Modelling of environmentally assisted cracking in the stainless steel and low alloy steel / water systems at 288°C

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1 INTRODUCTION

Failure of structural components by stress corrosion or corrosion fatigue presents a possible life limiting factor in the operation of Light Water Reactors. The objective of this investigation (Ford et.al. 1987) was to gain a quantitative knowledge of the mechanism of environmentally assisted cracking of ductile, structural steels in high temperature water. The specific uses of this knowledge were: (1) to provide a theoretical under-pinning to the empirically derived remedies for intergranular stress corrosion cracking of Type 304 stainless steel piping in Boiling Water Reactors, and (2) to evaluate the fundamental validity of the ASME XI (1980) life evaluation code for corrosion fatigue of low alloy pressure vessel steels in Light Water Reactor environments.

The approach taken was to propose a working hypothesis for the mechanism of environmentally assisted crack propagation and then to independently evaluate the parameters of fundamental importance in this mechanism. On the basis of these data, theoretical values of the subcritical crack propagation rate could be predicted for different steady state and transient conditions of environment (e.g., degree of aeration, impurity content), material (e.g., degree of grain boundary sensitization, sulphur content), or stress, (e.g., static load, cyclic load). These predictions could then be compared with observed data in order to evaluate the quantitative validity of the original working hypothesis before applying it to the practical analyses referred to above.

2 WORKING HYPOTHESIS AND ITS QUANTIFICATION

The slip dissolution/film rupture mechanism of environmentally assisted cracking was chosen as the working hypothesis for crack propagation. The reason for this choice was that previous investigation (Ford 1982) at temperatures <115C had indicated that it was valid quantitatively for low alloy and stainless steels in various aqueous environments; moreover, extrapolation of these low temperature data to 288C yielded predictions of crack growth rates in water which were of the right order of magnitude compared with the observed rates. The model relates crack advance to the oxidation reactions occurring at the crack tip where a thermodynamically stable oxide (or protective film) is ruptured by an increase in the strain in the underlying matrix (Fig. 1). The periodicity of this rupture event is related to the strain rate in the metal matrix and this, in turn, is controlled by either creep processes under constant load or applied strain rates under monotonically increasing or cyclic load conditions. Thus, the model is potentially applicable to not only stress corrosion (under constant stress) but also to corrosion fatigue under a variety of stress amplitude, mean stress, frequency, etc. combinations. In the ultimate analysis, the average crack propagation rate, V_T, may be related to the crack tip strain rate, $\dot{e}_{ct}$, via the power law relationship:

(1) $$V_T = A\,\dot{e}_{ct}^{\,n}$$

where A and n are parameters dependent on the material and environment compositions at the crack tip. There are limits to the validity of the relationship in Eqn. 1 which are observed at high and low crack tip strain rates (Fig. 2). At high crack tip strain rates (~0.01/s) a bare surface is maintained continuously at the crack tip, and the environmentally assisted crack propagation rate becomes independent of the crack tip strain rate, since it cannot exceed the Faradaic equivalent of the bare surface dissolution rate. Various phenomena may contribute to a lower validity limit for Eqn. 1. The most general, however, is the fact that sharp cracks cannot be maintained when the average crack tip propagation rate, V_T, approaches the oxidation rate on the crack sides, V_S; under this particular condition, the crack propagation rate will slow down with exposure time and crack arrest will occur due to blunting.

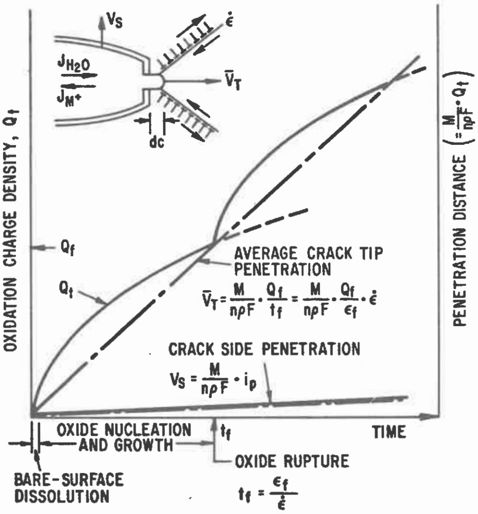

Figure 1. Schematic oxidation charge density/time relationships for a strained crack tip and unstrained crack sides.

