Significance of Crack Closure due to Residual Stretch and Stresses

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ABSTRACT

Fatigue crack closure characteristics due to residual stretch and stresses are analyzed. A real stress intensity factor is defined by using a superposition technique in linear elastic fracture mechanics. The analysis gives the theoretical definition for the effective stress intensity and shows a guide how to detect associated crack opening points. It is shown that this approach can be applicable for the prediction of fatigue crack growth rates in residual stress field.

KEYWORDS

Fatigue; fracture mechanics; crack closure; residual stretch; residual stresses.

INTRODUCTION

Due to fatigue crack closure, only a fraction of applied stress intensity factor range, ΔK, plays an important role in actual crack growth (Elber, 1971). This fraction is termed the effective stress intensity factor, ΔK_{eff}. The validity of the crack closure concept has been confirmed by experiments and analyses. However, the following important points remain still unclear.

(1) Definition of ΔK_{eff}: For plasticity induced crack closure as originally found by Elber, a range of the "effective" ΔK is clear. However, when partial crack surface contact occurs with an original crack tip open at minimum stress intensity factor, K_{min}, the conventional definition for the opening stress intensity factor, K_{op} (the tip opening point), can not be applied.

(2) Accuracy of unloading compliance method: In unloading compliance technique, as a nonlinear portion of the P–V curve approaches to the opening point asymptotically, the detected point might have some errors. Of course, the amount would depends on the closure mechanisms. So, the accuracy should be cleared up for many cases.

As the crack grows by fatigue, the asperities cause the crack closure which yields a contact (compressive) stress behind the crack tip. By using a superposition technique, it is shown that the real stress intensity factor at the crack tip can easily obtained from the contact stress. From this, more theoretical definition will be given to ΔK_{eff} in this paper. The validity is confirmed by the analysis of fatigue crack growth under various crack closure mechanisms, such as residual plastic stretch (Elber, 1971), fracture surface roughness (Minakawa and McEvily, 1981), or fretting oxide debris (Stewart, 1980). The results are compared with experiments (Nakamura and Kobayashi, 1988).

Further approach to fatigue crack growth rate prediction in residual stress field includes a method incorporating partial crack surface contact. The validity of the method is confirmed by comparing the prediction with experiments.

ANALYTICAL PROCEDURE

To assess the effect of asperities on fatigue crack closure, a fatigue crack growth simulation was conducted by using a modified Dugdale model developed by Newman (Newman, 1981). The model can leave elastic-plastic elements in the wake of the advancing crack tip as shown in Fig. 1. The simulation includes a loading and an unloading processes with advancing a crack tip (the growth increment per cycle was 0.05 of the maximum plastic zone size, ω_{max}) at each loading cycle under the condition of K_{max} = constant and $R = 0$ until the steady state of K_{op} and K_{cl} is reached. After that, several types of asperities were attached on the crack faces as shown in Fig. 2. These are

- case (a): the amount of residual stretch δ_R, being constant along the crack faces (plasticity induced crack closure alone, no asperities),
- case (b): with asperities remote from the crack tip (near the initial notch tip in this case),
- case (c): with asperities near the crack tip.

The details of the analytical procedure are shown elsewhere (Nakamura and Kobayashi, 1988).

The validity of the unloading compliance technique is discussed by analyzing the relation between the applied K and the crack mouse opening displacement COD. The detected opening point is denoted by K_{op}^*.

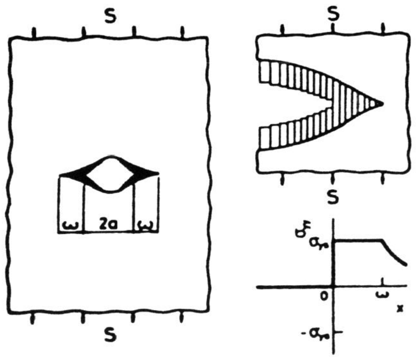


Fig. 1 Modefied Dugdale model.

