PAPER 70 (SESSION V)

Kinetic aspects of fatigue crack propagation

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Summary
An experimental study has been made of the geometrical changes at the tip of a growing fatigue crack by a plastic replication method. The results show that the so-called earing region attributed to the blunting and the resharpening of the crack tip was formed after 10 to 20 or more cycles, and did not correspond to each cycle. The crack propagation rate was also measured and showed that a crack propagates in a discontinuous manner.

A nucleation theory of fatigue crack propagation is shown to fit the data quantitatively and implies that fatigue life is the sum of a frequency dependent component and stress cycle dependent component.

Introduction

It is convenient to divide an *S-N* relationship into two stages, namely a finite life portion and an endurance limit. Unified engineering theories of metal fatigue [1, 2] are concerned mainly with the latter, being based on the condition of not initiating or not propagating some critical crack. The finite fatigue life portion should be approached from a crack propagation viewpoint. The nucleation theory of metal fatigue was previously proposed [3] from this viewpoint. In a recent article [4] this theory has been extended to explain fatigue crack propagation laws and the frequency dependence of fatigue life.

In the present paper, an experimental study has been made of the change in crack tip shape during propagation using a plastic replication method [5, 6]. The results implied that the so-called earing region, attributed to the blunting and the resharpening of the crack tip, was formed after about 20 cycles, and did not show a one-to-one correspondence with the stress cycles. The crack length was measured at a magnification of 1500; it was found that a crack propagated in a discontinuous manner.

Experimental study

It is usually believed that a fatigue crack propagates in a continuous manner, there being a one-to-one correspondence between stress cycle and striation spacing [7]., each earing occurring as a result of the blunting and the resharpening of the crack tip. Results for aluminum, nickel [8] and polymers [9] are shown in Fig. 1. However, it is not clear whether an earing region as shown in Fig. 1 is formed each cycle or whether the distance from one earing region to the next corresponds to several cycles. To clarify this point changes in the shape of the crack tip during successive loading and unloading cycles have been observed using a plastic replication method [5, 6].

The material used was a high strength steel (C: 0·16%, yield stress = 76 kg/mm^2, tensile strength = 84·5 kg/mm^2) and the specimens are the same [10] as used for a previous study of fatigue crack propagation. A specimen was tested at 20 ± 8 kg/mm^2 for $N = 5{\cdot}56 \times 10^5$ cycles in a 10 ton vibraphore fatigue testing machine as shown in Fig. 2. From then, fatigue testing was carried out at low frequency of one cycle per 30 minutes – a half cycle corresponding to 15 minutes. Plastic replicas, covering the region near the crack tip, were taken at the maximum and minimum stresses successively, every half cycle, for the next 40 cycles. Acetyle cellulose film replicas [6] were used and stripped, then lined with a plastic plate. Cr was then evaporated onto the replica surface in vacuum. Fig. 3 shows typical photographs of the plastic replicas selected from the 40 pairs of the photographs obtained. Blunting of the crack has occurred but it should be noted that a number of stress cycles are needed to form the next earing region after the previous one has been formed. That is, more than 19 cycles were needed to form the second complete earing region after the first earing region has been completed (Fig. 3 (a), (b), (c), (d)). Seven cycles were needed to form the third earing region after the second earing region has been completed (Fig. 3 (e), (f)) and more than 12 cycles were needed to initiate the fourth earing region after the third earing region has been formed (Fig. 3 (f), (g)).

The crack propagation rate was deduced from the plastic replicas. Fig. 4, shows that the fatigue crack propagates in a discontinuous manner; this is in accord with reference [4] in which it is predicted that a fatigue crack propagates by means of a number of incubation periods even when the growth curve is determined macroscopically by usual methods appear continuous. It was frequently observed that a microcrack initiated in a region adjacent to the tip of the main crack, and then joined to it.

The morphological aspects of the fatigue crack path were observed by a scanning electron microscope. A typical example is shown in Fig. 5 for the crack geometry of an unloaded crack, after 7×10^5 cycles at 20 ± 8 kg/mm^2. The earing appearance can be seen. It appears from these figures that a small branching crack associated with a part of the earing region may have occurred along the plane of heavy plastic deformation at the crack tip.

