Fracture 1977, Volume 2, ICF4, Waterloo, Canada, June 19 - 24, 1977

OBSERVATION OF CRACK CLOSURE PHENOMENA AT THE TIP OF A FATIGUE CRACK BY ELECTRON MICROSCOPY

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INTRODUCTION

It can be considered that crack closure phenomena [1] are closely related to the threshold condition of a fatigue crack [2 - 7]. Therefore, one of the authors has previously carried out fatigue tests, using plain specimens and specimens with a transverse hole, and has measured the crack opening displacements of non-propagating cracks in both specimens during one stress cycle [2, 3]. In these experiments, crack opening displacement was determined from the change in separation of characteristic marks on an electropolished surface by using an optical microscope, so that it was difficult to measure the crack opening displacement in places where suitable marks were rare, and the accuracy of measurement was insufficient.

In the present study, fine closely spaced parallel lines (the direction of the lines being at 45° to the specimen axis) were drawn on the surface of a specimen with a hole and the characteristic behaviour near the tip of a crack initiated at the hole edge in rotating bending was determined by measuring the displacement of the fine lines on electron micrographs taken at several stress levels. By using this method, the opening and closing behaviour of cracks in a region within 10 μm from the crack tip can be compared quantitatively.

When the crack initiated at the hole edge propagates under rotating bending stress, the shape of the cracked surface is nearly semicircular irrespective of stress amplitudes, if the size of the crack is small [8, 9]. This means that the crack growth rate is nearly the same along the crack front and there is a one-to-one correspondence between the crack growth rates at the surface and at the interior. Therefore, it is considered that observation of crack closure phenomena at the specimen surface is meaningful, although the behaviour of a crack at the surfaces may be different from that at the interior [4, 10, 11].

MATERIAL, SPECIMENS AND TESTING METHOD

The material used was a rolled round bar (about 22 mm in diameter and about 5.5 m in length) of 0.19% C steel. The specimens were machined after annealing for 60 minutes at 1153 K. The specimens were polished with emery paper after turning. The plain specimens and the specimens with a transverse hole (0.5 mm in diameter and 0.5 mm in depth) were annealed in vacuum to eliminate residual stress for 60 minutes at 873 K and fatigue tests were carried out after the surface layer of the specimens had been electropolished to a depth of about 30 μm.

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The specimens for observation of crack opening displacement (specimens with a transverse hole and fine lines) were polished with emery paper after electropolishing to the depth of about 30 μm, and then the polished specimens were annealed in vacuum for 60 minutes at 923 K to eliminate residual stress. Finally, the lines were drawn near the transverse hole by using chromic oxide powder.

The chemical composition and mechanical properties of this material are shown in Table 1. Figure 1 shows the microstructures of the material. Figure 2 shows the design of specimens.

The testing machine used is an Ono-type rotating bending fatigue testing machine (capacity : 15 N-m, rate of stress repetition : 50 Hz).

Crack length under repeated stress was measured by an optical microscope (x 400), by stopping the testing machine occasionally. The crack length means the length along the circumference including the diameter of the small hole.

The behaviour of a crack during one stress cycle was observed in the electron microscope (transmission or scanning type) using a plastic replica taken from the surface including the tip of the crack under several stress levels. The crack opening displacement was obtained by measuring the displacement of fine parallel lines on electron micrographs (x 10,000) of the crack, as shown in Figure 3. In the measurement of crack opening displacement, the vector of bending moment was taken to be perpendicular to the direction of the transverse hole.

RESULTS AND DISCUSSION

Figure 4 shows S-N curves of plain specimens, specimens with a hole, and specimens with a hole and lines. From this figure, it can be seen that there is no difference between the specimens with a hole and the specimens with a hole and lines.

Figure 5 shows an example of a non-propagating crack appearing in a specimen with a hole and lines. All of the following results are concerned with specimens with a hole and lines.

Figure 6 shows the crack propagation curves under a constant stress level.

Figure 7 shows the crack propagation curves when the stress level is raised by a step of 9.8 MPa after 10^7 cycles. In this case, the crack growth rate after the change in stress level becomes slightly smaller than that under a constant stress level, owing to a coaxing effect.

Figure 8 shows the crack propagation curves when the stress level is raised by a step of 4.9 MPa after each 10^7 cycles. In this case, the increase in fatigue limit due to the coaxing effect is 4.9 MPa.

