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THE INFLUENCE OF WATER VAPOUR ON FATIGUE CRACK PLASTICITY IN LOW CARBON STEEL

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INTRODUCTION

Most of the analytical models which have been developed to predict fatigue crack growth do not take into account environmental effects. The latter are known to alter crack growth rates profoundly, but the basis for such alteration remains unclear.

It has been explicitly assumed by some [1] that for the same stress intensity and stress ratio, identical crack tip opening displacements and plasticity will be realized in air and vacuum for any given material. On the other hand, several recent investigations have indicated that air environments can exert significant control over crack tip plasticity in aluminium alloys [2], pure iron [3], steels [4,5], titanium alloys [5], and a Ni-Cu alloy [6]. Indications are that crack tip closure is modified by the environment [2,5], that dislocation structures are changed [6], and that the plastic zone formed in vacuum may exceed in size that attending cracks propagating in air [3]. Moreover, Frandsen and Marcus [4] have shown that for certain steels, environmental hydrogen-assisted fatigue crack propagation seems to be related to changes taking place in the cyclic plastic zone.

Accordingly, an investigation was carried out to examine in some detail the possible effect of an aggressive environment (water vapour) upon fatigue crack tip plasticity, including crack tip opening, plastic zone size, and dislocation subcell formation. Special attention was paid to the inner cyclic plastic zone, using a relatively new diffraction technique performed in the scanning electron microscope.

EXPERIMENTAL PROCEDURE

Low carbon steel (0.05 C, 0.33 Mn, 0.046 Al, wt.%) with an upper yield stress of 218 MPa, and tensile elongation of 55.8% was obtained from Professor T. Yokobori in connection with a previous investigation [7]. Specimens 200 x 71 x 2.7 mm were heat treated, centre notched, and stress relieved as previously described.

Fatigue tests were performed in an electro-hydraulic fatigue machine at 15 Hz. Load shedding was used to maintain nearly constant stress intensities as the crack lengthened. The environments used were laboratory air having a relative humidity of 50-70% (10-15,000 ppm), and nitrogen with 20 ppm water vapour. A clear acrylic plastic environmental chamber was clamped to cover both sides of the centre notch and was O-ring sealed to the specimen. The water vapour concentration in the nitrogen was determined by a dew-point indicator within the environmental chamber.

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Fatigue tests were run in the following sequence: a crack was started in humid air at the lowest value of cyclic stress intensity (ΔK) to be used during the test. After establishing the crack growth rate and moving the crack tips beyond any plasticity effects caused by the notch, the specimen was replicated at both crack tips and the position marked with a Knoop indenter. The environmental chamber was then attached, and nitrogen flowed until the dew-point of the nitrogen reached 20 ppm (the residual water vapour content of the nitrogen). The specimen was then cycled at the same ΔK as for air, and the crack growth monitored. After suitable crack lengthening, cycling was stopped, and the environmental chamber removed. The crack was then manually loaded to the maximum level used cyclically, and the crack tip replicated with cellulose acetate.

Upon completion of the fatigue test, the crack area was cut from the specimen, cold mounted, and 0.5 to 1 mm of surface removed with 400 grit paper. The specimen was then electropolished to remove the damaged layer and examined in the SEM using the backscattered mode. Contrast is by the diffraction contrast (channeling) mechanism [8]. Voltages of 20 and 30 kv were used with specimen currents of 1 nanoamp.

Positive replicas were prepared by coating the negative cellulose acetate crack tip replicas with palladium, followed by electroless nickel plating, then stripping away the plastic, leaving the positive replicas [9]. These were examined in the SEM.

RESULTS

The effect of environment on the crack growth rate at various ΔK is shown in Figure 1, which is in reasonable agreement with data on a similar steel [10]. Figures 2 and 3 show the effect of changing environment at ΔK = 11 MPa$\sqrt{m}$. The plastic zone associated with the propagating crack is observable because of the formation of subgrains within the ferrite grains. Previous work [7] indicated that subcell formation can be detected by channeling contrast within what is thought to be the cyclic plastic zone. Thus, Figures 2 and 3 delineate the approximate extent of the cyclic plastic zone, but not the monotonic zone.

Subcell formation was previously found [7] to begin at a plastic strain of around 3%, which correlated well with the data of Keh and Weissman [1] for pure iron. The relationship between subgrain formation and plastic strain, however, needs further clarification. Figures 3a and 3b show the substructural change due to environmental change. Two effects are observed which may be attributed to the addition of water vapour to the environment: (1) the overall extent of subcell formation is decreased, and (2) the size of the subcells is increased. These effects are shown in Figure 4, which includes data from two cracks at ΔK = 11 MPa$\sqrt{m}$ at two depths from the surface, 0.05 and 1.0 mm. Considering subgrain formation alone, the addition of water vapour to the environment can be considered to correspond to decreasing the cyclic stress intensity, in that the extent of subcell formation is decreased, and the subcells formed are larger. The functional dependence of subgrain diameter on distance from the crack plane may also change, and this is being investigated further.