A typical example of scanning electron micrograph of the same series of plastic replicas as shown in Fig. 3 is shown in Fig. 6.

Some improvements in the previous crack propagation theory

In the previous paper [4] the crack nucleation rate per cycle μ_i was assumed constant for each ith incubation period. However, μ_i may be

assumed to increase during each incubation period, say, from zero to the probably saturated value as shown in Fig. 6. Then we may write μ_i as:

$$\mu_i = \mu_{is}\,(i - e^{-\alpha N_i}), \tag{1}$$

where

$$\mu_{is} = \frac{M}{\omega}\,(\sqrt{(c)}\sigma a)^{1/mkT} \tag{2}$$

corresponding to Equations (15) and (16) of reference [4]. In the case of α being small, Equation (1) may be written as:

$$\mu_i = \mu_{is}\,aN_i\,. \tag{3}$$

The probability of non-nucleation P is represented by:

$$P = \exp\,[-\int_0^{Ni} \mu_{is}\,aN_i]. \tag{4}$$

Putting $P = 0{\cdot}5$ in Equation (4), integrating Equation (4), and substituting Equation (2), the median value $\widetilde{N}_i$ of the repeated cycles required for the ith propagation (nucleation) is given by:

$$\widetilde{N}_i = \sqrt{\frac{2(-\ln\,0{\cdot}5)\omega}{M}}\,(\sqrt{(c)}\sigma a)^{-1/2mkT} \tag{5}$$

On the other hand, assuming that the increase of crack length after each incubation period is independent of the number of stages, and denoting it by ϵ, then

$$\frac{dc}{dn} = \epsilon \tag{6}$$

as in the previous paper [4].
Since for the ith incubation period

$$\frac{dN}{dn} \simeq \widetilde{N}_i, \tag{7}$$

then from Equations (6) and (7) we get:

$$\frac{dc}{dN} = \frac{dc}{dn}\Big/\frac{dN}{dn} = \frac{\epsilon}{\widetilde{N}_i}\,. \tag{8}$$

Substituting Equation (5) into Equation (8), we get:

$$\frac{dc}{dN} = \sqrt{\frac{M}{2(-\ln\,0{\cdot}5)\omega}}\;.\;\epsilon\left(\frac{\Delta K}{2}\right)^{1/2mkt} \tag{9}$$

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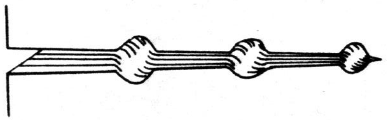


Fig. 1. Schematic illustration of earing region at fatigue crack tip during one loading cycle.

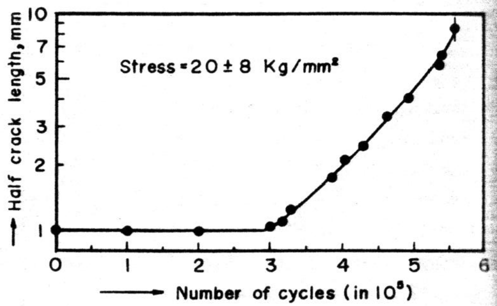
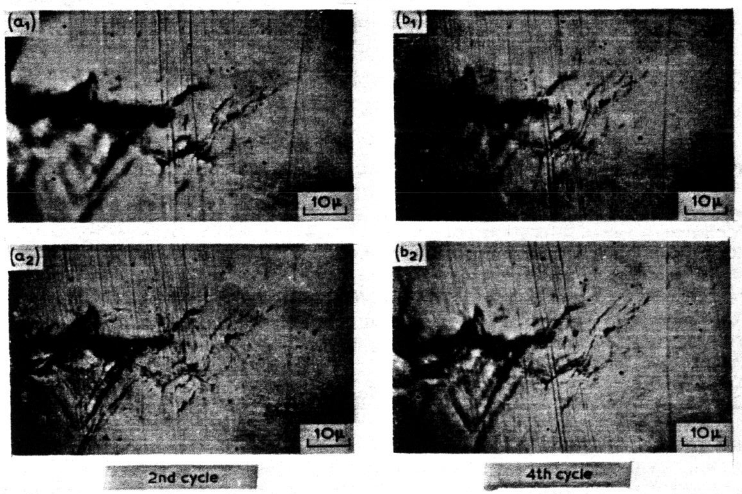


Fig. 2. Fatigue crack growth curve in terms of usual experimental technique.