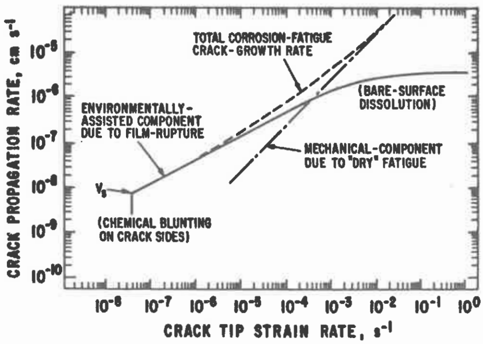

Figure 2. Strain rate dependence of the crack growth rate due to film rupture model.

Under either constant or monotonically increasing load conditions, the stress corrosion crack propagation rate is defined by Eqn. 1 (within the limits discussed above). Under cyclic loading conditions, however, the crack may also be moving forward by irreversible cyclic plastic deformation; this mechanical component of crack advance is additive to the oxidation related component, as shown by the dotted line in Fig. 2 for corrosion fatigue conditions.

In order to quantify such a model, the following processes must be defined: **1. The steady state and transient compositions** of the environment at the crack tip as a function of that in the bulk (external) solution; **2. The oxidation rates** for the material/environment system expected at a strained crack tip; and **3. The oxide fracture strain and the crack tip strain rate,** defined in terms of engineering parameters such as ΔK, R, frequency, K, etc.

These tasks have been completed and reported fully elsewhere (Ford, et.al. 1987, Andresen & Ford 1985, Andresen 1985, Ford & Emigh 1985, Taylor and Caramihas 1982, Taylor & Caramihas-Foust 1985). It is the purpose of this paper to illustrate the validity and practical use of prediction algorithms of the form in Eqn. 1. It is important to underline, however, that these algorithms are based on the fundamental observations in the tasks itemized above, and are in no way empirical in nature.

3 COMPARISON OF OBSERVED VS PREDICTED CRACK PROPAGATION RATES

Observed crack propagation rates for various combinations of stainless steel and low alloy steel microstructure, dissolved oxygen content, solution purity and stressing mode have been compared with the values predicted by the slip dissolution/film rupture model. The theoretical values have been derived from Eqn. 1, where the crack tip strain rate has been calculated for various stressing modes, and the values of A and n have been derived from oxidation rates on bared surfaces in the relevant material/environment systems calculated to exist at the crack tip. An example of the correlation between observed and predicted crack velocity / strain rate relationships is shown in Fig. 3 for furnace sensitized 304 stainless steel which has been stressed in aerated water at 288C under static (Ⓘ,etc.), monotonically increasing (α, β, etc.) and cyclic loading (•, x, etc.) conditions. Similar agreements between observation and theory were obtained when the environmental conditions were changed; for instance, the synergistic effects of corrosion potential (dissolved oxygen content) and solution conductivity (and hence, anionic activity) on the cracking susceptibility of sensitized stainless steel under constant load in water at 288C are clearly predicted (Fig. 4). The level of agreement between observation and theory for the stainless steel/water system is illustrated in Fig. 5 via the distribution of the ratio (calculated/observed) crack propagation rates over a wide range of material, environment, and loading conditions. The mean value of this ratio is 1.17, while the variance in the distribution can be directly (Ford et.al. 1987) correlated with the uncertainty in the system definition.

