Some Factors Influencing The Near-threshold Fatigue Crack Growth in a Machine Structural Steel*

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I. Introduction

There are surface and buried defects which are detected in the structures or components, and the former is directly influenced by environments but the latter is otherwise. It is well known, on the other hand, that near-threshold fatigue crack growth rates and threshold stress intensity factor range (ΔK_{th}) are particularly sensitive to environments and load ratio ($R=K_{min}/K_{max}$).¹⁻⁴⁾ Therefore, one must take account of not only mechanics but also environmental effects in assessing the presence of defects for the integrity of components subject to cyclic loading.

The object of the present investigation is to develop an improved understanding of near-threshold fatigue crack growth behavior through further considering crack closure with particular reference to the role of ambient atmosphere.

II. Experimental Procedures

The material used in this investigation was a quenched and tempered JIS 439 (AISI 4340) steel. The chemical composition in wt% and room temperature mechanical properties were as follows: C-0.40 %, Si-0.25 %, Mn-0.66 %, P-0.009 %, S-0.002 %, Ni-1.83 %, Cr-0.82 %, Mo-0.25 %, UTS=1 339 MPa, 0.2% PS=1 241 MPa, and $K_{10}=116 \text{ MPa}\sqrt{\text{m}}$. The average prior austenite grain size was 15 μm .

Fatigue crack growth tests were performed on a closed loop electrohydraulic fatigue machine using a sinusoidal waveform at a frequency of 20 Hz. The specimens were of 25.4 mm thick 1-T WOL type. Cracks were grown at a temperature of $25\pm 2^\circ\text{C}$ in two environments: as exposed to laboratory air of approximately 45~50 % relative humidity and as kept unaerated by hermetically sealing the notches with silicone rubber and fatigue precracks with polyester tape.

Crack growth was monitored utilizing the low frequency AC electrical potential technique capable of detecting changes in crack length of the order of 0.05 mm. Near-threshold crack growth rates were measured under load-shedding (decreasing ΔK) conditions, with the threshold ΔK_{th} values defined in terms of a growth rate of 10^{-11} m/cycle . For determining ΔK_{th} , the value of ΔK was progressively reduced by steps of 10 % or less. Crack closure load was measured by the unloading elastic compliance technique in which the unloading elastic displacement

was subtracted from the total displacement to reveal clear closure point.

III. Results and Discussion

In order to evaluate the effect of air on the near-threshold fatigue crack growth rates, a comparison was made between crack growth rates in air and those of unaerated state at the three R values as shown in Fig. 1. It is observed that the effect of unaeration is predominant only at a low load ratio such as 0.05. The threshold ΔK_{th} of unaerated state is lower about $1 \text{ MPa}\sqrt{\text{m}}$ compared with that in air at $R=0.05$. Little differences, however, are apparent at $R=0.5$ and 0.8.

In Fig. 2, examples of crack closure measurements at $R=0.05$ are illustrated. As can be seen in this figure, it is evident that the closure load is lowered by unaeration as compared with that in air: it is evident that the crack closure plays an important role in near-threshold crack growth behavior, as the crack cannot practically propagate while it is physically closed. In Fig. 3, fatigue crack growth rate (da/dN) is plotted as a function of effective stress intensity range (ΔK_{eff}) given by $K_{max}-K_{cl}$, where K_{cl} is the stress intensity factor to close the crack. As shown in Fig. 3, the differences in da/dN due to the influence of environments and R values are greatly reduced, e.g., da/dN data are essentially the same. Thus, it appears that the crack closure is the most important factor

Fig. 1. Fatigue crack growth rates in unaerated state at three stress ratios in comparison with those in air.

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Fig. 2. Examples of crack closure measurements in air and unaerated state at near-threshold levels.

Fig. 4. Effect of stress ratio on closure stress intensity factors in air and unaerated state.

Fig. 3. Fatigue crack growth rates as a function of effective stress intensity range, ΔK_{eff} .

Fig. 5. Comparison of crack opening ratios as a function of ΔK in air and unaerated state.

governing the near-threshold crack growth behavior.

To bring out more strikingly the role of closure, the information on closure was then briefly discussed in the light of the effect of R , ΔK , and grain size. Figure 4 shows the effect of R on K_{cl} levels at the threshold region. It can be seen that there are little differences between the values of K_{cl} in air and in unaerated state at $R=0.5$ and 0.8 where $K_{min} > K_{cl}$. The effect of environment on K_{cl} is apparent only at $R=0.05$ where $K_{min} < K_{cl}$.

In Fig. 5, the crack opening ratios, $\Delta K_{eff} / \Delta K$, were plotted as a function of ΔK . It is seen that the ratios decrease as the crack growth reaches the threshold level. That is to say, as the fatigue crack moves toward the threshold region, crack closure effect becomes much more significant. The crack closure effect in air is obviously higher than that of unaerated state at low ΔK values, whereas the differences between them become negligible at ΔK levels higher than approximately 20 MPa√m. In Fig. 6, the effect of unaeration on crack closure at $R=0.05$ is demon-

Fig. 6. Effect of unaeration on closure stress intensity factors as a function of ΔK .

strated in terms of the differences between K_{cl} (air) and K_{cl} (unaerated) as a function of ΔK . Furthermore, ΔK levels where maximum plastic zone size (ω_y) and cyclic plastic zone size (ω_c) become equal to the prior austenite grain size (d_γ) are illustrated

respectively. Here, the plastic zone sizes are given by,

$$\omega_y = \frac{1}{3\pi} \left(\frac{K_{\max}}{\sigma_y} \right)^2$$

$$\omega_c = \frac{1}{3\pi} \left(\frac{K_{\max}}{2\sigma_y} \right)^2$$

where, σ_y : the yield strength.

It can be seen that the differences are most prominent at low ΔK levels less than about $10 \text{ MPa}\sqrt{\text{m}}$, whereas it becomes less pronounced as ΔK increases.

Recent studies⁴⁻⁶⁾ have shown that at near-threshold levels, in addition to the role of plasticity and oxide induced crack closure, fracture surface roughness may promote the significance of the closure effect in plain strain condition. In such instances, it has been indicated that at low ΔK levels, where maximum plastic zone size is typically smaller than the grain size, fatigue crack growth take place along a single slip system giving rise to a Mode I+II displacement, and the resulting serrated or faceted fracture surface morphology coupled with crack tip Mode II displacement will generate a high closure effect. At higher stress intensities, on the other hand, where the extent of crack tip plasticity encompasses many grains, crack advance proceeds by the operation of two slip systems either simultaneously or alternately, resulting in the formation of ductile striations. Such crack growth is more planar in nature, and occurs in a pure Mode I displacement. It has been also shown that, in laboratory air and at low stress ratio, additional intergranular cracking is apparent at intermediate ΔK values, but at the near-threshold levels the fracture surfaces are generally transgranular.^{1,3,7)}

From the results shown in Fig. 6, it is concluded

that the effect of air on the near-threshold crack closure is associated with crack tip Mode II displacement. Although details of the mechanisms for enhancing oxide growth within cracks still remain uncertain, Mode II component should be considered as playing an important role. Such a sliding component should be essential to any fretting oxidation mechanism, hence in enhancing oxide formation within cracks.

IV. Closing Remarks

At near-threshold levels, crack closure mechanism originates from the fact that the cyclic crack tip opening displacements are of a size comparable to the fracture surface roughness and the thickness of corrosion debris within the crack. Thus, the crack closure mechanism is rather structure sensitive. It has been experimentally shown in the present work that the crack closure effect in air is further promoted by fretting oxidation mechanism which in turn is enhanced by the action of crack tip Mode II displacement.

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