

PREDICTED AND EXPERIMENTAL CORROSION FATIGUE CRACK GROWTH
 RATES OF ANODICALLY POLARISED STEEL IN DEAERATED SEA WATER

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A computer simulation model has been developed for predicting the corrosion fatigue behaviour of steel under anodic polarisation in deaerated sea water. Based on a distribution of sources of H^+ ions on the crack walls, the probability of H^+ ions reaching the crack tip could be calculated by modelling the solute transport. Assuming a critical hydrogen concentration in front of the crack tip the behaviour of da/dN vs ΔK could be predicted. The results are compared with experimental data.

INTRODUCTION

The accelerated corrosion fatigue (CF) crack growth rates of steel in seawater are generally accepted to be due to hydrogen embrittlement of the crack tip material. During strong anodic polarisation the crack tip area is shielded from the applied potential by a potential drop in the crack solution arising from the high current densities at the crack walls, so that the crack tip is essentially at the local corrosion potential (Edwards (1), Van der Wekken and Zuidema (2), and Van der Wekken (3)). A cathodic overpotential for hydrogen reduction in an acidified crack tip solution has been measured and it could be concluded that this acidification originated from the dissolution reaction at the crack walls. A major role in the transport of H^+ ions can be ascribed to Flow Enhanced Diffusion (FED), a transport mechanism resulting from the interaction of diffusion and periodic flow ((3), Van der Wekken and Janssen (4)) which can be described in terms of an effective diffusion coefficient D_{eff} and depends on the crack dimensions and the dimensionless parameter G :

$$G = d_{av} (\omega/D)^{1/2} \quad (1)$$

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where d_{av} = the average local distance between the crack walls, ω = the radial frequency and D = the solute diffusion coefficient.

By means of computer simulation calculations it is possible to determine D_{eff} , which may be several orders of magnitude larger than D (Van der Wekken (5)). Migration due to the electrical field can usually be neglected in the presence of FED (Van der Wekken (6)). The knowledge of D_{eff} has been used as a basis for predicting the behaviour of the crack growth rate da/dN (3, Van der Wekken (7)). While in later studies (Van der Wekken (8,9)) a single source of H^+ ions was placed near the crack mouth, the present modelling takes into account that acidification results from anodic dissolution along the whole length of the crack. The production rate of H^+ ions along the crack walls is assumed to be proportional to the anodic current density. Inside the crack the laminar flow during a small change $d\alpha$ in the crack tip angle α was assumed to be parabolic, while in the bulk solution facing the crack mouth the velocity of the solution in the crack length direction was assumed to be equal to the average velocity at the crack mouth. Details of the model calculations of the path of a particle resulting from flow and diffusion inside the crack have been presented previously (7-9). Solute particles were allowed random diffusion jumps b in the crack length direction as well as perpendicular to the crack walls. The sinusoidal cycle was divided in m steps, as illustrated in the figures 1a and 1b, while m and b were chosen in correspondence with the Einstein relationship for random walk diffusion:

$$m \cdot b^2 = 2TD \quad (2)$$

where T = the period of a cycle.

The diffusion jump b should be chosen much smaller than the distance between crack walls, which means that m has to be sufficiently high. The flow calculations were checked to be sufficiently accurate to avoid systematic particle drift. As a result of the random diffusion jumps during fatigue cycling, the path of individual particles becomes unpredictable. Some particles will end up in the bulk solution and may again enter the crack. A particle was considered 'lost' in the bulk solution after having diffused up to a distance of the maximum CMOD from the centre plane of the crack. A fraction of the particles originating from the crack walls will eventually, after continued cycling, reach the crack tip. Using large numbers of particles, it was possible to determine the probability that H^+ ions, originating from the crack walls according to a given source distribution, would reach the crack tip.

The shape of the current density distributions along the crack walls was derived from data published by Edwards (1), who found, going from the crack tip, that the current density was increasing approximately quadratically with the distance along the crack length. A corresponding source distribution for H^+ ions was used in the present calculations. The electrical field is expected to penetrate deeper into the crack as the crack becomes wider. Under constant external anodic polarisation the source strength for H^+ ions at the crack mouth was therefore kept constant while the penetration depth of the source distribution in the crack was taken to be proportional to $CMOD_{av}$, the average CMOD. The number of H^+ ions produced per unit time at the crack walls will then also be proportional to $CMOD_{av}$. For given loading conditions a large number of H^+ ions was taken randomly from the statistical distribution along the crack walls to determine the probability P that H^+ ions would reach the tip, where they were assumed to be reduced and absorbed into the material. As a result there is an effective line source for hydrogen

