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Fatigue Crack Retardation and Retardation Mechanism in Variable Loading
(The Effects of Crack Tip Branching in Crack Growth Retardation)

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ABSTRACT

In order to study the fatigue crack and retardation mechanism in variable loading, the effects of crack tip branching in crack growth retardation were examined. The characteristics of crack tip branching behavior were considered with respect to microstructure and crack tip branching angle was examined. Crack tip branching was observed along the grain boundary of ferrite and pearlite structure. It was found that the branching angle ranges from 25 to 53 degrees. Using the finite element method, the variable of crack driving force to branching angle was examined. The effective crack driving force (K_{eff}) decreased as the branching angle increased. The rate of decrease was 33% for kinked type and 29% for forked one. It was confirmed that the effect of crack tip branching is a very important factor in crack growth retardation. Therefore, crack branching effect should be considered in building the hypothetical model to predict crack growth retardation.

Keywords : Crack growth retardation, Crack tip branching, Crack tip branching angle, Kinked type branch, Forked type branch, Effective crack driving force, Retardation mechanism.

1. Introduction

The most common type of fatigue crack for metals under variable amplitude loading is the crack growth retardation. The previous research states that growth retardation due to single overload could be characterized by crack tip blunting, crack tip branching, strain hardening, compressive residual stress, and plasticity induced crack closure[1-4]. But, most of the research on growth retardation is limited to compressive residual stress and plasticity induced crack closure due to difficulty in test and analysis[5-7]. It is obvious that compressive residual stress induced from plastic deformation by overload and plasticity induced crack closure are important factors in understanding crack growth retardation. But, there are several signs of limitation to be regarded as a dominant mechanism. For example, there is a difference in quantity between the retardation zone and the plastic deformation area obtained by tests[8-10]. Therefore, it is difficult to explain the phenomena after overload using plastic deformation only. To overcome this limitation, crack tip branching is proposed as the second mechanism to explain the retardation behavior[2,11]. One of the characteristics related to growth direction in retardation zone is that the crack tip branching caused by unloading overload. At this time, the length of the crack tip is quite shorter than the main crack. Also, loading type at the crack tip becomes a combination of mode I and mode II, while the overall type is mode I. Therefore, the driving force for a crack is an important factor in estimating the retardation behavior caused by overload. Taking into account crack the branching effects, new estimation model for crack retardation is proposed in this study. By finite element analysis and tests, the variation of crack driving force due to the occurrence of the crack tip branching is examined. As a result, new estimation model is presented by modifying widely used Willenborg model.

2. Test

To study the crack retardation under overload and the behavior of crack branching in retardation zone, fatigue test is performed for the case of single overload. The shape of the specimen used in the test is shown in Fig. 1, and its chemical composition and mechanical properties are summarized in Table 1 and 2 respectively. The overload is applied at 0.01Hz, and its magnitude was two times its applied load. When the crack growth retardation is detected due to overload, its behavior is examined in detail by a movable microscope.

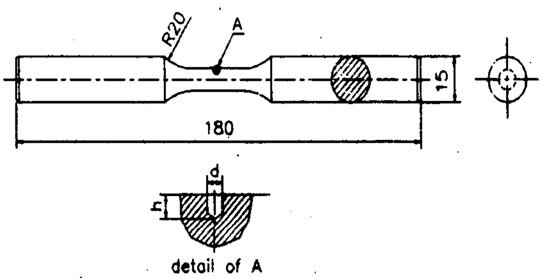


Fig. 1 The shape of fatigue test specimen

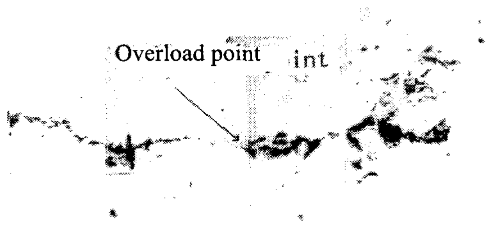
Table 1 The chemical composition of testing material

