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INFLUENCE OF MECHANICAL FACTORS ON THE FATIGUE CRACK CLOSURE

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INTRODUCTION

Several investigations have been made on the fatigue crack closure [2 - 10], since the importance of this phenomenon was pointed out by Elber [1]. However, details of this have not been fully understood, because many mechanical and metallurgical factors have influence on this phenomenon in a complicated manner.

An analytical approach to the fatigue crack closure has been developed by the present authors by using finite element technique, and some applications of this approach have been made [11, 12]. All the results obtained hitherto are promising to predict the crack closure behaviour by this approach, not only qualitatively but also quantitatively. In the present paper, therefore, some analyses are made on the influence of mechanical factors on the fatigue crack closure behaviour by using the same technique, and the essential factors which govern this phenomenon are explored.

METHOD OF ANALYSIS

The method of the analysis used in this study was the same as that in previous papers [11, 12] and only brief descriptions are made in this paper. A simple model is considered in this analysis. A crack is forced to extend by a prescribed length of Δl in every loading cycle. No fracture criterion is utilized for the crack extension. This process of crack propagation under cyclic loading is analyzed by using the finite element technique which is essentially the elastic-plastic analysis with some special developments for this study, the details of which were given elsewhere [11, 12]. Similar techniques have also been developed independently by Newman and Armen [13], and Miyamoto [14]. The prescribed length of crack extension, Δl, is selected as one or two percent of the initial crack length, l_0, which is equal to a side length of crack tip triangular finite elements. Therefore, the incremental crack length in every loading cycle is always constant irrespective of stress amplitude, stress ratio and so on. The process of the crack extension is made by releasing the displacement constraint of the crack tip node, when the reaction force of it comes up to zero during the loading process. The kinematic hardening theory is assumed to take into account the Bauschinger effect to some extent in the analysis.

The characteristic values assumed in this analysis are as follows unless otherwise stated; Young's modulus E = 1.96 x 10^5 MN/m^2 (20000 kg/mm^2), strain hardening rate H' = 0.06E, and cyclic yield stress σ_y = 2.94 x 10^2 MN/m^2 (30 kg/mm^2). The specimen geometries selected for the present analysis are the centre-notched (CN) and the double-edge-notched (DEN) specimens as shown in Figures 1a and 1b. The analysis was made both under

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the plane stress and plane strain conditions.

RESULTS AND DISCUSSION

Before examining the influence of several factors on the fatigue crack closure behaviour, some basic results of the present analysis are presented. Figure 2 illustrates a typical example of variation of crack opening and closing levels as a crack propagates under a zero-tension plane stress loading condition. Semi-solid circles in the figure illustrate the stress levels at which the crack was extended in this case for reference. The crack closure at a positive load is really observed in the figure. The crack closure level rises as the crack propagates from the initial saw-cut crack and reaches a stabilized level after some crack extension. Figure 3 shows the behaviour of crack opening and closing processes after the crack closure level has been stabilized. It is noted that the crack closes at the crack tip first under the unloading process and opens up at the crack tip last under the loading process. This may be a characteristic behaviour of a propagating fatigue crack as pointed out in a previous paper [11].

Influence of Stress Level and Material Parameters

The influence of the stress or stress intensity level on the crack closure behaviour was examined by using CN specimens under zero-tension loading. The results are shown in Figures 4, 5 and 6. Figures 4 and 5 illustrate the stabilized crack closure level, σ_0, against the maximum stress, σ_{max}, and a dimensionless crack closure level, σ_0/σ_{max}, against σ_{max}, respectively.[*] The dimensionless crack closure level in Figure 5 is replotted in Figure 6 against the monotonic plastic zone size. The monotonic plastic zone size is defined here as the size along the crack growth direction as seen in Figure 6. In Figures 4, 5 and 6, the stabilized crack opening level could also be used instead of the closure level, but the trends of the behaviour would not be different. From Figures 4 and 5, the crack closure level rises as the stress level, σ_{max}, or the stress intensity level, K_{max}, increases under the plane stress condition, but it seems to be saturated at higher stress levels. The similar trend of increase is also observed under the plain strain condition, but the crack closure behaviour seems to be much different from that under the plane stress condition. On the other hand, the plot of Figure 6 shows that the dimensionless crack closure levels are not different between the two conditions, if the comparison is made on the basis of the plastic zone size instead of the nominal stress. From these results, it may be considered that there is no essential difference in the crack closure behaviour between the plane stress and plane strain conditions, although an apparent difference is observed to exist in the comparison on the nominal stress or stress intensity factor basis. These results may also indicate that the plastic zone size along the crack growth direction is one of the important parameters influencing the fatigue crack closure. The shape of the plastic zone itself seems to be less important.

