, where crack might stop to propagate under repeated two-step test. However, under three-step loading Δl_L increased again with n_i after the minimum value by the effect of medium loading so that the average propagation rate for low level loadings was found to be faster than that of repeated two-step test, but not to exceed the rate of the constant amplitude test as shown in Fig. 11.

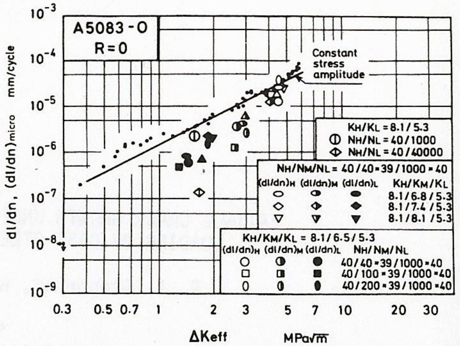


Fig. 11. ΔK_{eff} - dl/dn relation for repeated three-step test.

From the above mentioned testing results, therefore, it may be concluded that the fatigue crack propagation rate under varying loadings of arbitrary conditions can be conservatively estimated by the modified Miner's rule of crack propagation based on the effective stress intensity range, ΔK_{eff}.

Behavior of Crack Opening Point

In the previous section it was shown that crack propagation rates could be estimated by ΔK_{eff}. However, it is not convenient for actual use to measure ΔK_{eff} for the varying loadings concerned by experiments one by one. So in this section in order to obtain a method estimating ΔK_{eff} for varying loadings the behavior of crack opening point, K_{op}, was examined. Figure 12 shows the relation between K_{max} and K_{op} corresponding to high and low level loadings under repeated two-step test on A5083-O which were measured separately by the unloading elastic compliance method.(see Fig.3) The crack opening point for high level loading, $(K_{op})_H$ and that for low level loading, $(K_{op})_L$, are represented by same kind of symbols for the same test condition. It can be seen in the figure that $(K_{op})_H$ and $(K_{op})_L$ have equal value in repeated

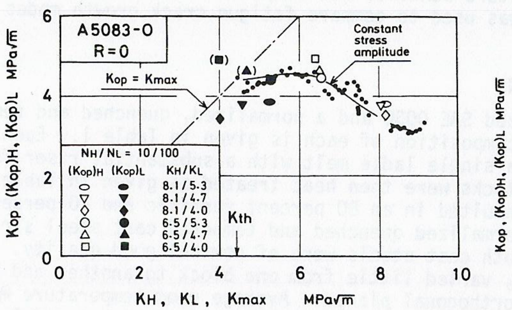


Fig. 12. K_{max} - K_{op} relation for repeated two-step test on A5083-O.

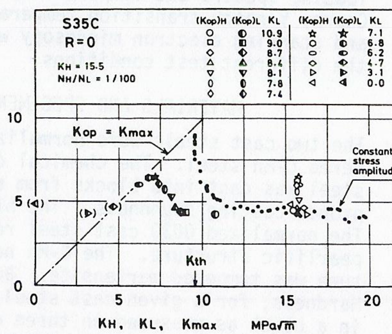


Fig. 13. K_{max} - K_{op} relation for repeated two-step test on S35C.

two-step loadings investigated and nearly equal to that for K_H in K_{max} - K_{op} relation of constant amplitude test. It may be the reason for this behavior that the crack closure behavior is controlled by the highest value of K in loadings because the propagated length of one block load is very small compared with the plastic zone size made by the highest K. Figure 13 shows the K_{max} - K_{op} relations under repeated two-step loadings as well as constant amplitude loadings on S35C. The similar behaviors of K_{op} are observed with this materials, too, except the test conditions that the levels of K_L are fairly low or the number of low level loading cycles becomes large (see Fig. 14) where the strain aging due to cycles of N_L may increase K_{op} levels. Increse of K_{op}, however, is not observed in the low K_L level region where crack does not open during loading cycles of K_L. Moreover, it was suggested that the increase of K_{op} could be prevented under three-step loading. Therefore, it may be concluded that the crack opening point under varying loading conditions is necessary to be conservatively estimated by that of constant amplitude test corresponding to the highest value of K in the varying loadings without considering the increase of the opening point.

