DIRECT SEM OBSERVATIONS OF GROWING FATIGUE CRACK

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Fatigue crack growth experiments were conducted on grain-orientated silicon iron in a high-resolution, field emission type scanning electron microscope equipped with specially designed servo-hydraulic fatigue loading system and direct, real time observations of crack growth were made. Both microscopic and macroscopic crack growth directions were found to change with growth rates, indicating that there exists close interrelationship between fatigue crack growth rate and growth mode. Microscopical closure behavior at the crack tip during one loading cycle was investigated and compared with the closure behavior mechanically monitored by unloading elastic compliance technique.

INTRODUCTION

The study of fatigue crack growth mechanisms is important for substantial understanding and accurate prediction of fatigue crack growth behavior. A considerable amount of microscopical approaches has been made to identify detailed mechanisms[1-3]. However, the majority of them has been based on post growth observations. One of most desirable approaches may be to make direct, real time observations of growing fatigue crack.

In the early work, one of the present authors and others have designed fatigue loading facilities operating in SEM to realize such a approach, and have conducted fatigue crack growth tests on grain-orientated 3% silicon iron to elucidate the mechanism of Mode I crack growth. The principal results obtained have been reported elsewhere[4, 5].

In this work, in order to investigate the dependence of microscopical crack growth modes on growth rates, fatigue crack growth tests were carried out under ΔK-increasing-decreasing loading condition in a high-resolution field emission SEM and growing fatigue cracks were stroboscopically observed. In addition, static sequential observations were made to study microscopical closure behavior at the crack tip.

MATERIAL AND EXPERIMENTAL PROCEDURE

The material investigated is grain orientated 3% silicon iron. Its chemical composition and mechanical properties are given in Table 1.

The dimensions and crystallographic orientation of test specimen are shown in Fig. 1. The loading axis is perpendicular to the rolling direction, [100]. When the specimen is stressed, among four slip directions only two

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TABLE 1 - Chemical composition (%) and mechanical properties

C	Si	Mn	S	O	Yield point MPa	Tensile strength MPa	Reduction of area %
0.006	3.03	0.09	0.009	0.0194	290	385	61.6

slip directions, [1$\bar{1}$1] and [11$\bar{1}$], lying in the plane of the sheet can operate and since other slip directions, [111] and [$\bar{1}$11], in the plane perpendicular to the sheet do not operate, nearly perfect plane strain deformation results even right on the specimen surfaces[4,6,7]. The specimens were mechanically polished with emery papers and finally electro-polished. Fine magnesium oxides were scattered on a surface of the specimen as location markers and then the surface was gold coated to enhance resolution in SEM images.

Fatigue crack growth tests were performed on the stage of SEM using a specially designed servo-hydraulic testing system at a stress ratio of zero at a frequency of 0.5 Hz. Whenever necessary, the loading frequency was reduced to 0.1 Hz to observe the crack tip region stroboscopically at maximum load and positive photographs were taken. The technical details for stroboscopically observing SEM images has been described elsewhere[5].

The load-point displacement was detected with a beam type extensometer and the bulk closure behavior of fatigue crack was monitored throughout testing by mini-computer aided unloading elastic compliance technique[8]. As the test material plastic-deforms easily, the hysteresis loop obtained by the technique normally involves plastic deformation component even at low stress intensities,as demonstrated in Fig. 2(a), which makes it difficult to identify the crack opening level. An attempt was made to eliminate the plastic deformation component from the hysteresis loop of Fig. 2(a) by means of computer programming. The resultant loop so obtained is shown in Fig. 2 (b), where the crack opening point can be determined more easily.

In addition, sequential still-microphotographs of the crack tip region were obtained during one loading cycle to investigate microscopical closure behavior at the crack tip in detail.

EXPERIMENTAL RESULTS AND DISCUSSION

Fatigue crack growth directions and growth rates

Figure 3 shows the microscopic growth direction and macroscopic path of fatigue crack advancing under ΔK-increasing-decreasing sequence as illustrated in the upper part of the figure. The microscopical results are dynamic, real time observations, while the macroscopic crack path is photographed after the test was finished. Fatigue crack growth directions are found to vary with the change of ΔK, both macroscopically and microscopically.