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[*] The values of the stress intensity factors for σ_0 and σ_{max} are given by $K_0(\mathrm{MPa \cdot m^{1/2}}) = 9.35 \times 10^{-2}\ \sigma_0(\mathrm{MN/m^2})$ and $K_{max} = 9.35 \times 10^{-2}\ \sigma_{max}$, respectively. Therefore, $\sigma_0/\sigma_{max} = K_0/K_{max}$ and $U = \Delta K_{eff}/\Delta K = 1 - K_0/K_{max} = 1 - \sigma_0/\sigma_{max}$ in this case.

The material parameters examined in this study were the strain hardening rate and the cyclic yield stress. The influence of the strain hardening rate on the crack closure level is illustrated in Figure 7. Here the strain hardening rate, H', was varied as $0.006E$, $0.06E$ and $0.18E$, being the other characteristic values unchanged. Again the CN specimens were used for the analysis. As in Figure 7, the crack closure level rises as the strain hardening rate decreases. This trend is not different between the plane stress and plane strain condition. This effect of hardening rate on the crack closure level may be explained in terms of the induced compressive residual stress around the crack tip by the cyclic loading. The larger compressive residual stress is found to exist for the lower strain hardening rate as illustrated in Figure 8.

On the influence of the cyclic yield stress level on the fatigue crack closure, the present analysis predicts that the dimensionless crack closure level, σ_0/σ_{max}, remains unchanged, if the maximum stress is increased linearly with the increase of the yield stress so that the plastic zone size remains unchanged. This also indicates that a master curve expression could be made on a σ_0/σ_{max} versus σ_{max}/σ_y or K_{max}/σ_y plot. An example of the predicted crack closure behaviour for the zero-tension loading under the plane stress condition is illustrated in Figure 9. It is expected from this result that the crack closure level decreases at low stress or stress intensity levels while it increases at high stress or stress intensity levels, as the yield stress increases.

Effect of Bi-Axial Loading

The effect of bi-axial loading on the crack closure is examined using the CN specimens as shown in Figure 1a under the plane stress condition. A cyclic transverse stress, σ_2, is applied as well as the mode I cyclic loading, σ_1. The phases of the transverse stress are selected as 0° (in-phase, $\sigma_2/\sigma_1 = 1$) and 180° (out-of-phase, $\sigma_2/\sigma_1 = -1$). The analysis was made under a tention-compression loading as well as a zero-tension loading. The maximum stress, σ_{max}, is selected as 1.18×10^2 MN/m^2 (12 kg/mm^2) for all the cases analyzed.

The obtained results of the crack closure levels for those cases are shown in Table 1. For the tension-compression loading, the crack closure level is affected by the out-of-phase bi-axial loading, although it is little affected by the in-phase bi-axial loading. For the zero-tension loading, on the other hand, both the in-phase and out-of-phase bi-axial loadings give little effect on the crack closure.

In order to discuss this effect of bi-axial loading on the crack closure, the behaviour of the plastic zone is examined. Figure 10 illustrates the monotonic plastic zones as well as the cyclic plastic zones for all the cases analyzed. It is seen in the figure that the shape of the monotonic plastic zone is much influenced by the transverse stress, particularly the out-of-phase transverse stress, but that the plastic zone size along the crack growth direction is litted affected. It is also seen that the cyclic plastic zone size along the crack direction is much influenced by the tension-compression out-of-phase transverse loading, although it is little influenced by the other transverse loadings.