Material	Composition				
	C	Si	Mn	P	S
SS41	0.16	0.18	0.66	0.029	0.042

Table 2 The mechanical properties of testing material

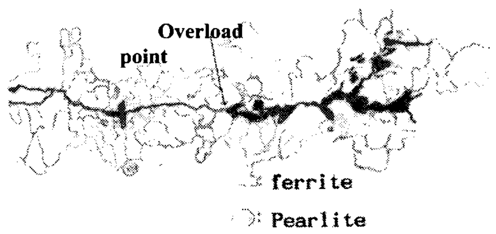
Yield strength (Mpa)	Tensile strength (Mpa)	Elongation	Reduction of area (%)	Micro Vickers hardness(Hv)
280	432	36.97	55.05	162.44

In Fig. 2, crack tip branching induced by overload is shown. Fig. 2 indicates the appearance of crack tip branching by overload. But, it appears not right after applying the overload but after crack tip blunting. In general, the crack tip branching appears when the crack driving force is very low. The crack tip branching (Fig. 2(a)) is caused by reduced stress concentration due to crack tip blunting and low driving force because of compressive stress at the crack tip under overload.



(a) Branching Shape

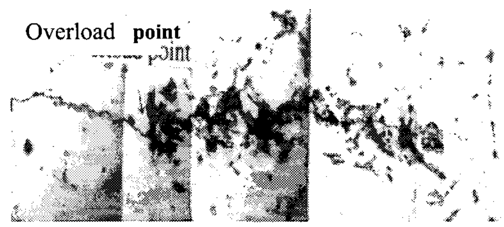
(b) Etched shape of (a)



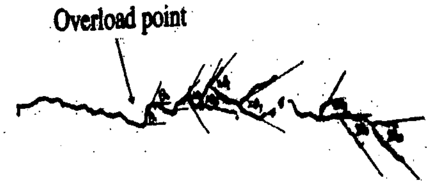
(c) Shape of (a)+(b)

Fig. 2 The crack tip branching and microstructure

In Fig. 3, the picture of the shape for the crack tip branching in the retardation zone is taken after 9× 104 cycle is passed after applying overload. In this figure, one can easily see that its crack propagation path becomes irregular and its crack branch appears. Here, the main types of the crack branch are kinked type (bent in one side only) and forked type (bent in both sides). Also, the crack branch is visible over the entire range of retardation.



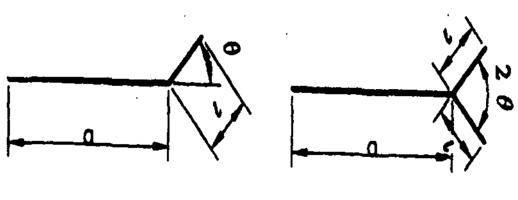
(a) Shape of branching



(b) Variation of crack branching angle

Fig. 3 The crack tip branching after 9× 104 cycle

It seems that the crack branching angle would influence the crack driving force at the crack tip. To examine the effect due to variation in branching angle, the crack branching shape is projected to a transparent paper (Fig. 3(b)).



(a) Kinked type (b) Forked type

Fig. 4 The schematic of crack branching type

The crack branching angle is measured based on the main crack direction. As shown in Fig. 4, angle is defined as θ in kinked type and 2θ in forked type. By the same method, crack tip branching angle is measured. The result shows that its angle is not uniform but ranges from 25 to 53 degrees. It s average angle resulted in 34 degree. Based on these results for the case of overload, crack behavior could be characterized as follows: crack tip branching is formed at the crack tip → came back toward the main crack propagation direction → formed crack branching again.

3. The variation of the crack driving force by type

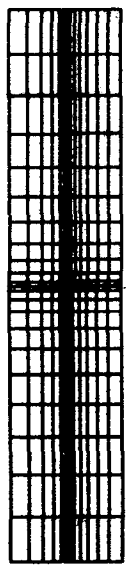
The finite element analysis is used to study the effects of crack driving force upon crack tip branching. As a result, stress intensity factor is calculated for each type.