If the macroscopic and microscopic growth directions are defined as the directions over the distance of 0.3-0.5 mm and 1-2 μm behind the crack tip, respectively, the growth directions vary with crack length as shown in Fig. 4(a). θ therein denotes the deviation angle from the ideal Mode I crack growth direction. The crack opening ratio, U, and growth rate, da/dn, are also plotted against crack length in Figs. 4(b) and (c). In the early growth zone of 0.3 mm which is thought to be the starting-notch affected zone, the macroscopic growth direction, θ_{mac}, is about 15°. For a while

after crack passed the zone, macroscopic crack advances at an angle of 30° and then, θ_{mac} decreases with increase of da/dn, until θ_{mac} becomes zero at a growth rate of about 1×10^{-7} m/cycle. Under ΔK-decreasing, θ_{mac} increases as da/dn decreases, adversely.

On the other hand, the microscopic growth direction, θ_{mic}, is almost 55° coincident with the slip direction, when crack grows at a low growth rate as 1×10^{-8} m/cycle in the outside of the notch affected zone. As da/dn increases, θ_{mic} approaches to zero, similar to θ_{mac}, but as found in Fig. 3, crack advances microscopically in zigzag manner until nearly perfect Mode I crack growth will be realized in the high growth rate region above 1×10^{-7} m/cycle. Under ΔK-decreasing, θ_{mic} increases as da/dn decreases, but the dependence of θ_{mic} on da/dn appears rather different from that under ΔK-increasing.

These observations indicate that fatigue crack growth directions are closely correlated with growth rates, and the lower the growth rate is, the more crack growth involves Mode II component. Further, this finding means Fig. 4(b) shows that the crack opening ratio, U, decreases as Mode II growth becomes significant.

Figure 5 shows fractographs obtained at the locations as indicated in Fig. 3. With the change in crack growth mode, fracture surfaces are found to vary from asperate, transgranular surfaces at low growth rates in the mixed Mode of I and II to striated ones in the high growth rate region of Mode I growth. Fracture surface irregularities appear more marked at intermediate growth rate than at low and high growth rates.

From the observations of growth mode and fracture surfaces it is inferred that when the applied ΔK is so high that two preferential slip directions operate to identical extent, simultaneously, fatigue crack grows in Mode I through the striation mechanism. However, at lower ΔK levels, normally one slip direction operates more intensely relative to the other, which results in the mixed growth Mode of I and II , and after certain period alternatively the other becomes more activated,so that crack advances microscopically in zigzag manner. Further, since the period while each slip direction operates more actively,varies depending on ΔK levels, eventually macroscopic growth direction deviates from the ideal Mode I growth, depending on ΔK levels or corresponding growth rates. It is worthy of note that except for the high growth rate region above about 1×10^{-7} m/cycle, fatigue cracks normally grow in the mixed Mode of I and II even in macroscopical sense.

According to the crack growth mechanism just described it is easily anticipated that at lower ΔK levels, fracture surface roughness significantly affects fatigue crack closure, as proposed originally by Minakawa and McEvily[9]. However, more importantly, fractographical study indicates that the roughness is more marked at intermediate growth rates than at extremly low ones. This finding may be expected to provide an important clue to reasonable explanation of complicated closure behavior in near threshold region appearing under ΔK-decreasing, although more detailed work needs to be done.

Fatigue crack growth rates were plotted against stress intensity range, ΔK, and effective stress intensity range, ΔK_{eff}, in Fig. 6. Crack growth rates in terms of ΔK are slower due to loading sequence effect under ΔK -decreasing than under ΔK-increasing. However, in the da/dn versus ΔK_{eff} plots there is found no difference between under ΔK-increasing and under ΔK -decreasing, indicating that fatigue crack growth rate is fundamentally governed by the effective stress intensity range in the vacuum environment.

as well as in the normal atmosphere.

Crack closure behavior during one loading cycle

Figure 7 shows sequential still microphotographs of fatigue crack tip region during unloading-reloading one cycle. The fine-lined loop in the figure denotes the load-differential displacement hysteresis during sequential observation, while the bold-lined one is the hysteresis dynamically monitored under cyclic loading of 0.5 Hz just before breaking fatigue test to begin the observation. The crack is nearly Mode I crack so that the crack preceeds in the direction perpendicular to the loading axis and the crack tip blunts extensively at maximum load. As load decreases, the crack opening displacement decreases from full blunted state at maximum load and near Point 4 the crack begins to close from the crack tip. At zero load the crack tip closes almost fully, but over relatively long distance behind the crack tip contact occurs mainly at fracture surface asperities. On reloading, the crack tip begins to open before Point 7 is reached and thereafter, crack opening displacement increases monotonically. Such microscopical closure behavior at each observation point is almost consistent with the behavior anticipated from the macroscopically monitored fine-lined hysteresis loop.