From the comparison of the crack closure behaviour in Table 1 with the plastic zone behaviour of Figure 10, it is found that the crack closure level seems to decrease as the cyclic plastic zone size along the crack growth direction increases, and that the shape of the plastic zone again seems to be less important factor in this case. It may be said from these results that the cyclic plastic zone size along the crack direction is another essential parameter which influences the fatigue crack closure behaviour as well as the monotonic plastic zone size along the crack direction.

Influence of Loading History

It has been found experimentally that the fatigue crack growth rate is much influenced by loading histories. This effect may be explained in terms of the fatigue crack closure. Here we examine the influence of continuously decreasing and increasing amplitude of loading on the crack closure behaviour. The effects of single overloading and block loading of high-low or low-high sequences were reported elsewhere [12]. The analysis was made on the DEN specimen as shown in Figure 1b under the plane stress zero-tension loading condition.

The results are illustrated in Figures 11a and b for the decreasing loading and Figure 11c for the increasing loading. In any cases the maximum stress, σ_{max}, was controlled so that a prescribed value of $d(\Delta K)/d(2l)$ was kept constant as a crack propagates. The dotted lines in the figures illustrate the crack closure levels for the current values of ΔK which were obtained from the analysis under the constant amplitude loading.

It is seen in the figures that the crack closure level is increased under the decreasing loading as compared with that under the constant amplitude loading, while it is decreased under the increasing loading. It is also seen that the higher decreasing rate of ΔK results in the higher crack closure level. Examining the behaviour of the plastic zone of these cases and comparing this with the crack closure behaviour obtained above, it is likely that the effect of loading histories become less remarkable under the conditions where the plastic zone extends ahead beyond the prior plastic zone with cyclic crack extension. Under the high decreasing rate of ΔK, the plastic zone could not extend beyond the prior one and this would result in the higher crack closure level as seen in Figure 11b. Further, it is noted that the decreasing load effect on the crack closure becomes remarkable as the initial value of the stress intensity factor range is increased, even if the decreasing rate of ΔK remains unchanged.

SUMMARY

The effects of several mechanical parameters on the fatigue crack closure were examined, and the essential factors influencing this phenomenon were explored. The present results showed that both the monotonic and cyclic plastic zone sizes along the crack growth direction seem to be important parameters which govern the fatigue crack closure phenomenon. Further study is needed for more understanding of this phenomenon.

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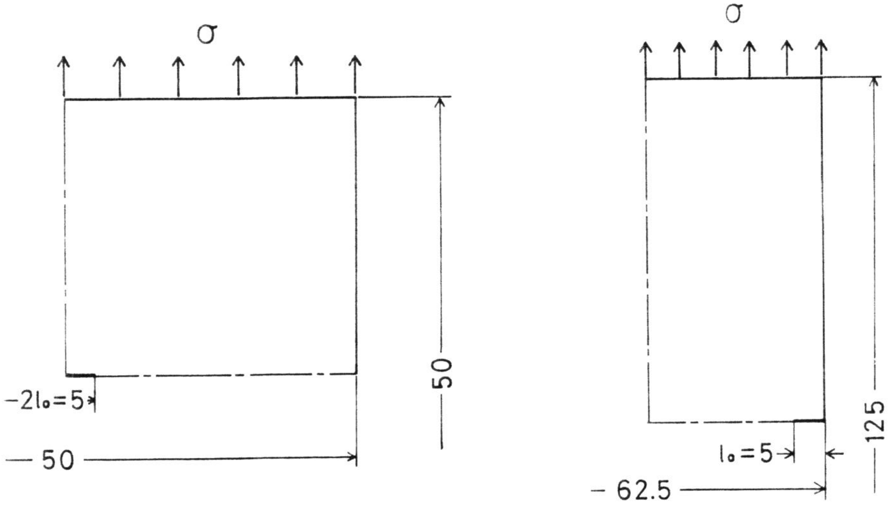


(a) CN Specimen

(b) DEN Specimen

Figure 1 The Specimen Geometries Analyzed (Length in mm)