3.1 Finite Element Model

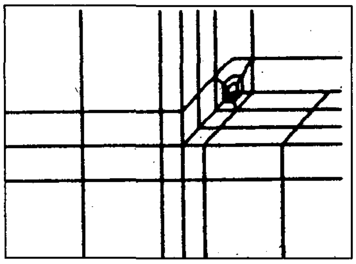
In crack retardation zone, two types of crack tip branching were shown: kinked and forked type, and its angle ranges from 25 to 53 degrees (Fig.3). Therefore, the variation of the crack driving force at each branching angle(0° ,15° ,30° ,45° ,60°) is examined for kinked and forked type case. The test proves that crack tip branching is only limited to crack tip. Therefore, to minimize the effect of crack tip branching and maximize the branching angle, small crack branching size(ι) is chosen relative to the length of the main crack (a). As a result, its ratio(ι /a) was chosen to be 0.02. The detailed finite element analysis model is shown in Fig. 5. In total, ten FE models were used, five models for each type.

3.2 The variation of the stress intensity factor by crack branching angle

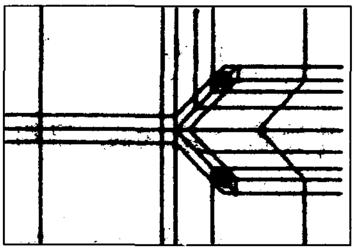
In general, when crack branching is formed at the crack tip, crack mode becomes a combination of mode I and II. In this section, the variation of the stress intensity factor at various branching angles is examined. For the calculation of stress intensity factor, CTOD method is used. In Fig. 6 and 7, the variation of stress intensity factor is examined as the crack tip branching angle θ is changed. x and y axis represents crack branching angle θ and stress intensity factor at the crack tip, respectively. But, since the loading at the tip becomes combination type locally, y axis is set to be dimensionless such that the stress intensity factor is zero ($K_{\theta=0}$) at mode I ($K_{I,\theta}$) and mode II ($K_{II,\theta}$)



(a) Finite element analysis model



(b) An illustration of kinked type (θ =45°)



(c) An illustration of forked type (θ =45°)

Fig. 5. Finite element analysis model

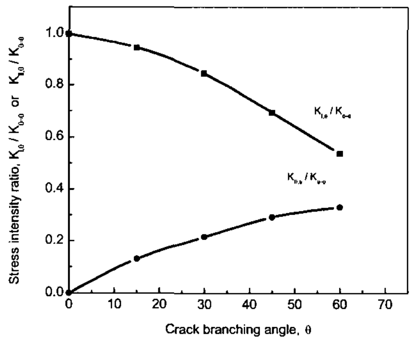


Fig. 6 The variation of crack driving force on kinked type

As shown in Fig. 6, $K_{I\theta}/K_{\theta=0°}$ decreases as θ increases for kinked type, while $K_{II\theta}/K_{\theta=0°}$ increases as θ increases. For the case of 45° crack tip branching angle, $K_{I\theta}/K_{\theta=0°}$ resulted to 0.68 (decreased 32%), and $K_{II\theta}/K_{\theta=0°}$ resulted to 0.28 (increased 28%). For the forked type case, $K_{I\theta}/K_{\theta=0°}$ was 0.7 (decreased 30%) for 45° crack tip branching angle, which is similar to the kinked type results. Global Distribution is very similar for both types, but decreasing rate is slow until 10° degrees for the kinked type. But, the rate was almost uniform for the forked type case. But, $K_{II,\theta}$ distribution was quite different from kinked type. $K_{II,\theta}$ is negative (-0.18) at θ =15° and increases gradually up to 0.3 **for** 60° To study the effective driving force in this combination mode, the following equation regarding maximum principle stress is derived.

$$K_{eff} = (K_I^2+K_{II}^2)^{1/2} \tag{3-1}$$

K_{eff} : effective stress intensity factor

In the above equation, effective stress intensity factor (K_{eff}) represents the actual crack propagation, where the actual force is calculated taking into account K_I and K_{II} in combination mode. Fig. 8 and Fig. 9 show the change of K_{eff} as crack tip branching angle changes. As clearly shown in the above Fig. 8-9, $K_{eff}/K_{\theta=0°}$ decreases as crack tip branching angle θ increases. For the case of kinked type (Fig. 8), $K_{eff}/K_{\theta=0°}$ resulted at 0.67 for crank branching angle of 45 degree, where it is 33 percent less than the case with no crack branching. Also, the decreasing rate is similar to the case of $K_{I,\theta}/K_{\theta=0°}$ Therefore, it is significant that effective crack driving force (K_{eff}) is influenced more by $K_{I,\theta}$ variation and not by $K_{II,\theta}$ changes. In Fig.9, the variation of effective crack driving force (K_{eff}) is shown for forked type. For the branching angle of 45 degree (θ =45°), $K_{eff}/K_{\theta=0°}$ resulted to 0.71, which is similar to the case of $K_{I,\theta}/K_{\theta=0°}$. Though there is a small difference due to increase of $K_{II,\theta}/K_{\theta=0°}$, it could be ignored. In other words, the effective driving force (K_{eff}) decreases as crack branching angle increase for forked type. In this case, $K_{II,\theta}$ change has little influence on K_{eff} changes. From the above results, we could conclude that K_{eff} decreases as the crack branching angle θ increases. From Fig. 8 and 9, we were able to obtain the following equation representing the relation between crack branching angle θ and crack driving force by curve fitting.