Replication of the crack tip indicates that the environment also affects crack tip opening displacement (CTOD) and deformation at the crack tip. Figures 5a and 5b are examples of the crack tip yielding for ΔK = 11 MPa$\sqrt{m}$. Two differences are evident: the CTOD and the magnitude and

spacial extent of crack tip deformation are all greater for dry nitrogen (Figure 5b) than for moist air (Figure 5a). It is difficult to measure the exact values of these parameters because of uncertainty in the position of the crack tip. Values of CTOD and the other parameters measured and computed are summarized in Table 1.

DISCUSSION

The effect of increasing water vapour from 20 ppm to 10-15,000 ppm on fatigue crack propagation at ΔK = 11 MPa$\sqrt{m}$ and 15 Hz at 22°C may be summarized as follows: CTOD decreases by about 50%, cyclic plastic zone size decreases by a factor of 2.2, and crack growth rate remains approximately the same. In addition to the change in plastic zone size, the subcell size increases from 1 to 2 μm at the crack plane, and the rate of subcell size increase goes up by a factor of 2.3.

Although it is not possible to determine the mechanism by which these changes are occurring without considerably more experimental effort, it is interesting to examine some of the possibilities at this time. One of the most obvious ways plastic zone size and CTOD could be influenced by water vapour is if the fatigue crack changed from propagation under conditions of plane stress (dry) to those of plane strain (wet). Using the calculations of Broek [14] and Levy, et al. [15], the ratio of plastic zone size (plane stress/plane strain) = 1.4, which is insufficient to explain the measured ratio of 2.24. The crack propagation data of Jack and Price [10] indicate that for a similar material of the same thickness, the transition from plane strain to plane stress occurs in moist air at ΔK = 15.9 MPa$\sqrt{m}$. For the dry environment to exert a similar effect, an effective increase in ΔK of 4.9 MPa$\sqrt{m}$ would be required, a factor of about 1.5, which also does not explain the magnitude of the effect seen.

A decrease in crack tip plasticity is consistent with a decrease in CTOD, in that a decrease in crack tip deformation necessitates less accommodation strain. Thus, the effect of adding water vapour, as determined by microscopic observation, can be explained on the basis of a decrease in work done by the crack on the specimen. The question thus raised is why the CTOD and PZS are decreased upon adding moisture, under the same loading conditions, and with essentially the same growth rate.

Observed values of CTOD in the absence of water vapour (Table 1) have shown good agreement with values calculated by the relation

$$\text{CTOD} \propto \frac{(\Delta K)^2}{E\sigma_y}$$

In order for water vapour to decrease CTOD at constant ΔK, the effective strength of the material must therefore be increased. A film forming-cracking mechanism does not appear to fit this circumstance because a film cannot affect E or σ_y sufficiently to explain the change in CTOD observed.

Water vapour in the presence of Fe is known to dissociate as $H_2O \rightarrow H^+ + OH^-$, which can further dissociate as $OH^- \rightarrow O^{--} + H^+$. There is thus the possibility of either O^- or H^+ being transported into the lattice by diffusion or by dislocation "sweep-in", that is, enhanced diffusion of H^+ or O^{--} along with dislocation motion. The possibilities of both atomic species entering the iron have been discussed [16,17]. The

hydrogen ion is sufficiently small to be highly mobile, whereas the oxygen ion is thought to be much larger [18] and presumably of lower mobility. Tien, et al. [16], estimate the range of H^+ diffusion in iron at 20°C by "random walk" to be about 9 μm, and as much as 66,500 μm by dislocation "sweep-in" at a cyclic frequency of 10 Hz. Similar calculations for O^{--} have not been made.

For there to be sufficient hydrogen penetration into the metal to raise the yield strength within the observed plastic zone, dislocation "sweep-in" would be necessary. It has been noted [2] that humidity may reduce the crack closure stress, resulting in an increased effective ΔK. Dislocation "sweep-in" is a means of realizing this [2], since the reduced local ductility in the presence of the hydrogen causes a reduction in residual strain within the plastic zone.