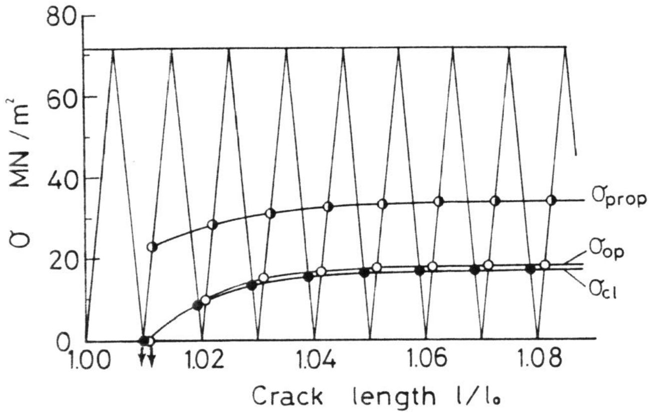


Figure 2 A Typical Example of Variation of the Crack Opening and Closing Levels with Crack Length (DEN Specimen, Zero-Tension Plane Stress)

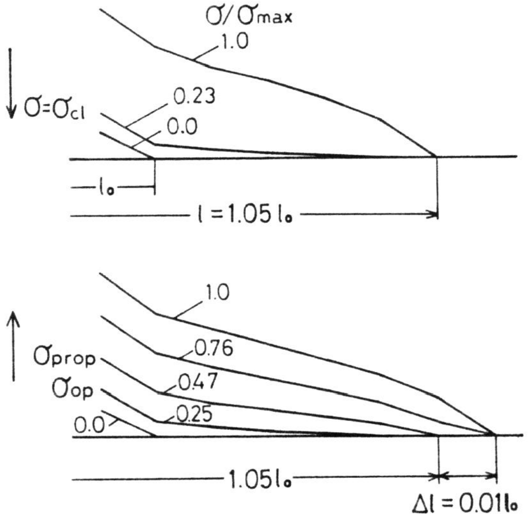


Figure 3 The Crack Closing and Opening Processes After The Crack Closure Level has Been Stabilized for the Example Shown in Figure 2

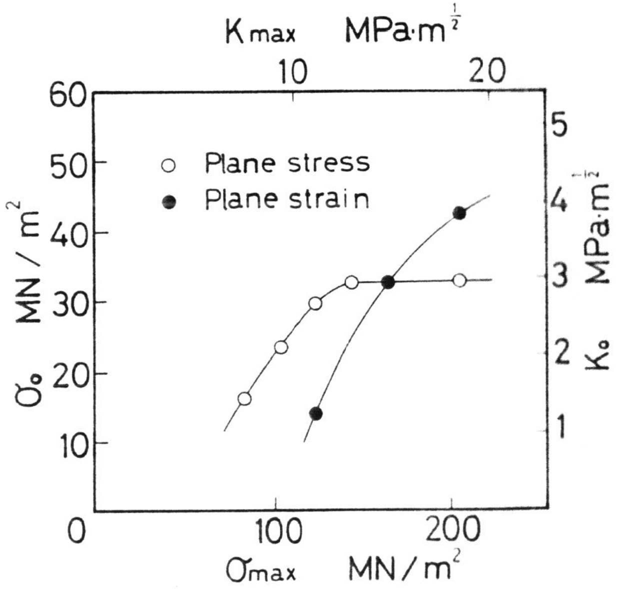


Figure 4 The Influence of the Stress or Stress Intensity Level on the Crack Closure Level

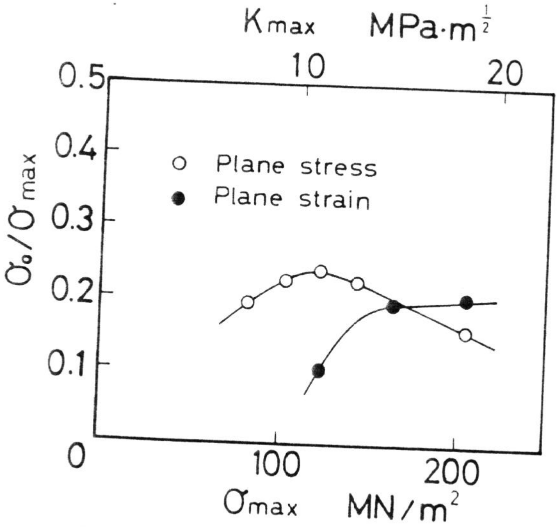


Figure 5 The Dimensionless Crack Closure Level as a Function of the Maximum Stress or the Maximum Stress Intensity Factor