i) for kinked type

$$K_{eff} = (0.9993 - 0.00123\theta - 1.62 \times 10\text{-}4\theta^2 + 9.0598 \times 10\text{-}7\theta^3)K_I$$

ii) for forked type

$$K_{eff} = (1.0037 - 0.011\theta - 1.229 \times 10\text{-}4\theta^2 + 8.0 \times 10\text{-}7\theta^3)K_I$$

It is significant that decreased driving force at the crack tip would worsen the retardation. Therefore, we could conclude that the study on the characteristics of crack tip is very important in understanding the crack retardation phenomena. Accordingly, the current estimation model (13) should be modified to take into account the crack tip branching effects since it is only based upon compressive residual stress field and crack closure.

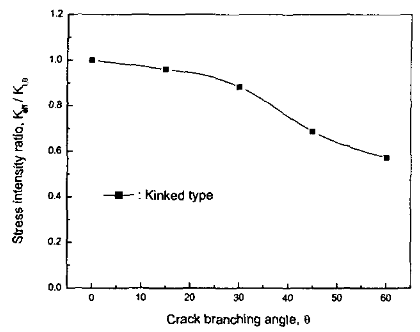


Fig. 7 The variation of effective crack driving force on kinked type

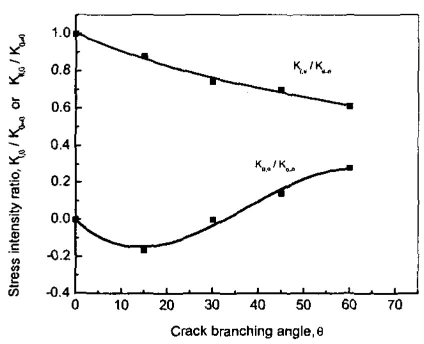


Fig. 8 The variation of crack driving force on forked type

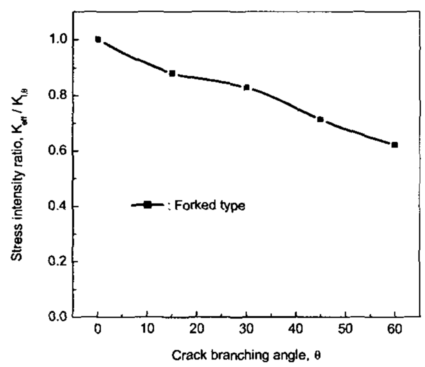


Fig. 9 The variation of effective crack driving force on forked type

4. Conclusion

From this study, the results are summarized as follows.

1) In the retardation zone, the crack tip branching was noticed along the border line of ferrite and pearlite structure.
2) Most of the crack branching type was the kinked type and forked type. Its angle ranged from 23 to 53 degree, and the average was 34 degree.
3) As the angle between the main crack and the branch increased, the effective crack driving force (K_{eff}) decreased. For the case of 45 degree ($\theta=45°$) the crack driving force decreased by 33 percent for kinked type and 30 percent for forked type.
4) From the finite element analyses the following relation are derived between the crack tip branching angle and the effective crack driving force.

For the kinked type :

$$K_{eff} = (0.9993 - 0.00123\theta - 1.62 \times 10^{-4}\theta^2 + 9.0598 \times 10^{-7}\theta^3)K_I$$

For the forked type :

$$K_{eff} = (1.0037 - 0.011\theta - 1.229 \times 10^{-4}\theta^2 + 8.0 \times 10^{-7}\theta^3)K_I$$

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