Short-crack modelling of the effect of corrosion pits on the fatigue limit of a 12% Cr steel

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EPRI organised an international research project [1], where ultrasonic testing was used to determine the fatigue limit of plain specimens of 12% Cr steel at $R > 0$ with artificially produced, sub-mm size corrosion pits. Moreover, the plain fatigue limit of uncorroded specimens was determined at $R > 0$, and fatigue-crack-growth testing, including the threshold, was carried out at $R$-values ranging from $-1$ to 0.9. This comprehensive set of fatigue data constitutes an ideal basis for investigating the capability of a variety of methods to predict the fatigue limit of pitted specimens.

A pre-pitting procedure was used to produce single, nearly spheroidal corrosion pits as shown in Fig. 1. The semi-width-to-depth ratio $r/d$ was typically around 0.5. It was therefore decided to model two extremes: a semi-spherical pit with $r/d = 1$ and a cylindrical “pit” with $r/d = 0$. To simplify the analysis, the fatigue behaviour of the semi-spherical surface pit was approximated by that of a spherical pore in a wide body.

Consider an annular crack of depth $a$ at the equator of a spherical pore. For a shallow crack, $a \ll a^*$, the asymptotic stress intensity factor is given by

$$\Delta K = 1.12K_t\Delta S\sqrt{\pi a}, \quad K_t = \{\nu = 0.3\} = 2.05,$$

for a deep crack, $a \gg a^*$, by

$$\Delta K = (2/\pi)\Delta S\sqrt{\pi(a + r)}.$$

Interpolation between the two asymptotes, in good agreement with a numerical solution presented by Murakami [2], is accomplished through

$$\Delta K = (2/\pi)\Delta S\sqrt{\pi(a + \theta r)}, \quad 0 \leq \theta < 1,$$

where the interpolation function $\theta$ is defined as

$$\theta = 1 - e^{-a/a^*}, \quad a^* = r/(k^2 - 1), \quad k = 1.12K_t/(2/\pi).$$

The driving force for fatigue-crack growth is assumed to be given by an “equivalent” stress-intensity range, $\Delta K_{eq}$, based on original ideas by El Haddad and Härkegård as recently described by Zambrano and Härkegård [3]. Formally, $\Delta K_{eq}$ is obtained by adding to the physical crack depth, $a$, a suitably chosen “intrinsic” crack depth, $a_0$. Thus, for a shallow annular crack, $a \ll a^*$, the asymptotic $\Delta K_{eq}$ is

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given by
\[ \Delta K_{eq} = 1.12 K_t \Delta S \sqrt{\pi (a + a_{0s})}, \quad a_{0s} = (1/\pi) (\Delta K_{th}/1.12 \Delta \sigma_A)^2, \]  
for a deep crack, \( a \gg a^* \), by
\[ \Delta K_{eq} = (2/\pi) \Delta S \sqrt{\pi (a + r + a_{0d})}, \quad a_{0d} = (1/\pi) (\Delta K_{th}/(2/\pi) \Delta \sigma_A)^2. \]  
Interpolation between the two asymptotes is obtained by
\[ \Delta K_{eq} = (2/\pi) \Delta S \sqrt{\pi [a + \theta r + \theta a_{0d} + (1 - \theta) K_t^2 a_{0s}]} \]  
By adjusting \( \Delta S \) so that \( \Delta K_{eq,\min} = \Delta K_{th}(R) \), the model predicts the fatigue limit of a specimen with a single corrosion pit. Fig. 2 shows the predicted fatigue limit, \( \Delta S \), vs. the (semi-spherical) pit radius, \( r \), for three different stress ratios. In the same diagram have been plotted data from ultrasonic fatigue testing [1]. Three categories of data points have been identified: “failure” from a few 100 000 cycles and upwards, and “no crack” or a (short) “self-arrested crack” (SAC) observed after more than 10\(^9\) cycles. With the exception of an odd data point at \( r > 0.1 \text{mm} \), predictions are conservative. Clearly, the predictions for a cylindrical “pit” (\( r/d = 0 \)) would fall below those for the semi-spherical pit. Investigations of the predictive capability of other criteria such as those due to Smith and Miller [4] and Murakami [5] are ongoing.
References