As discussed in the previous study, K_{op} is superior than K_{cl} as a parameter describing the crack growth rate, da/dN (Nakamura and Kobayashi, 1988). Thus, the discussions are made only for K_{op} in this study.

REAL STRESS INTENSITY FACTOR IN RESIDUAL STRESS FIELD

When a initial residual stress distribution (the stress is $\sigma_R{}^i(x)$) is given for an uncracked body, the associated stress intensity factor, K_R, for a cracked body is calculated by applying a negative $\sigma_R{}^i(x)$ $(-\sigma_R{}^i(x))$ on the crack surfaces. By introducing a superposition technique, it is given as

$$K_R = \int_0^a \sigma_R{}^i(x)\ m(a,x)dx \tag{1}$$

$$= \int_0^a -\sigma_R{}^i(x)\ M(a,x)dx \tag{2}$$

where a is the crack length, $m(a,x)$ and $M(a,x)$ are weight functions for the residual stresses of the uncracked body and for the traction acting on the crack surfaces, respectively. Of course, these functions are in a relation of

$$m(a,x) = -M(a,x). \tag{3}$$

The real stress intensity factor range, ΔK_r, and stress ratio, R_r, are given as

$$\Delta K_r = K_{max} - K_{min} \qquad (= K_{max} + K_R \text{ for } K_{min} + K_R < 0) \tag{4}$$

$$R_r = (K_{min} + K_R)/(K_{max} + K_R) \qquad (= 0, \text{ for } Rr \leq 0). \tag{5}$$

A vertical crack face displacement $V_R(a,x)$, a half of crack opening displacement $COD(x)$, associated with the traction $-\sigma_R{}^i$ is given as

$$V_R(a,x) = (1/E)\int_x^a K_R(a)m(a,x)da \tag{6}$$

under the plane stress condition, where E is the Young's modulus.

When a crack grows from a compressive stress field, $V_R(a,x)$ becomes negative as shown by doted lines in Fig. 3(a) which is physically unacceptable. Actually, a crack surface contact occurs in this case. Thus, a contact stress, σ_{co}, is applied (Fig. 3(c)) to prevent such crack surface

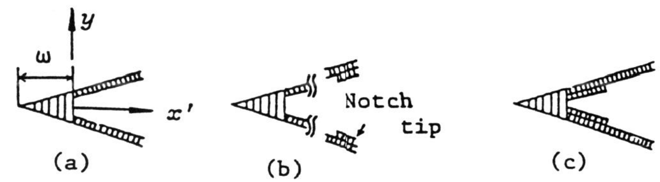
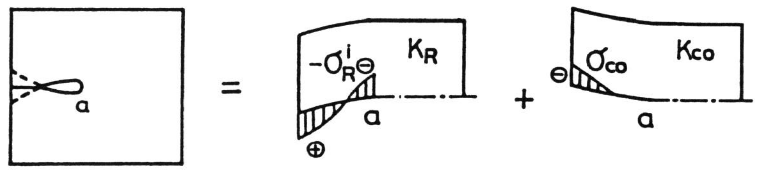


Fig. 2. Three cases of asperities.



(a) (b) (c)

Fig. 3. Superposition technique considering crack surface contact.

overlapping (Todoroki *et al.*, 1988b). A stress intensity factor, K_{co} (≥ 0), associated with σ_{co} is given as

$$K_{co} = \int_0^a \sigma_{co}(x)M(a,x)dx. \tag{7}$$

By using Eqs. (1) and (7), the real stress intensity factor, K_r, ΔK_r and R_r can be defined as

$$K_r = K + K_R + K_{co} \tag{8}$$

$$\begin{aligned}\Delta K_r &= (K_{max} + K_R + K_{co}(max)) - (K_{min} + K_R + K_{co}(min)) \\ &= K_{max} + K_{co}(max) - K_{min} - K_{co}(min)\end{aligned} \tag{9}$$

$$R_r = (K_{min} + K_R + K_{co}(min))/(K_{max} + K_R + K_{co}(max)) \tag{10}$$

where $K_{co}(max)$ and $K_{co}(min)$ are K_{co} at $K = K_{max}$ and $K = K_{min}$, respectively.