In sequential observation where load is hold as applied while taking photographs, holding load particularly at maximum level causes often the increase in displacement, as can be found in Fig. 7. The increase in displacement results in the increase in CTOD so that the crack will close at much lower level than under cyclic loading without accompanying load holding. Therefore, the crack closure behavior in sequential observation is not always representative of true closure behavior of growing fatigue crack, particularly for unloading process. However, the crack opening point which will be determined as the tangential point of the loading part of load - differential displacement hysteresis loop with the vertical line, is almost identical for both sequential observation and cyclic loading.

Figure 8 shows another example of crack closure. In this case the crack path has been abruptly bent at 2μm behind the crack tip as if rather large debris had adhered on a crack wall, and two small cracks of different length whose directions are coincident with the preferential slip directions, emanate from the blunted crack tip. Nucleation of such small cracks at blunted crack tips has been frequently observed,particularly in the intermediate growth rate region. Decreasing load from maximum level, crack walls shift in both vertical and slip directions and small cracks fully close before Point 4 is reached. At Point 4, the debris-like bent portion behind the blunted crack tip begins to contact against the opposite crack wall, although the blunted crack tip opening displacement is still large. In this example, considerable mismatch is found even at minimum load. On reloading, the crack opens forward to the crack tip, reversely. The microscopically observed crack opening level coincides well with the anticipated one from the hysteresis loop.

The above microscopical observations of crack closure indicate that fatigue cracks normally close backward from the crack tip on unloading, and on loading open forward to the crack tip. However, even at fully unloaded state crack walls usually contact discontinuously with microscopically considerable mismatch in the near crack tip region. This finding may mean that fracture surface roughness plays more important role in crack closure phenomenon than as has been expected, particularly for ductile materials.

CONCLUSIONS

Direct, real time observations of growing fatigue crack under cyclic loading and detailed study of microscopical crack closure behavior were made. The dependence of fatigue crack growth mechanism on the load level was also discussed. The principal conclusions obtained are summarized below:

(1) Fatigue crack growth directions are closely interrelated with growth rates, so that the lower the growth rate is, the more crack growth involves Mode II component.

(2) Crack growth mode influences the crack opening ratio, U.

(3) Fatigue crack normally closes backward from the crack tip on unloading, and on loading opens forward to the crack tip. However, even at fully unloaded state crack walls contact discontinuously with microscopically considerable mismatch in the near crack tip region.

(4) The crack opening point measured by the unloading elastic compliance technique is found to agree well with the microscopically observed crack opening point.

(5) Fatigue crack growth rate is essentially governed by the effective stress intensity range for the vacuum environment as well as for normal atmosphere.

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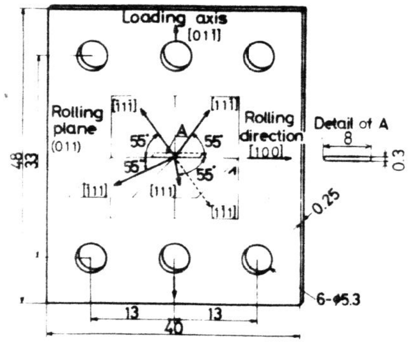