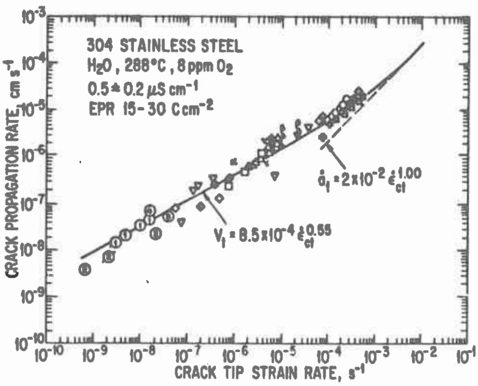

Figure 3. Observed and predicted crack propagation rate vs crack tip strain rate relationship for 304 stainless steel.

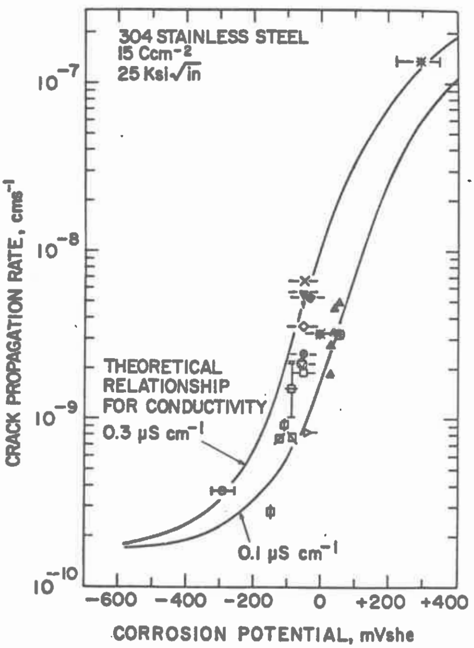

Figure 4. Comparison of observed vs predicted relationships between crack propagation rate and corrosion potential for sens 304 stainless steel at constant load.

In the case of pressure vessel steels in water at 288 C, it was predicted that environmentally assisted cracking might be expected under certain system conditions, especially where a "high" dissolved sulphur content is maintained at the crack tip (Fig. 6). The achievement of such an environmental condition is predictable from considerations of liquid mass transport in the crack (Andresen 1987, Ford et.al. 1987). The accuracy of the predictions in Fig. 6 are shown in Fig. 5 via the distribution of the (calculated/observed) crack propagation rate ratio for A533B, A508 and SA333 low alloy steels in water at 288C under a variety of environmental, material and stressing conditions. It was also predicted that, in these particular alloy steel/water systems, a limiting condition for the maintenance of sharp crack propagation would be reached and this would be evidenced by "threshold" stress intensity amplitudes and "critical" loading frequencies. In this investigation, (Ford et.al. 1987) an argument is put forward that this limiting condition is associated with the onset of chemical blunting of the crack at certain combinations of frequency, stress intensity and mean stress. Although such a "blunting" argument gives reasonable predictions of the onset of environmentally assisted cracking, it is recognized that other limiting criteria might be operating.