diffusing into the material at the crack tip. The strength S_{Htip} of this source is proportional to $\text{CMOD}_{\text{av}} \cdot P$:

$$S_{\text{Htip}} \div \text{CMOD}_{\text{av}} \cdot P \quad (3)$$

The H-concentration $C(r)$ at a distance r in front of a moving line source moving with velocity V has been calculated to be (Johnson (10)):

$$C(r) \div \beta \cdot K_0(Vr/2D_{\text{H}}) \exp(-Vr/2D_{\text{H}}) \quad (4)$$

where K_0 = a modified Bessel function of the second kind of order zero, β is proportional to the source strength, and D_{H} = the diffusion coefficient for hydrogen. It will be assumed that the crack will be extended during each cycle over a critical distance r_{cr} through the embrittled zone, where the hydrogen concentration C_{H} exceeds a critical value $(C_{\text{H}})_{\text{cr}}$, which may depend on ΔK . Since $V = da/dt$ and $r_{\text{cr}} = da/dN$, while $da/dt = f \cdot da/dN$ and $\beta \div S_{\text{Htip}}$, substitution in eq.(4) yields:

$$S_{\text{Htip}} \cdot K_0\{f \cdot (da/dN)^2 / 2D_{\text{H}}\} \cdot \exp\{-f \cdot (da/dN)^2 / 2D_{\text{H}}\} = \text{constant} \quad (5)$$

According to eq.(5), in loading situations where S_{Htip} is independent of the frequency, which was found to apply for example at high ΔK values (see figure 2), $f \cdot (da/dN)^2$ is expected to be constant. It follows that under these conditions

$$da/dN \div f^{-1/2} \quad (6)$$

This $f^{-1/2}$ dependence, differs significantly from the proportionality to f^{-1} proposed earlier (3,7-9), when da/dt was assumed to be proportional to the flux of H^+ ions to the crack tip. In the present work it will be assumed that the environmental contribution to the crack growth rate is proportional to S_{Htip} as given by eq.(3), but that the hydrogen diffusion mechanism in the material introduces a frequency dependence according to eq.(6), so that

$$(da/dN)_{\text{env}} \div S_{\text{Htip}} \cdot f^{-1/2} \quad (7)$$

or

$$(da/dN)_{\text{env}} \div \text{CMOD}_{\text{av}} \cdot P \cdot f^{-1/2} \quad (8)$$

EXPERIMENTAL

Crack growth rates under sinusoidal constant load amplitude testing were measured using CT specimens of structural Steel FeE355-KT, produced by Hoogovens, the Netherlands. The measurements were performed in air and under anodic polarisation at -500 mV vs Ag/AgCl in deaerated artificial ASTM sea water. The crack length was measured by means of a potential drop technique. The sides of the crack in the standard specimens of $12.5 \times 12.5 \times 2.5$ cm were shielded, while a V-shaped precrack with a non standard tip angle of nearly 180° was used in order to obtain a approximately two dimensional flow pattern, in correspondence with the model calculations.

RESULTS AND DISCUSSION

The predicted behaviour of the source strength S_{Htip} is shown in figure 2. Figure 3 shows experimental da/dN data obtained in sea water at 0.1, 1 and 10 Hz and data obtained in

air, as well as a representation of the corresponding theoretically predicted crack growth rates. The measurements on short cracks at 0.1 Hz were very time consuming. Data at this frequency were therefore obtained only for longer crack lengths. Theoretical and experimental results could be matched, regarding the experimental CF rate $(da/dN)_{CF}$ as a superposition of the rate in air $(da/dN)_{air}$ and the environmental contribution:

$$(da/dN)_{CF} = (da/dN)_{air} + (da/dN)_{env}$$

or, using eq.(8):

$$(da/dN)_{CF} = (da/dN)_{air} + \phi \cdot C_{MOD} \cdot P \cdot f^{-1/2} \quad (9)$$

where the fitting parameter ϕ was chosen to obtain exact correspondence with the experimental data at 0.1Hz and $\log \Delta K = 7.6$. Experimental and theoretical curves for the various frequencies were then found to match quite well in the high ΔK range. At low ΔK and at 0.1 Hz the predicted crack growth rates are too high. The observed deviations especially occur in short and narrow cracks and at a low frequency. Under these conditions G values are small (<1) and FED is not significant, so that the role of ion migration in the electrical field in the crack solution may not be negligible (6). Under anodic polarisation the positively charged H^+ ions will then be less likely to reach the crack tip. The incorporation of a migration term in the transport calculations should therefore be the next step in the development of the present model.