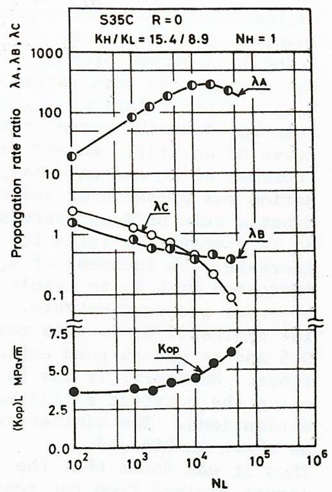


Fig. 14. Crack propagation rate ratios and K_{op}. (repeated two-step test, effect of N_L)

ESTIMATION METHOD OF CRACK PROPAGATION RATE UNDER VARYING LOADING CONDITIONS

An estimation method of fatigue crack propagation rate under varying loading conditions can be derived from the test results shown in the previous sections as follows; Fatigue crack propagation rate was represented by the following equation in terms of ΔK_{eff},

$$dl/dn = C\,(\Delta K_{eff})^m \qquad (3)$$

where C and m are material constants and can be determined by the constant amplitude test.

And the effective stress intensity range, ΔK_{eff}, for varying loading could be evaluated by

$$\Delta K_{eff} = K_{max} - (K_{op})_H \qquad (4)$$

where $(K_{op})_H$ is the crack opening point for the highest level loading in varying loadings which is equal to that of constant amplitude test under the same level loading.

By substituting eq. (4) into eq. (3), the modified equation for crack propagation is represented in terms of K_{max}.

$$dl/dn = C\,[\,K_{max} - (K_{op})_H\,] \qquad (5)$$

Then fatigue crack propagation rate under varying loading conditions can be estimated based on the linear accumulation law of crack propagation using this curve. Modified crack propagation curves are shown in Figs. 5, 6 and 7 by chained lines, and were found to give a good estimation of crack propagation for both materials.

Figures 14 and 15 show the comparison between some

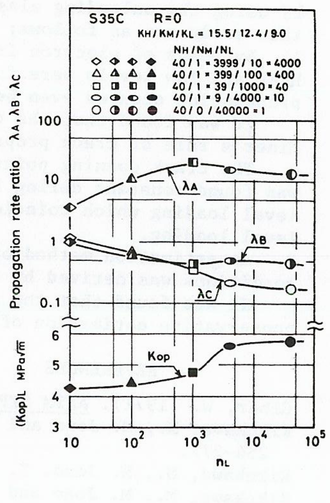


Fig. 15. Crack propagation rate ratios and K_{op}. (repeated three-step test)

estimation methods for crack propagation rate under repeated two- and three- step loadings on S35C, where the estimated results are represented by the rate ratios of actually observed propagation rates to estimated propagation rates. That is, λ_A is the propagation rate ratio to the estimated rate by using the Miner's rule based on K_{max} - dl/dn relation. λ_B and λ_C were calucurated by using the modified Miner's rule based on the actually measured ΔK_{eff} and by the linear accumulation law on the curve of eq. (5), respectively. In Fig. 14, it was found that λ_A increased with increase of N_L and gave dangerous estimation. The reason of this dangerous estimation was omission of crack propagation below the threshold condition as to the Miner's rule on K_{max} whereas crack actually propagated below the threshold level. So if propagation rates for low level loadings were constant λ_A should continue to increase with increase of N_L. However, as shown in the bottom of the figure, K_{op} increased with N_L to result in the decrease of ΔK_{eff} and consequently the decrease of crack propagation rate. Therefore, λ_A showed the maximum value of about 300 at 10^4 cycles of N_L in this case. On the otherhand, λ_B was found to lie between 2 and 0.5 and to give a good estimation of crack propagation under varying loading conditions. Moreover, it was found that λ_C calculated based on the convenient method using the constant amplitude testing results could give approximate and conservative estimations. The similar results were also found for the repeated three-step tests as shown in Fig. 15.
Thus it was found that the estimation method based on the modified propagation curves derived from the constant amplitude test could be applicable for the crack propagation under varying loading conditions.

CONCLUSIONS

Fatigue crack propagation tests were carried out on a carbon steel and an aluminum alloy with repeated two- and three-step loadings at relatively low stress intensity level. Crack propagation rates and crack closure behavior were investigated by using the unloading elastic compliance method. The main results obtained in this study are as follows;

1. By means of electron fractography, striations corresponding to block loadings of high and low levels were found on the fractured surface, which confirmed that crack propagation occured even below the threshold level under varying loading conditions.
   It was found that the crack propagation rate could be estimated by the modified Miner's rule of crack propagation based on the effective stress intensity range ΔK_{eff}.
2. The crack opening point, K_{op}, under stationary varying loadings of short period was found constant during loading cycles and nearly equal to that of the highest level loading which coincided with the constant amplitude test result of the same level loading.
3. An estimation method of fatigue crack propagation rate under varying loading conditions was derived by considering the above mentioned crack closure behavior.
   It was found that the proposed method could give a good approximation or conservative estimation of crack propagation rate.

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