Figure 9 shows the crack propagation curves when the stress at the fatigue limit, σ = 162 MPa, is applied after the crack size became almost equal to the size of a non-propagating crack under repetitions of an overstress, σ = 196 MPa, where non-propagating crack implies the one produced under the stress at the fatigue limit, σ = 162 MPa.

The crack opening displacement within 70 μm of the tip of the crack was measured on the electron micrographs of cracks taken under the conditions shown in Figures 6 - 9. The results are shown in Figures 10 - 13, 15 and 16.

In this experiment, it may be considered that the error of the measurement is within ±0.01 μm in the case of the transmission electron microscope.

The accuracy of the measurement by the scanning electron microscope is considerably lower than that of the transmission type.

Figure 10 shows the crack opening displacement of the non-propagating crack at a stress equal to the fatigue limit after 10^7 cycles at the limit σ = 162 MPa, and the opening displacement of the same crack due to an overstress σ = 172 MPa. (This crack continued to propagate until fracture at this stress.)

Figure 11 shows the crack opening displacement of the propagating crack under an overstress, σ = 167 MPa, after 10^7 cycles at the limit σ = 162 MPa. This crack stopped propagating after slight propagation, owing to the coaxing effect.

Figure 12 shows the crack opening displacement of the non-propagating crack in the case when σ = 167 MPa was repeated for 10^7 cycles after 10^7 cycles at the limit σ = 162 MPa. This crack is a non-propagating crack as the fatigue limit was raised by the coaxing effect.

Figure 13 shows the crack opening displacement of the propagating crack under the constant stress level σ = 167 MPa. This crack is nearly equal in size to the non-propagating crack in the case where the fatigue limit was raised to 167 MPa by the coaxing effect.

Figure 14 shows the electron micrographs near the tip of the crack shown in Figure 13.

Figure 15 shows the crack opening displacement of the propagating crack under a constant stress level, σ = 196 MPa. The crack is nearly equal in size to the non-propagating crack obtained after 10^7 cycles at σ = 162 MPa. This crack propagated slightly after the change in stress level from 196 to 162 MPa, but did not propagate further (see Figure 9).

Figure 16 shows the crack opening displacement of the non-propagating crack after 10^7 cycles at σ = 162 MPa on the crack shown in Figure 15.

The experimental results are summarized as follows:
1) In the case when the fatigue cracks stop propagating, the crack opening displacements due to the maximum tensile stress during one stress cycle are nearly equal to each other within 10 μm from the crack tip (Figures 10, 12 and 16). The tip of the non-propagating crack is then almost closed even under the maximum tensile stress, so far as it is observed on the surface (Figures 10, 12 and 16). The crack opening displacement was measured on the non-propagating cracks formed in the case when a certain constant stress was repeated from the beginning, in the case when the fatigue limit was raised by coaxing effect, and in the case when the stress level was dropped. Judging from these experimental results, it seems that opening and closing behaviour near the tips of the non-propagating cracks was similar, and that the crack tips were almost closed, so far as surface observation showed, although it is considered that there

are many cases where a crack stops propagating. The crack opening displacement due to the maximum stress during one stress cycle is then 0.03 - 0.05 μm at the point 10 μm distant from the crack tip.
2) In the case where the fatigue limit is raised by the coaxing effect, the crack tip is clearly open just after the stress level is changed to the final fatigue limit.

However, the crack opening is considerably smaller in comparison with that of a crack of almost the same size which is produced by the stress of final fatigue limit from the beginning (Figures 11 and 13).

Therefore, in the case where the fatigue limit is raised by the coaxing effect, the crack stops propagating after slight propagation in the early stages. From this result, it can be concluded that the opening near the crack tip is clearly different depending on the stress history, even in the case where the same stress is repeated in specimens with a crack of the same size.
3) In Figure 15, the crack has the same size as the non-propagating crack formed after 10^7 cycles at the fatigue limit. In this case, the opening of the crack tip can be seen under the tensile stress σ = 152 MPa. If a crack of the same size is formed at a stress of σ = 162 MPa from the beginning, the tip of the crack will not open at this stress. This result explains why a few repetitions of an overstress in rotating bending fatigue tests of cracked specimens accelerate the propagation of the crack [12].
4) The opening of the non-propagating crack formed in the case where the stress is dropped from σ = 196 MPa to σ = 162 MPa, is larger, except near the crack tip (i.e. within 10 μm) than the opening of the non-propagating crack formed in the case where the stress of σ = 162 MPa is repeated from the beginning or the fatigue limit is raised by the coaxing effect (Figures 10, 12 and 16).