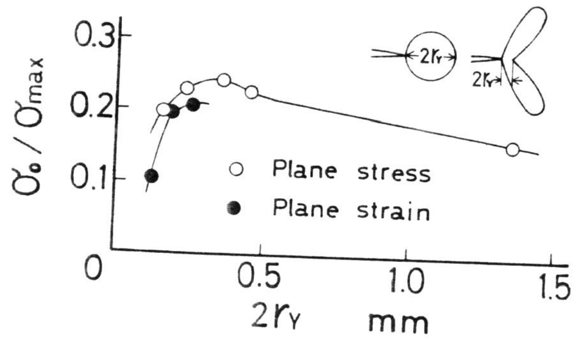


Figure 6 The Dimensionless Crack Closure Level as a Function of the Plastic Zone Size Along the Crack Growth Direction

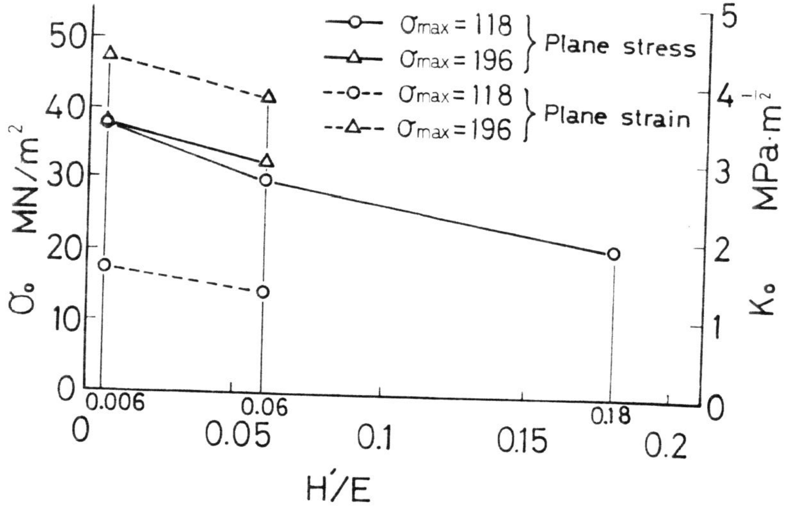


Figure 7 The Influence of the Strain Hardening Rate on the Crack Closure Level

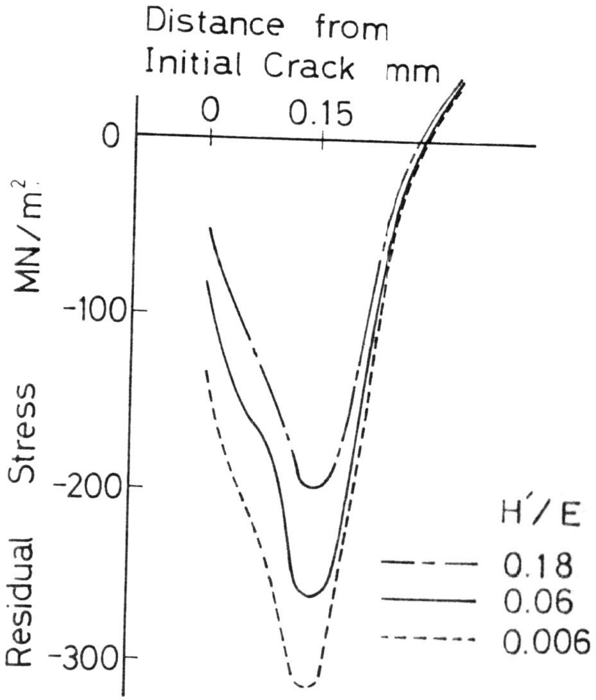


Figure 8 Comparison of the Residual Stress Distributions Around the Crack Tip for the Three Different Strain Hardening Rate