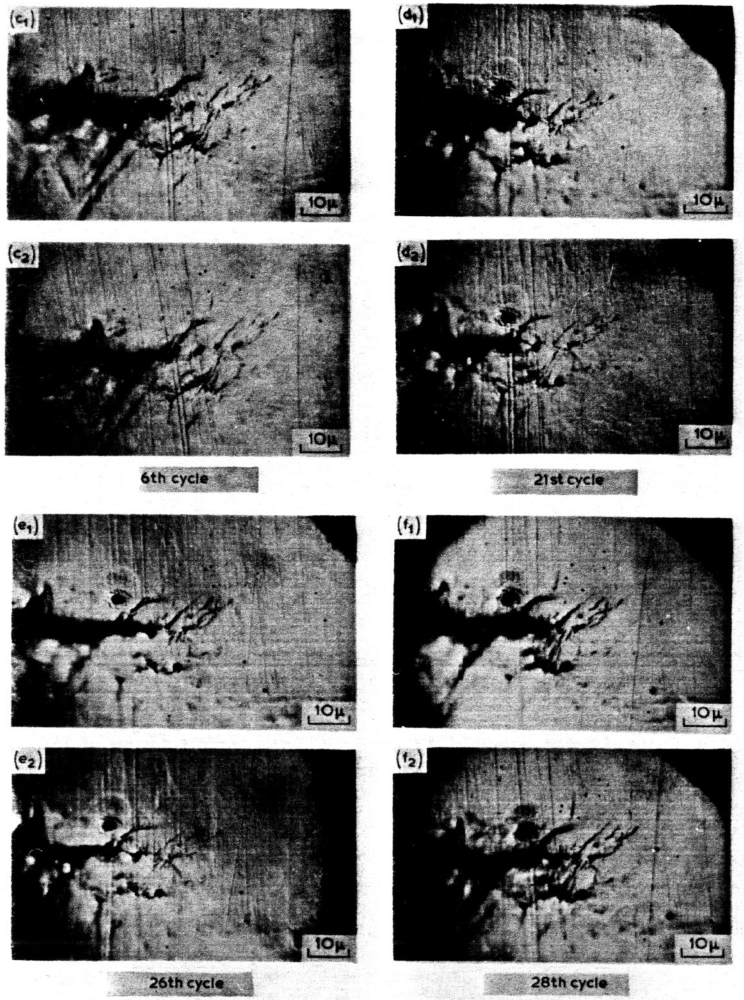
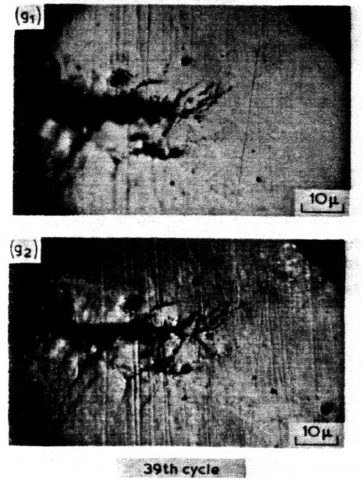


Fig. 3. Typical photographs of series of plastic replicas taken successively, every half cycle. (a_1), (b_1), (c_1), (d_1), (e_1), (f_1) and (g_1) correspond to maximum stress, respectively and (a_2), (b_2), (c_2), (d_2), (e_2) and (f_2) correspond to minimum stress, respectively.