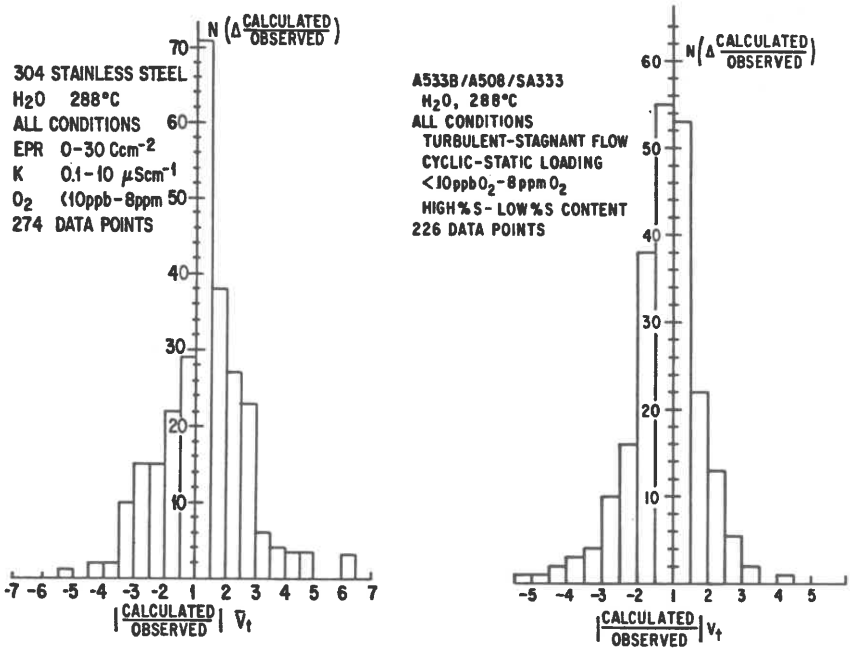

Figure 5. Frequency distributions of the calculated/observed propagation rate ratio for 304 stainless steel and A533B, A508, or SA333 low alloy steel in 288C water.

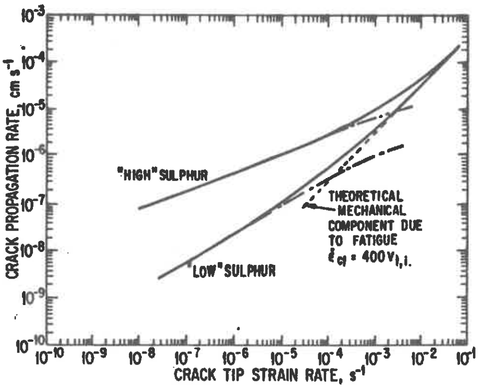

Figure 6. Theoretical crack growth rate vs crack tip strain rate for the low alloy steel/water system at 288C with material and environmental conditions where "high" or "low" activities of dissolved sulphur species exist at the crack tip.

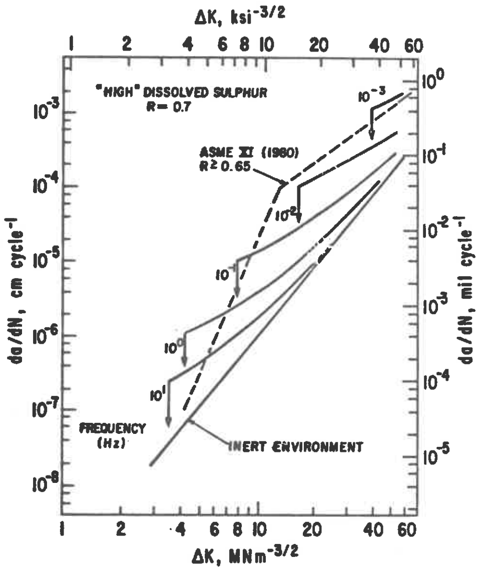

Figure 7. Theoretical da/dN vs ΔK relationships for A533B/A508 pressure vessel steel cyclically loaded at various frequencies under R = 0.7 conditions.

4 CONSEQUENCE OF A QUANTITATIVE MECHANISTIC UNDERSTANDING OF CRACK PROPAGATION PROCESSES

The fact that the environmentally assisted crack propagation rates for stainless and pressure vessel steels in water at 288C can be predicted with reasonable accuracy from first principles has considerable practical impact. First, it gives a methodology whereby the fundamental validity of empirically derived remedies and life time evaluation codes can be examined, and, second, it presents the beginning of a process for optimizing plant operating conditions vis a vis resistance to environmentally assisted cracking.

In many cases, remedies are formulated on the basis of "accelerated" tests, whereby early failure is achieved by, for instance, constant extension rate testing, intermittent fatigue loading, or the introduction of aggressive anions. The soundness of such acceleration methods have been assessed by the (validated) slip dissolution/film rupture model (Ford et.al. 1987).

With respect to the validity of the current ASME XI (1980) lifetime evaluation codes for low alloy steel pressure vessels and piping undergoing corrosion fatigue, it is apparent that the maximum theoretical (da/dN) vs Δ K values approximate those in that evaluation code (Fig. 7). It is also apparent, however, that the use of the cyclic based code can be conservative. This is especially the case if the pressure vessel is operating under the majority of the stressing, material, and environmental conditions shown in Fig. 7. Under these corrosion fatigue conditions, it makes more engineering sense to utilize a time based code (Gilman 1985).