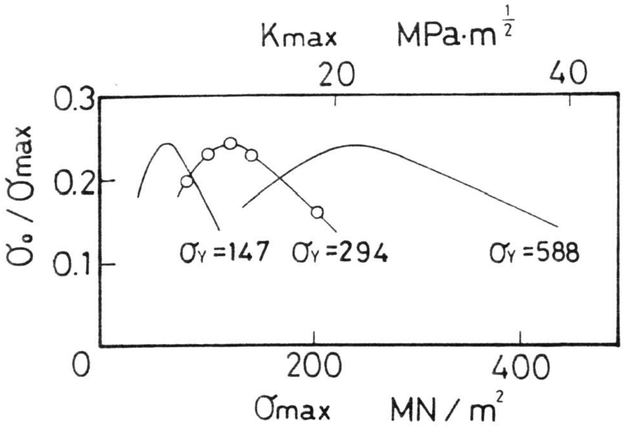
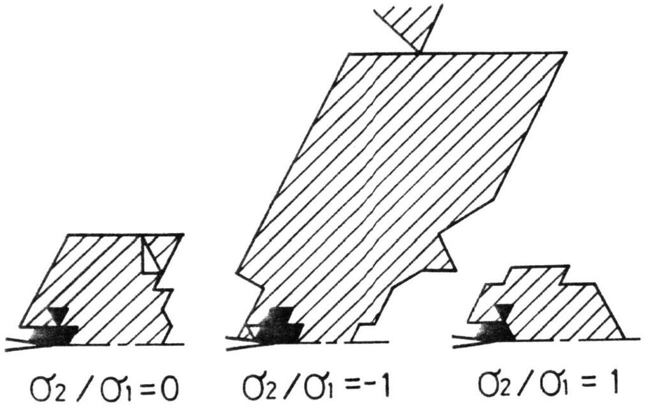
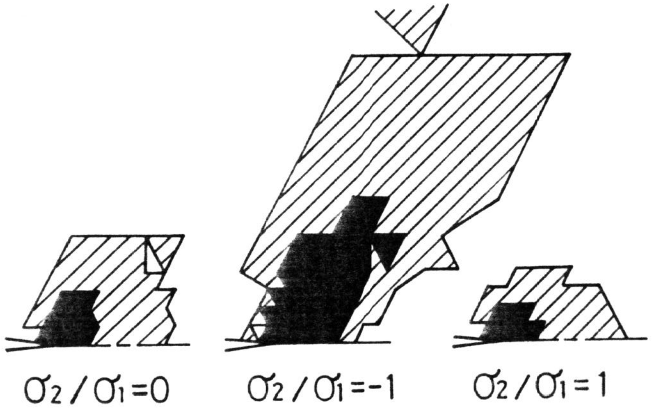


Figure 9 The Effect of the Cyclic Yield Stress Level on the Crack Closure Level under the Plane Stress Zero-Tension Loading