CRACK CLOSURE DUE TO ASPERITIES

In plasticity induced crack closure, the residual plastic stretch yields residual stresses behind the crack tip and hence K_R. So, by Eq.(9), ΔK_{eff} and K_{op} can be defined as

$$\Delta K_{eff} = K_{max} - (K_{min} + K_{co}(min)) \tag{11}$$

$$= K_{max} - K_{op} \tag{12}$$

because $K_{co}(max)$ is usually zero. As K_R due to asperities in Eq.(8) is unknown during fatigue crack growth, it is difficult to calculate K_r. So, it is convenient to introduce a new parameter, an applied stress intensity (K_{app}), defined as

$$K_{app} = K + K_{co}. \tag{13}$$

By using K_{app}, K_{op} is defined as

$$K_{op} = K_{app} \quad \text{(at } K = K_{min}). \tag{14}$$

The relation between K_{app} and K for the case (a) is shown in Fig. 4. Until the crack tip opens, K_{app} remains constant ($K_{app}/K_{max} = 0.51$). As the crack tip is closed during $K_{min} \leq K < K_{op}$, the crack tip singularity vanishes. Thus, K_r in Eq.(8) is zero and the following equation can stands.

$$\begin{aligned}K_r &= K_R + (K + K_{co}) \\ &= K_R + K_{app} = K_R + K_{op} = 0 \quad (\text{ for } K_{min} \leq K < K_{op}).\end{aligned} \tag{15}$$

From these results, K_{op} for case (a) is equal with
(i) the negative value of stress intensity factor due to asperities, $-K_R$,
(ii) K_{app} during $K_{min} \leq K < K_{op}$, or
(iii) K when the crack tip opens (or when K_{co} becomes zero).

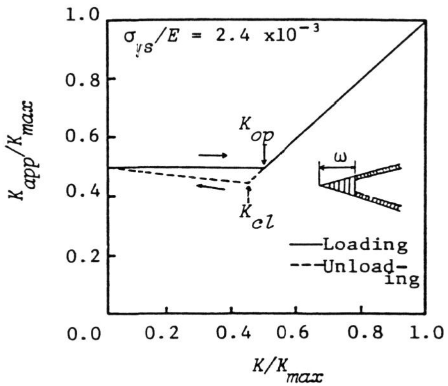


Fig. 4. K_{app}-K relation for case (a).

Of course, the last definition agrees with the conventional one (Elber, 1971). From Eq.(10),it is shown that the real stress ratio is given as

$$R_r = 0. \tag{16}$$

The relation between K_{app} and K for the case (b) is typically shown in Fig. 5, where the total asperity thickness, δ_R', near the notch tip along x'/ω_{max} = 1.2-2.4 is twice of the original residual plastic stretch, δ_R. For this case, the first surface contact occurs near the notch tip with the original crack tip opens (partial crack surface contact). During the partial crack surface contact, the relation between K and K_{app} becomes nonlinear. However, asperities have no influence on K_{op}. It is shown that the crack tip actually opens at K_{op} defined by Eq.(14).

Further increase in thickness of asperities brings the condition where the crack tip is still open at K=K_{min}, which brings increase in K_{op}. Thus, asperities remote from the crack tip have a influence on K_{op}, only when the partial crack surface contact occurs. Among the above three definitions [(i)-(iii)] for K_{op}, only the second one (Eq.(14)) is applicable in this case.

The relation between K_{app} and K for the case (c) shows the same trend as the case (a), because no partial crack surface contact occurs.