CONCLUSIONS

1) When fatigue cracks stop propagating, the crack opening displacements due to the maximum tensile stress are nearly equal to each other within 10 μm of the crack tip. The tip of the non-propagating crack is then almost closed, even under the maximum tensile stress, so far as can be seen on the specimen surface.
2) In the case where the fatigue limit is raised by the coaxing effect, the crack tip is open just after the stress level has been raised. However, the crack opening is considerably smaller in comparison with the opening of a crack of the same size formed by stress repetitions of the final fatigue limit from the beginning.
3) The opening near the tip of a crack formed by repetitions of an overstress is larger than that of a crack of the same size formed by repetitions of the stress at the fatigue limit, under the same tensile stress.

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Table 1 Chemical Composition (%) and Mechanical Properties of 0.19% C Steel

C	Si	Mn	P	S	Cu	Ni	Cr
0.19	0.24	0.45	0.012	0.016	0.10	0.07	0.15

Lower yield point	=	273 MPa
Ultimate tensile strength	=	456 MPa
Elongation	=	29.5 %
Reduction of area	=	62.4 %

(a) (b)

Figure 1 Microstructures of the Material
(a) Longitudinal Section
(b) Transverse Section

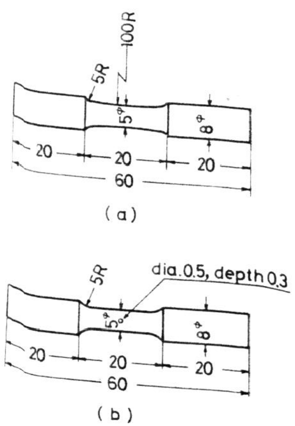


Figure 2 Shapes of Specimens (Unit; mm)
(a) Plain Specimen
(b) Specimen with a Transverse Hole

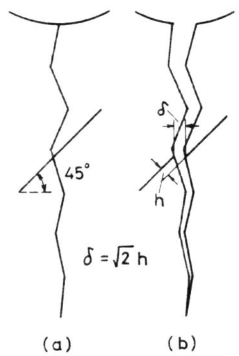


Figure 3 Measuring Method of Crack Opening Displacement δ
(a) Under Compression
(b) Under Tension

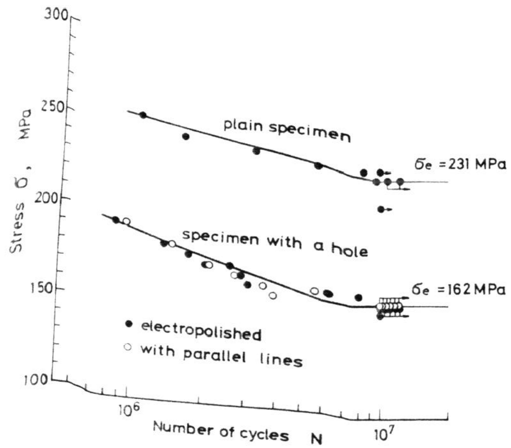


Figure 4 S-N Curves of Each Specimen

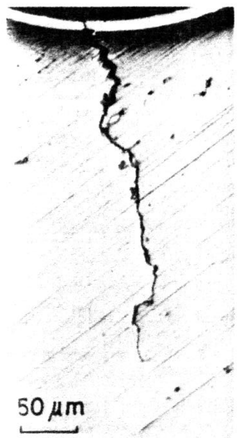


Figure 5 An Example of a Non-Propagating Crack Appearing in a Specimen with a Hole and Lines