Fig. 1 Dimensions and crystallographic orientation of test specimen

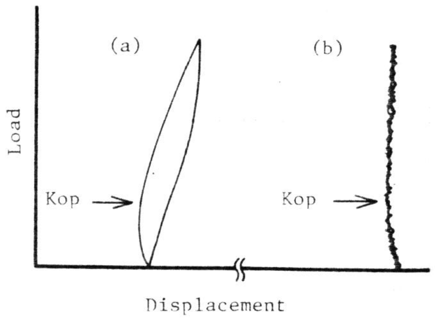


Fig. 2 Load - differential displacement hysteresis loop

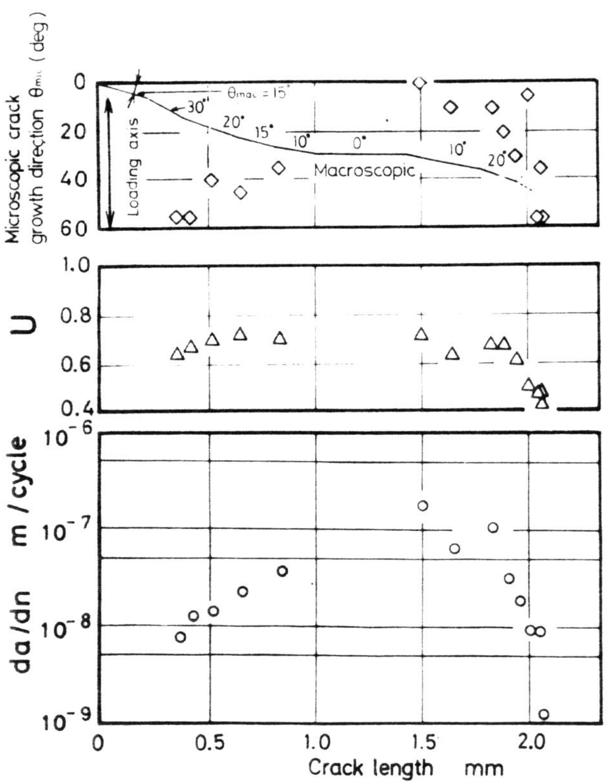


Fig. 4 Behaviors of crack growth mode, opening ratio and growth rate

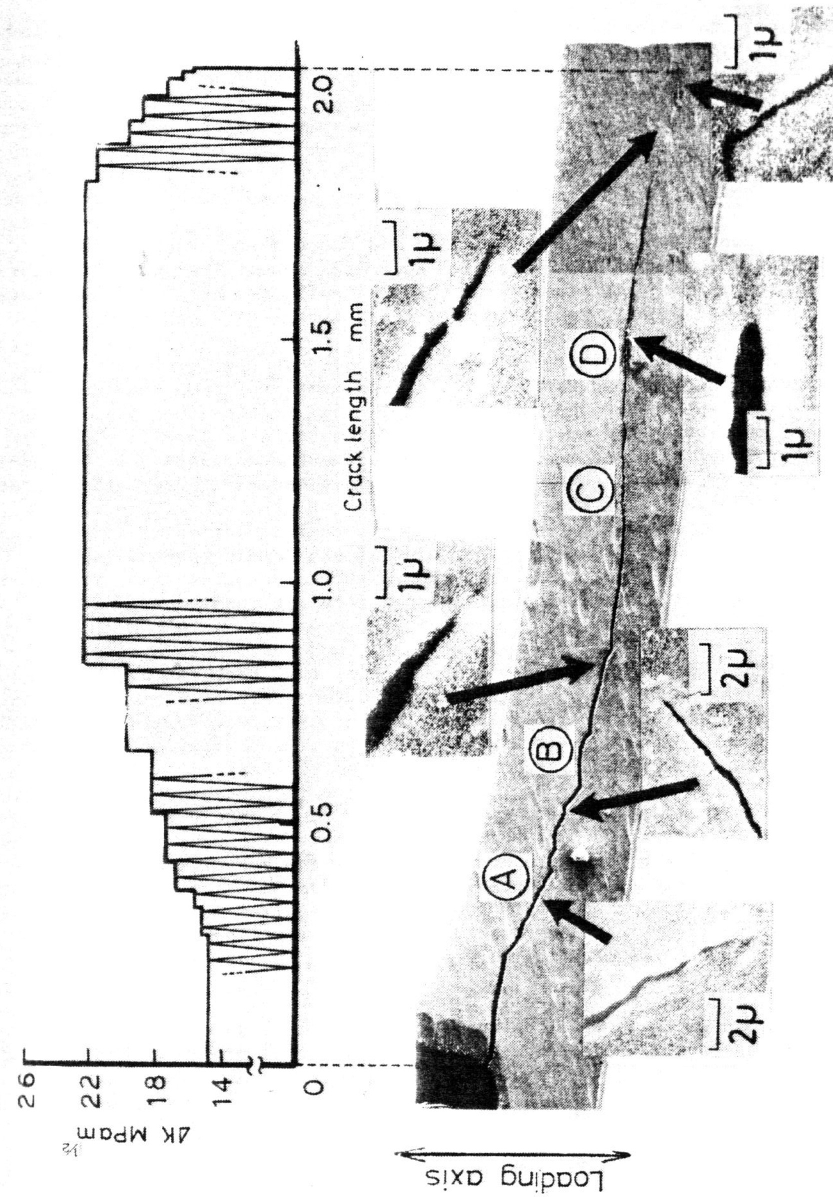


Fig. 3 Macroscopic crack path and microscopical observations of growth directions