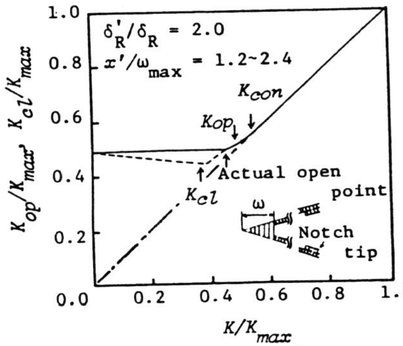


Fig. 5. K_{app}-K relation for case (b).

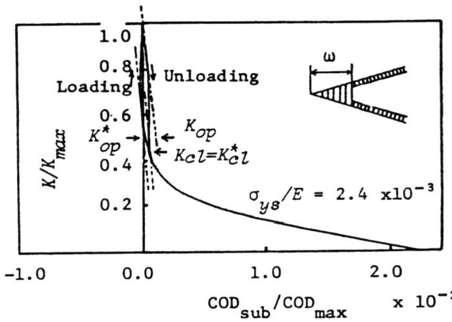


Fig. 6. K-COD_{sub} relation for case (a).

DETECTION OF CRACK CLOSURE

The relation between K and the subtracted COD, COD_{sub}, for the case (a) is shown in Fig. 6, where COD_{sub} is the nonlinear component of the crack mouse displacement COD, COD_{max} is COD at $K = K_{max}$ and dashed lines are the tangents of the unloading curves at $K = K_{max}$. The intersections between the hysteresis loop and the dashed lines give the detection of $K_{op}^* = 0.51K_{max}$ (from loading portion of the curve) and it was found that it agrees with both the actual tip opening point and K_{op} by Eq.(14).

The relations between K and COD_{sub} for the cases (a) to (c) are typically shown in Fig. 7. For the case (b), the first crack surface contact occurs near the notch tip with the crack tip open which causes a sudden compliance change. Thicker the asperities attached, higher the detected value of K_{op}^*. As stated earlier, however, the asperities have no (or a little depend on the asperity thickness) influence on actual K_{op}. The detected value of K_{op}^* (point B) gives the overestimated value of K_{op}.

For the case (c), thicker the asperities attached, increasing the actual values of K_{op} (point B). Thus, asperities near the crack tip have a significant influence on K_{op}. However, it becomes more difficult to detect K_{op} precisely because the compliance change near $K = K_{op}$ becomes smaller. Thus, the detected value of K_{op}^* (point C) tend to give the underestimated value of K_{op} and K_{cl}. This phenomena always happens under relatively high K_{op}/K_{max} (under high stress ratio or near the threshold where the oxide and/or fracture surface roughness induced crack closure prevail).

Experimentally, the validity of the crack closure concept has been confirmed by comparing da/dN versus ΔK_{eff} curve with closure-free da/dN versus ΔK curve. Sometimes, it is difficult to deduce the candidate for the closure-free curve. Although the Dugdale model adapted here has inherent limitations in terms of its application, the results obtained here may give some suggestion regarding this point.

The da/dN versus ΔK curves at R=0.1 for a high strength steel, AISI 4340, tempered at 773 K tested in air and in synthetic seawater are shown in Fig. 8 (Kobayashi and Nakamura, 1987). No environmental effect or no interaction effect between stress corrosion cracking (SCC) and fatigue crack growth is observed. On the other hand, da/dN versus ΔK_{eff} curve in synthetic seawater tends to deviate to upwards as ΔK decreases. The threshold stress intensity for SCC, K_{ISCC}, is 69.6 MPa$\sqrt{m}$ for this material and is considerably higher compared with the level of ΔK tested. Accordingly, this acceleration has been interpreted as the effect of stress induced corrosion dissolution at

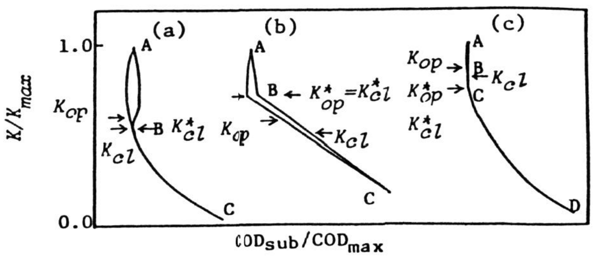


Fig. 7. K–COD_{sub} relation for cases (a) to (c).

the crack tip (Endo *et al.*, 1983). However, thick corrosion products were observed only near the initial notch tip on the fracture surface. As suggested from Fig. 7(b), the detected value of K_{op}^* gives the overestimated value of K_{op} in this case, which is believed to have yielded the above mentioned results.