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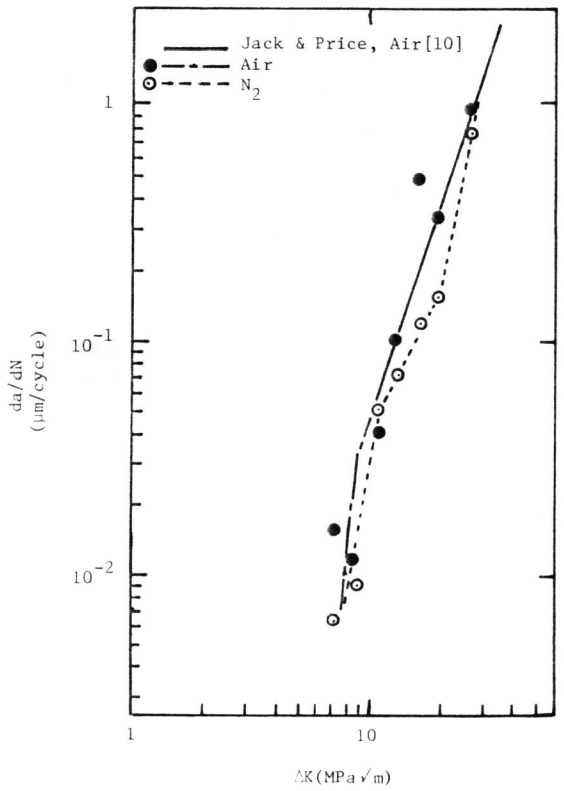


Figure 1 Crack Growth Rate vs Cyclic Stress Intensity for Moist Air (60% R.H.) and Dry (20 ppm Water Vapor) Nitrogen

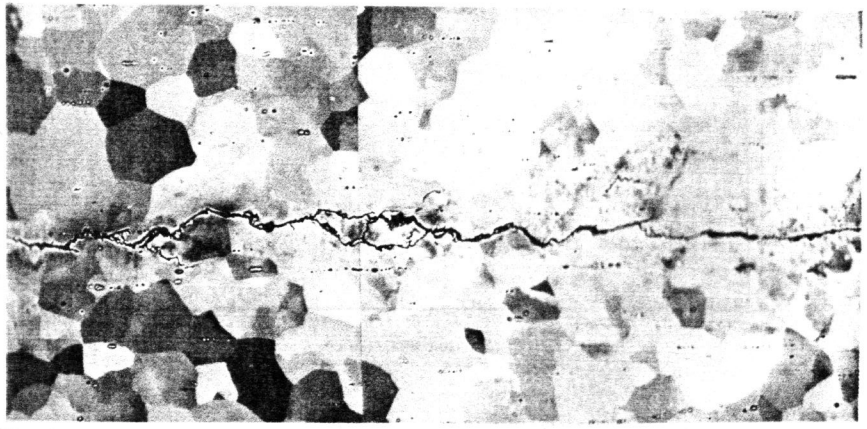
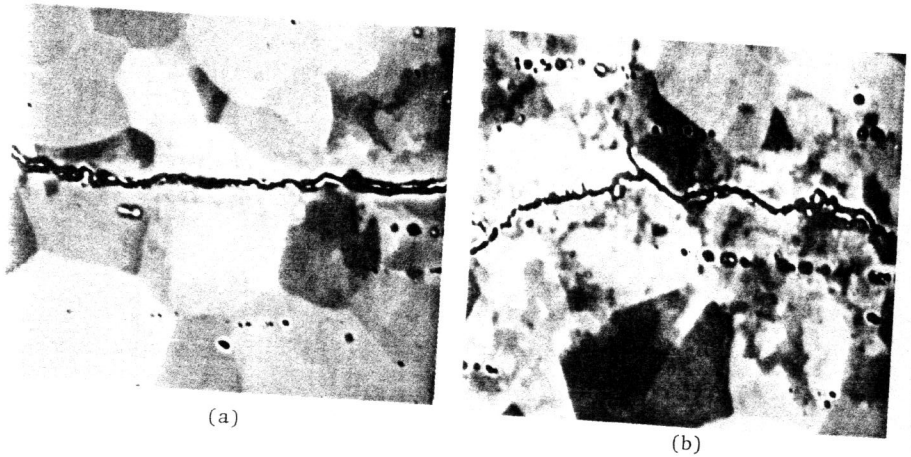


Figure 2 Fatigue Crack at ΔK = 11 MPa√m Showing the Formation of Subgrains Due in Moist Air (Left Side) and Dry Nitrogen (Right Side) Environments. Backscattered Electrons. 400X



(a) (b)

Figure 3 Same Area as Figure 2. 1000X
(a) Crack Propagated in Moist Air
(b) Crack Propagated in Dry Nitrogen