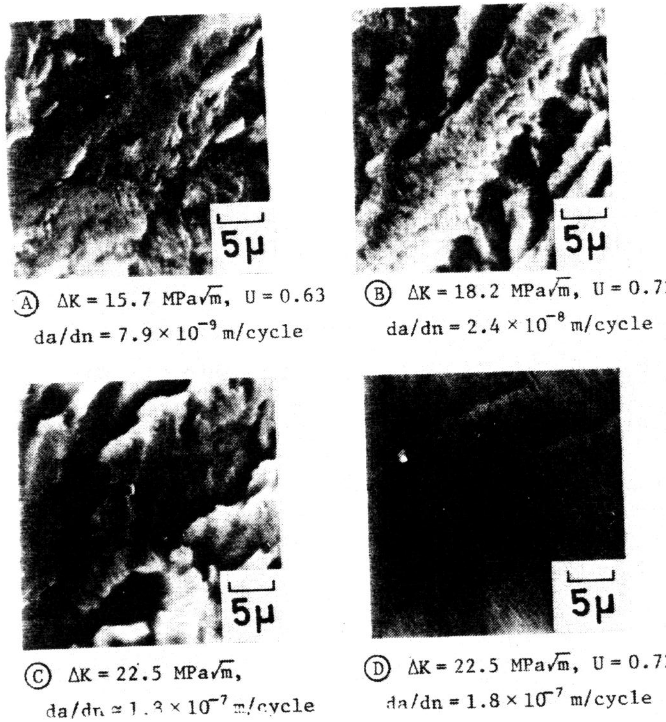


Fig. 5 Fractographs of fatigue fracture surface

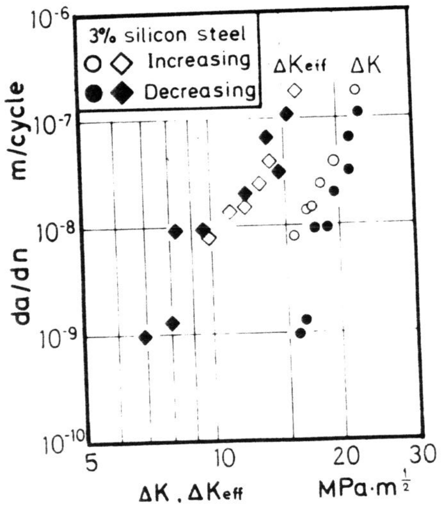


Fig. 6 Relationships between da/dn and ΔK, ΔK_{eff}

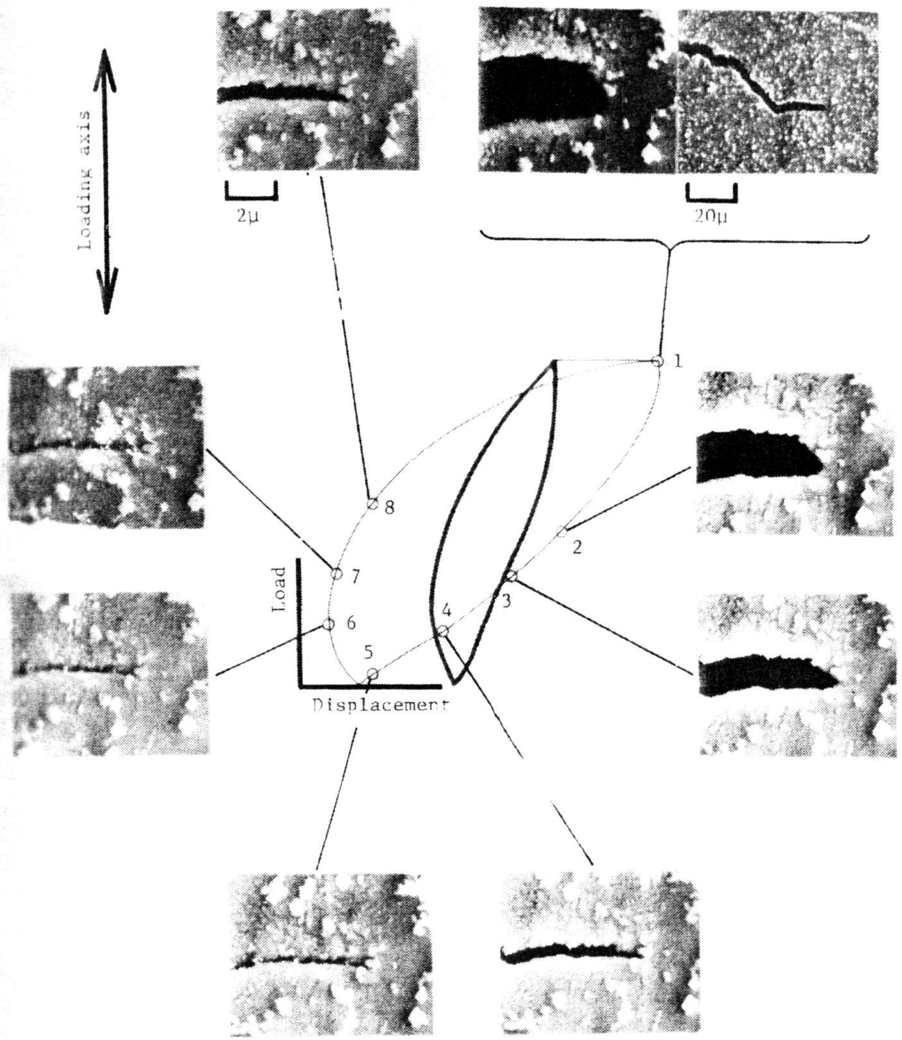