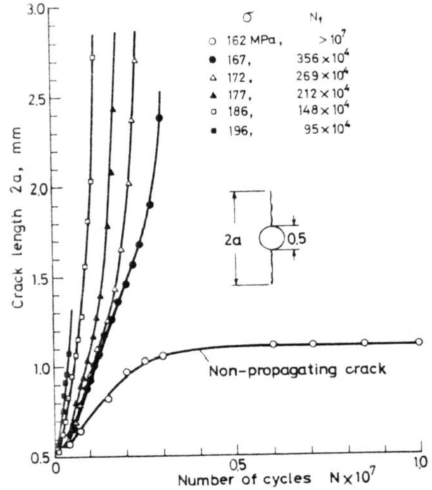


Figure 6 Crack Propagation Curves Under Constant Stress Levels

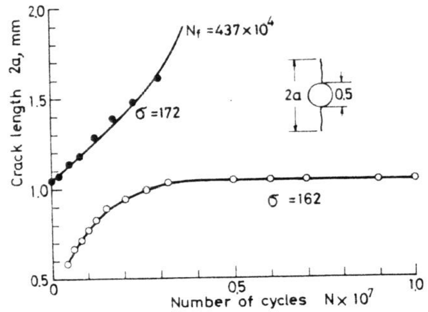


Figure 7 Crack Propagation Curves in the Case when the Stress Level is Raised by a Step of 9.8 MPa after each 10^7 Cycles

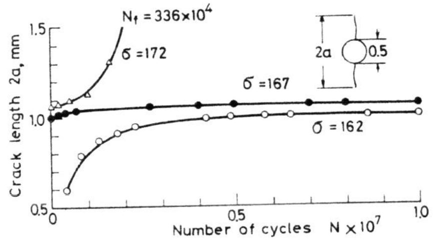


Figure 8 Crack Propagation Curves in the Case when the Stress Level is Raised by a Step of 4.9 MPa after each 10^7 Cycles

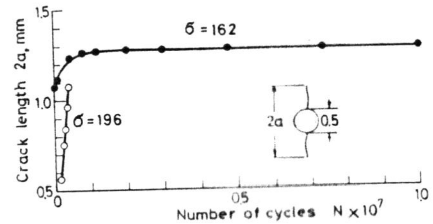


Figure 9 Crack Propagation Curves in the Case when the Stress Level is Dropped from an Overstress to the Stress at the Fatigue Limit

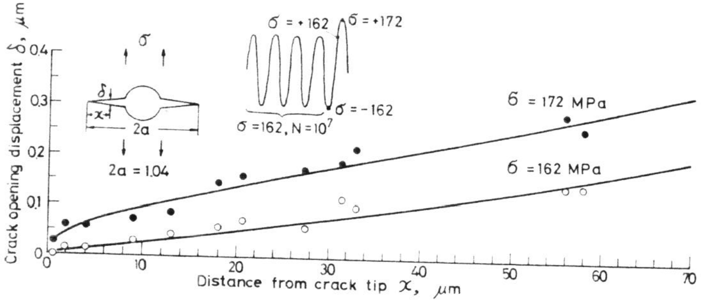


Figure 10 Crack Opening Displacement of the Non-Propagating Crack After 10^7 Cycles at the Fatigue Limit (by Transmission Type)

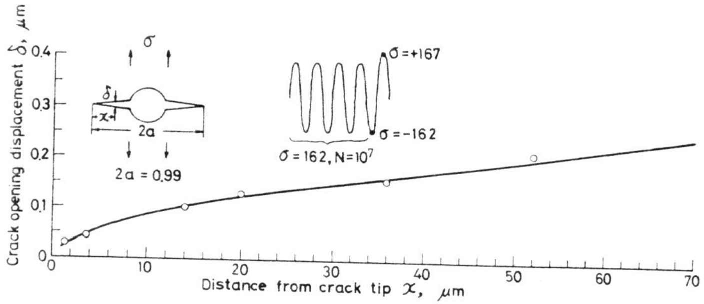


Figure 11 Crack Opening Displacement of the Propagating Crack Under an Overstress just after 10^7 Cycles at the Fatigue Limit (by Scanning Type)

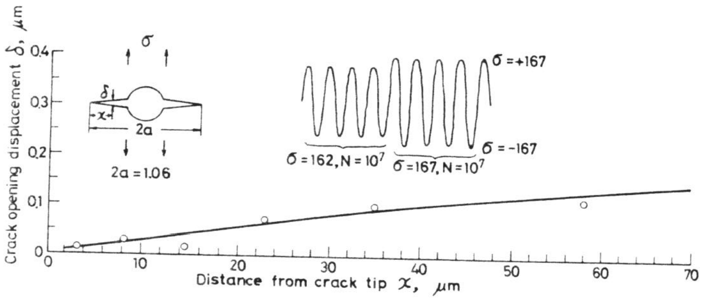


Figure 12 Crack Opening Displacement of the Non-Propagating Crack in the Case when the Fatigue Limit is Raised by the Coaxing Effect (by Scanning Type)