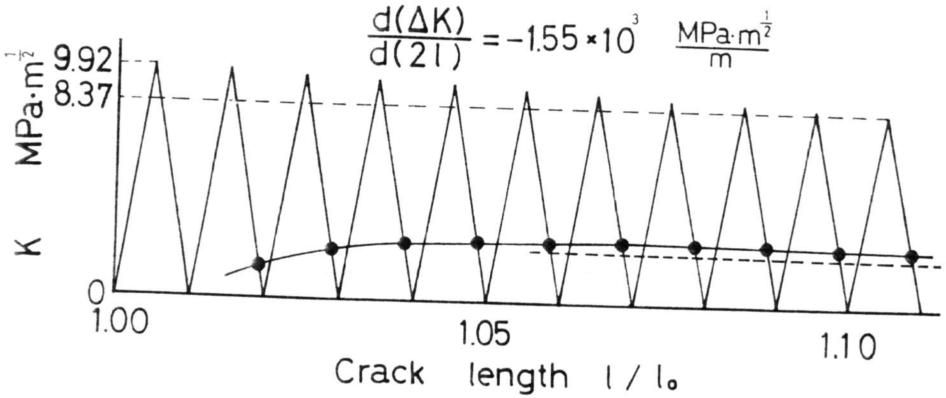


(a) zero-tension

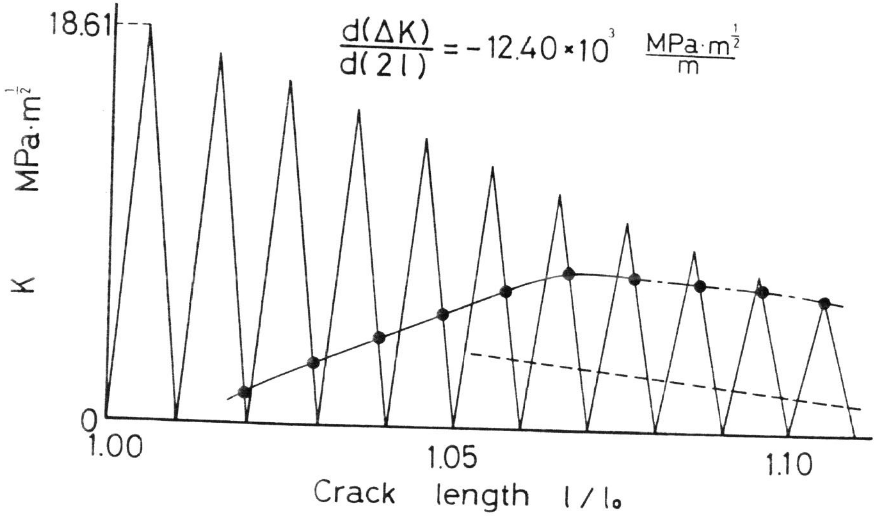


(b) tension-compression

Figure 10 Comparison of the Plastic Zones Around the Crack Tip Under the Bi-axial Loading

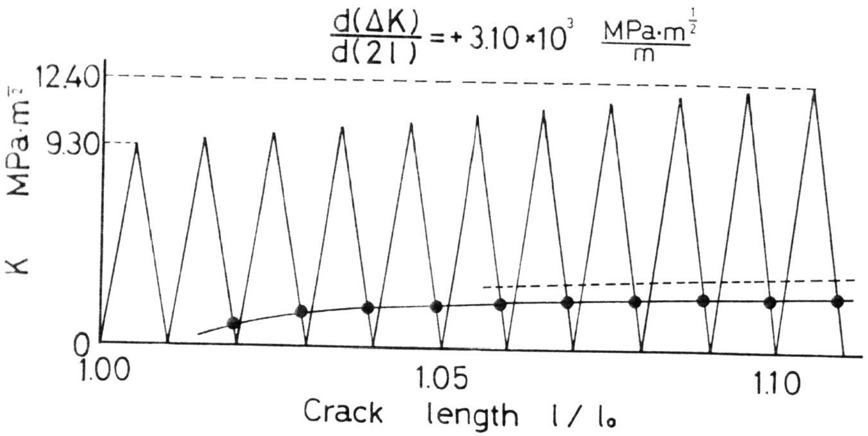


(a)



(b)

Figure 11 The Effect of Loading Histories on the Crack Closure Level



(c)

Figure 11 The Effect of Loading Histories on the Crack Closure Level

Table 1 The Effect of Bi-axial Loading on the Crack Closure Level

Loading Conditions		σ_0/σ_{max}	$U = \Delta K_{eff}/\Delta K$**
Zero-Tension $\sigma_1 = 0 - + \sigma_{max}$	$\sigma_2/\sigma_1 = 0$	0.24	0.76
	-1	0.26	0.71
	1	0.24	0.76
Tension Compression $\sigma_1 = \pm \sigma_{max}$	0	0.06	0.47
	-1	-0.20	0.60
	1	0.09	0.46

** $\Delta K = 2K_{max}$ for Tension-Compression