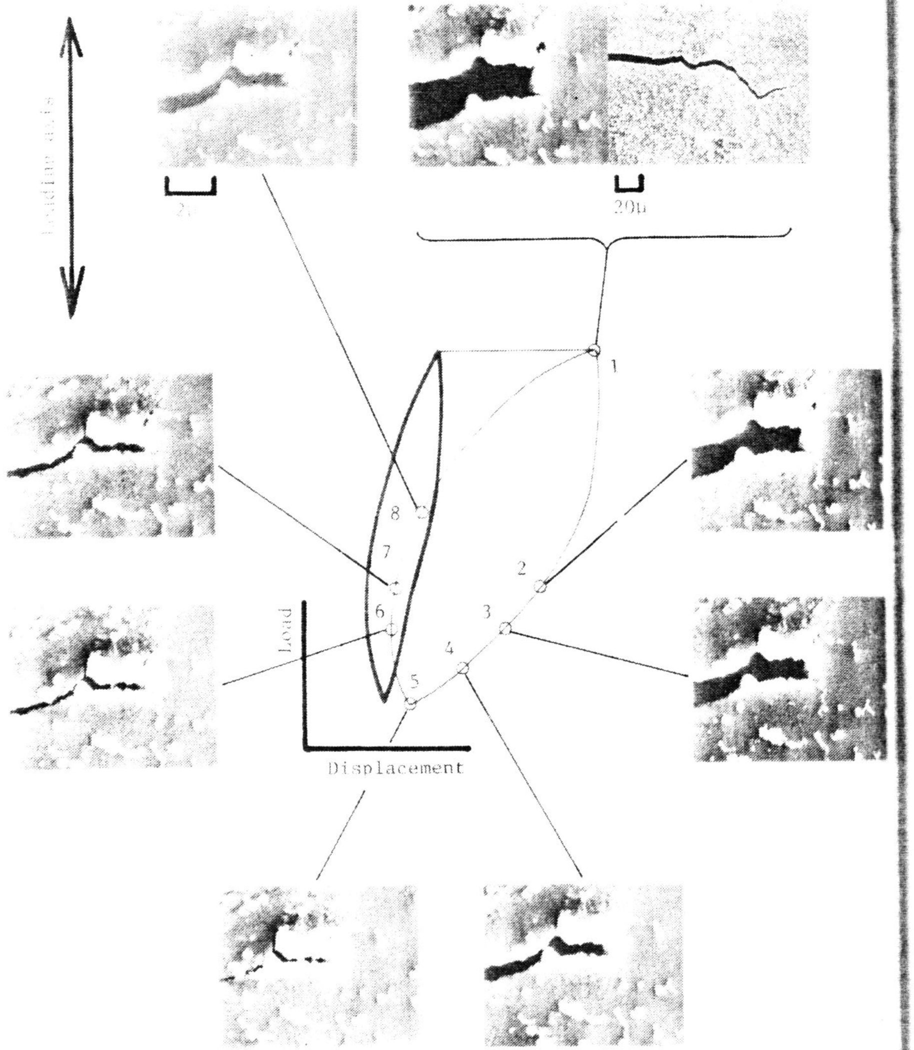


Fig. 7 Sequential observations of fatigue crack tip during one loading cycle - I



g. 8 Sequential observations of fatigue crack tip during one loading cycle - II