PREDICTION IN RESIDUAL STRESS FIELD

Results of Eqs. (8)-(10) can be directly applicable to the prediction of fatigue crack growth rates in residual stress field due to welding or plastic work. Unlike stresses due to asperities, such initial residual stresses without the contribution of asperities may be measured which enable us to treat such stresses as one of applied stresses. For the same ΔK_r and R_r, K_{op} due to asperities (residual plastic stretch, fracture surface roughness, etc.) becomes the same. Thus, da/dN is estimated from the da/dN–ΔK curve for the base metal at $\Delta K = \Delta K_r$ and $R = R_r$.

Conventionally, ΔK_r and R_r have been calculated from Eqs. (4) and (5) for given initial residual stresses. Under a compressive residual stress field with tensile residual stresses only near the crack tip, however, the partial crack surface contact as shown in Fig. 3 can occur which is the same as the case (b) in Fig. 2. Thus, in life prediction, Eqs. (9) and (10) must be used. A typical example is shown in Fig. 9 (Todoroki, *et al.*, 1988b). Without considering the effect of partial crack surface contact (doted curve), the prediction gives the overestimation for experiments (open symbols). If that effect is considered (solid curve), the prediction shows a good agreement with experiments.

CONCLUSION

Fatigue crack closure characteristics due to residual stretch and stresses

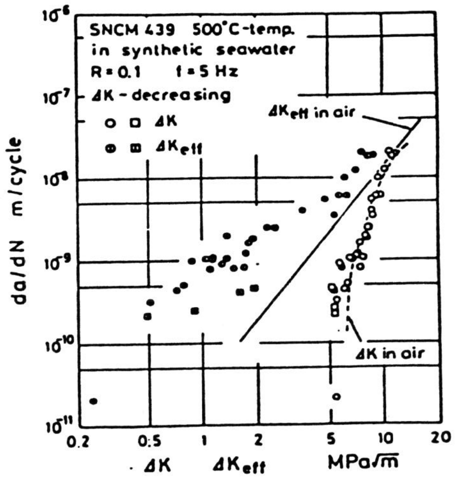


Fig. 8. da/dN–ΔK and da/dN–ΔK_{eff} relations at R = 0.1 in synthetic seawater (AISI 4340 tempered at 773K).

are analyzed. A real stress intensity factor is defined by using a superposition technique in linear elastic fracture mechanics. The analysis gives the theoretical definition for the effective stress intensity and shows a guide how to detect associated crack opening points. It is shown that this approach can be applicable for the prediction of fatigue crack growth rates in residual stress field.

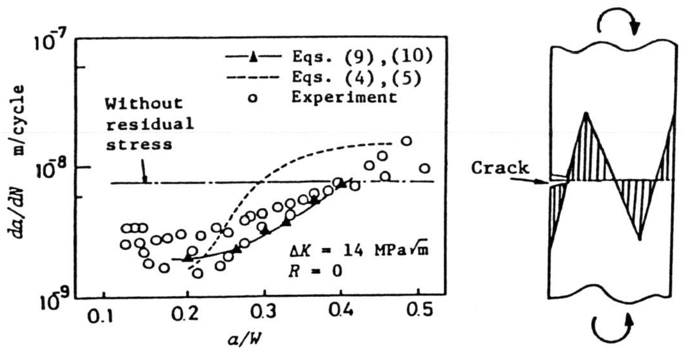


Fig. 9. Comparison between predictions and experiments of *da/dN* in residual stress field induced by plastic bending.

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