With respect to the empirically derived remedies for sensitized stainless steel piping in Boiling Water Reactors, it was verified (Ford et.al. 1987) that the actions of reducing the degree of tensile stress, decreasing the corrosion potential (by, for instance introducing hydrogen into the feed water), increasing the water purity or decreasing the degree of grain boundary sensitization should decrease the crack propagation rate by the amounts observed in qualification tests performed by the reactor manufacturers and confirmed by other laboratories. Moreover, the theory predicts the observed variation in cracking susceptibility of piping with, eg., water conductivity and suggests the combinations of corrosion potential and solution conductivity that must be achieved to ensure satisfactory stress corrosion resistance (Fig. 8).

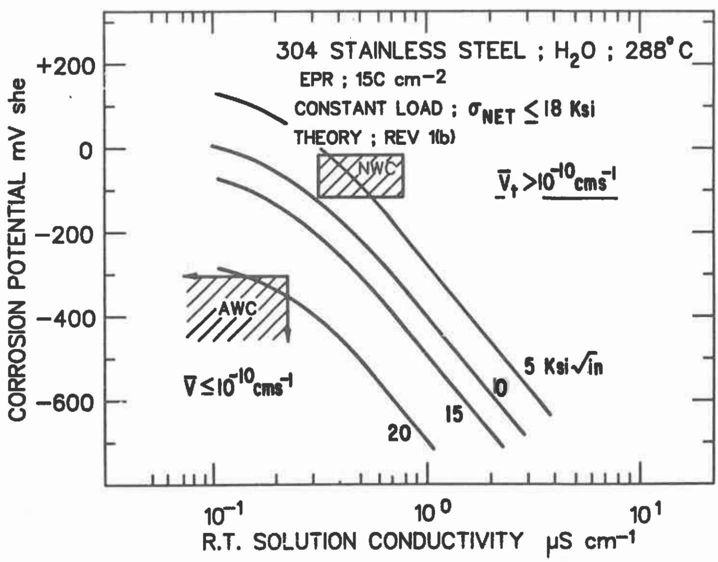

Figure 8. Combinations of corrosion potential, solution conductivity and stress intensity values which will give crack growth rates on sensitized 304 stainless steel which are either > or $<10^{-10}$ cm s^{-1}.

5 CONCLUSIONS

1. The slip dissolution/film rupture model for environmentally assisted crack propagation is capable of predicting the observed crack propagation rates for the stainless steel and low alloy steel/water systems at 288C for a wide range of material, environment, and loading conditions. The absolute accuracy of the prediction depends critically on the accuracy of the system definition. Thus, there is a strong practical argument for combining the model prediction capabilities with system monitors which accurately define the actual operating conditions.
2. The material variables that can be accounted for are the degree of grain boundary sensitization in Type 304 stainless steel and the sulphur content in the low alloy A533B or A508 pressure vessel steel. The environmental variables that can be accounted for are the oxygen content, the solution flow rate, and the anion content as monitored by the solution conductivity. The effects of these variables are fundamentally related to their effect on the crack tip environment and oxidation rates on a bared surface, and how they alter the values of A and **n** in Eqn. (1).
3. The mechanism correctly predicts the effect on the crack propagation rate of a wide range of stressing parameters, spanning constant load, monotonically increasing load, and cyclic load for various load amplitudes, mean load and frequency conditions. These stress effects are accounted for through changes in the crack tip strain rate.
4. The validated mechanism gives a theoretical underpinning to the empirically derived remedies for intergranular stress corrosion cracking of sensitized stainless steel in oxygenated water, and confirms that, for extended time periods, the ASME XI (1980) lifetime evaluation code for corrosion fatigue of low alloy pressure vessel steels is probably conservative.

6 ACKNOWLEDGEMENTS

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