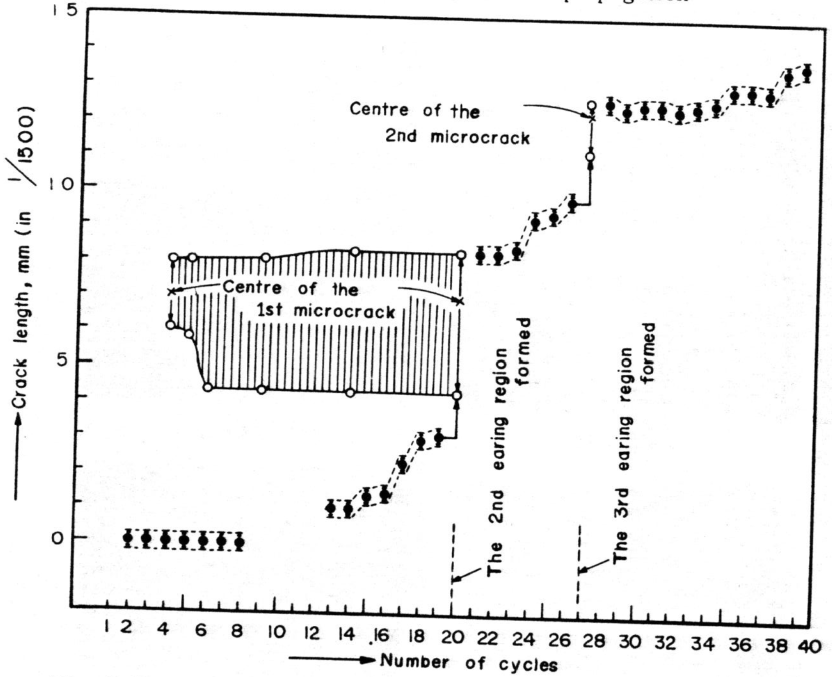


Fig. 4. Fatigue crack growth curve in terms of the magnification of 1500 from the series of plastic replicas taken successively, every half cycle.

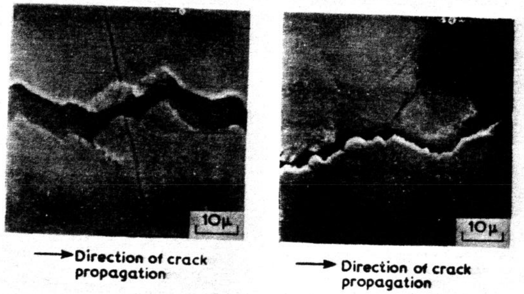


Fig. 5. Photos of the fatigue crack path by scanning electron microscope. The same material as shown in Fig. 3. The specimen in unloaded condition, after being subjected up to 7 × 10⁵ cycles under the same repeating condition of loading.

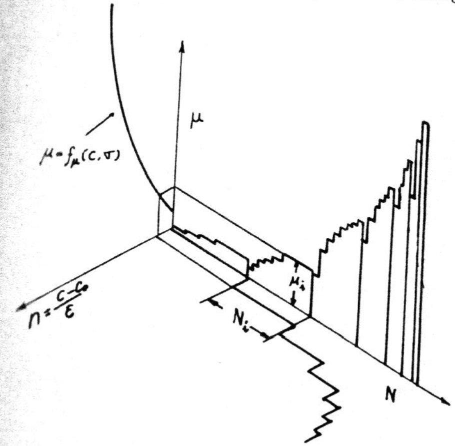


Fig. 6. Schematic illustration of the relation between. μ, N_i and n.

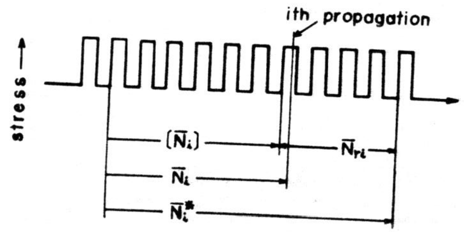


Fig. 7. Schematic illustration of the relation, $\bar{N}_i$, $\bar{N}_i^*$ and $\bar{N}_{ri}$.

Fig. 8. A typical example of scanning electron micrograph of the same series of plastic replicas as shown in Fig. 3. The example corresponds to the maximum stress for the 31st cycle.