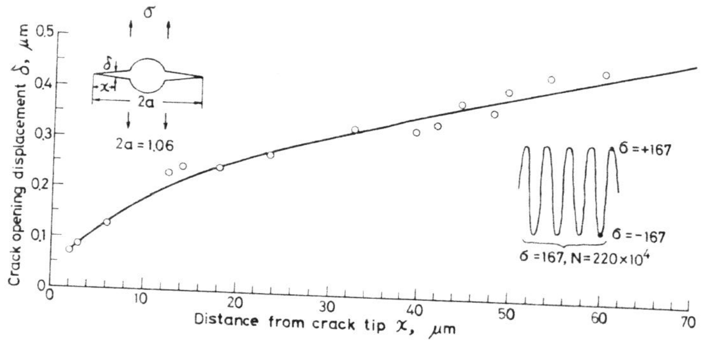
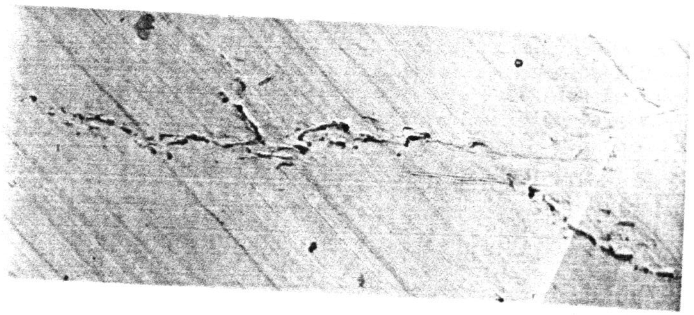


Figure 13 Crack Opening Displacement of the Propagating Crack under a Constant Stress Level σ = 167 MPa (by Transmission Type)



(a)

(b)

Figure 14 Electron Micrographs Near the Tip of the Propagating Crack Shown in Figure 13

(a) Under the Minimum Stress σ = -167 MPa
(b) Under the Maximum Stress σ = +167 MPa

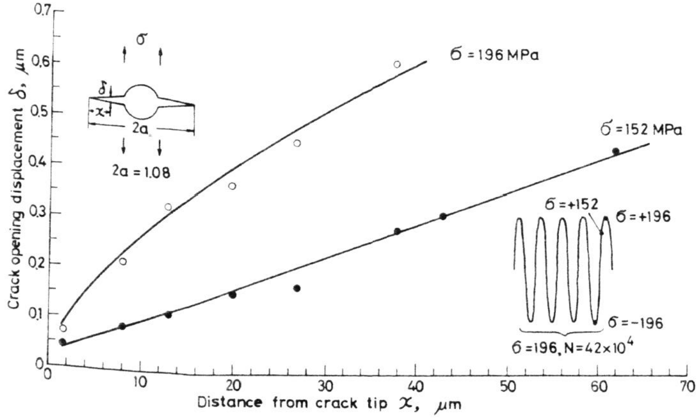


Figure 15 Crack Opening Displacement of the Propagating Crack Under a Constant Stress Level σ = 196 MPa (by Transmission Type)

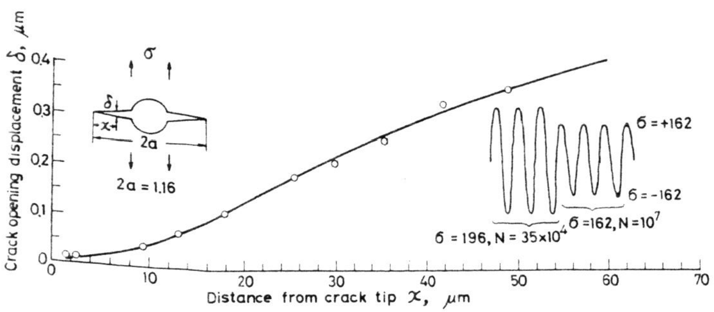


Figure 16 Crack Opening Displacement of the Non-Propagating Crack Formed in the Case when the Stress is Dropped from an Overstress to the Stress at the Fatigue Limit (by Transmission Type)