CONCLUSIONS

1. In the CF crack growth mechanism of anodically polarised steel in sea water the transport of H^+ ions to the crack tip can be considered the rate determining step.
2. A major role in the H^+ ion transport in CF cracks is played by Flow Enhanced Diffusion, a mechanism arising from the interaction of diffusion and periodic flow.
3. The tip of the CF crack can be represented as a moving line source for H atoms.
4. Assuming that da/dN is determined by a zone where the H-concentration exceeds a critical level, a frequency dependence of da/dN can be predicted according to $f^{-1/2}$.
5. A simulation model for H^+ ion transport to the crack tip has been developed which predicts the behaviour of da/dN as a function of the frequency and ΔK .
6. Experimental data and theoretical predictions could be matched by superposition of a theoretical environmental contribution and the experimental crack growth rate in air.

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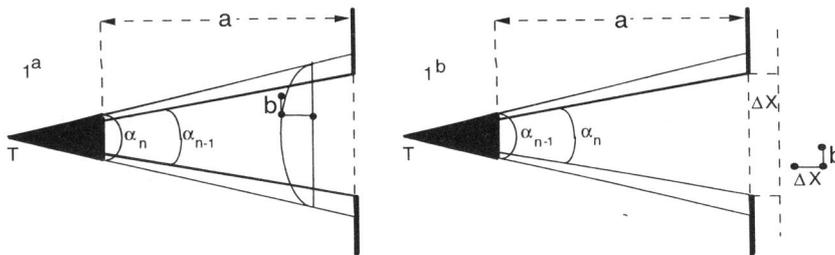


Figure 1 Steps in the calculation of solute transport inside and outside of the crack.

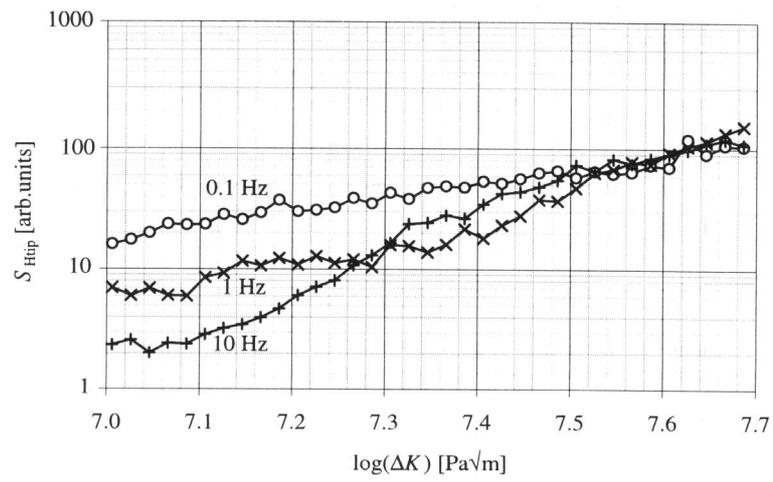


Figure 2 The theoretically calculated behaviour of the source strength S_{Htip} .

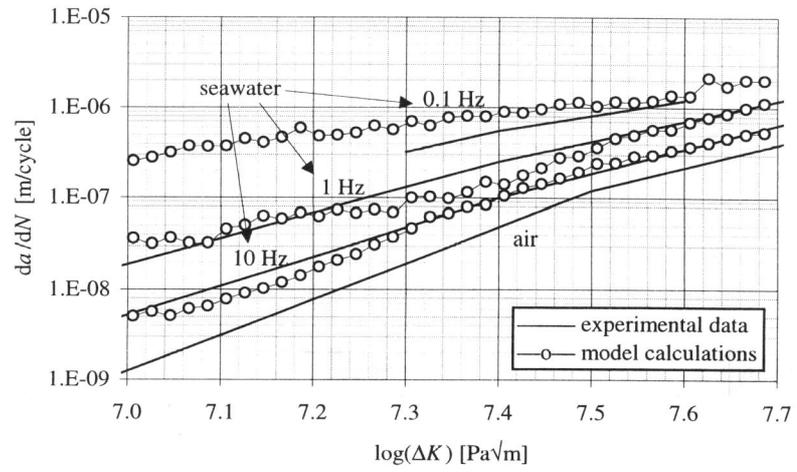


Figure 3 Experimental and theoretical crack growth rates according to eq. (9).