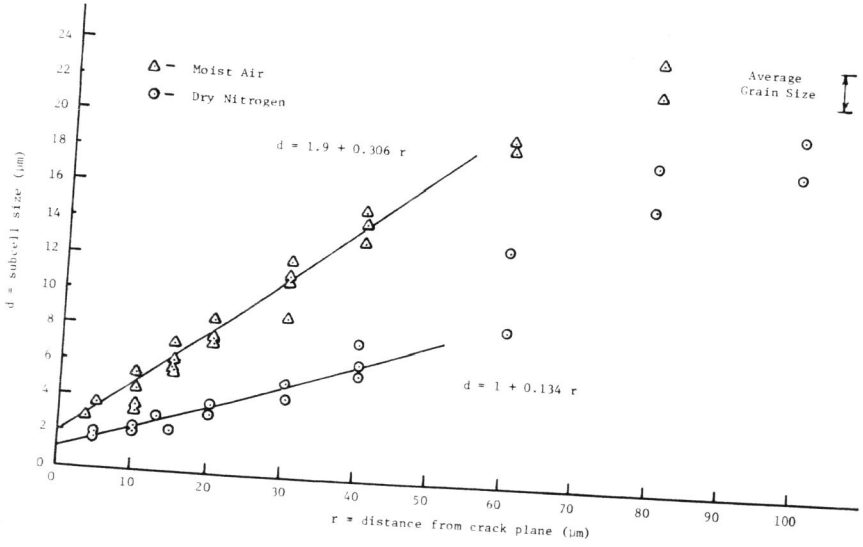
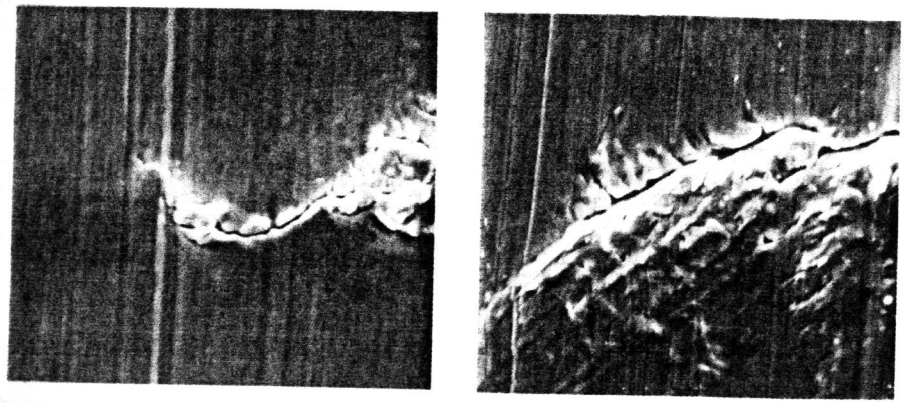


Figure 4 Subgrain Size vs Distance Perpendicular to the Crack Plane and Direction. Data are for Two Cracks and for Depths of 0.5 and 1 mm Below the Surface



(a) (b)

Figure 5 Positive Replicas of the Crack Tips Under Load (ΔK = 11 MPa$\sqrt{m}$) in (a) Moist Air and (b) Dry Nitrogen, Showing the Large Differences in Both Crack Tip Opening Displacement and Magnitude and Extent of Crack Tip Strain. 1000X

Table 1 Steel, 0.05 Wt.%C, 218 MPa Upper Yield, ΔK = 11 MPa$\sqrt{m}$, R = 0.01, Average Grain Size = 25 μm

	Moist Air (0-15,000 ppm)	Dry Nitrogen (20 ppm)
CTOD measured (μm)	.1-.2	.4
CTOD computed (μm)*		.3-.7
Largest value of measurable surface strain (%)	0	50
Plastic zone size, $r_p^c(90)$ (μm)†	66	146
Subcell size at crack plane (μm)	1.9	1
α**	0.026	0.069
α_{90}^c (plane stress)††	0.005 - 0.0098	
α_{90}^c (plane strain)††	0.0035 - 0.0038	
Crack growth rate (da/dN) (μm/cycle)	0.0063	0.005

*CTOD = $\alpha(\Delta K)^2/E\sigma_y$, α = 0.112 - 0.247, depending on strain hardening exponent [12].

†Cyclic plastic zone size 90° from crack plane and direction = $r_p^c(90)$.

**$r_p^c(90) = \alpha_{90}^c \left(\frac{\Delta K}{\sigma_y}\right)^2$, σ_y = upper yield stress.

††Based on numerical calculation of the monotonic zone size r_p^m [12-15] and the idea of Rice [13] that $r_p^c = \frac{1}{4} r_p^m$.