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STRESS CORROSION CRACK GROWTH FOR SHORT CRACKS WITH PARTICULAR REFERENCE TO THE ZIRCALOY-2/IODINE SYSTEM

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INTRODUCTION

A study of the behaviour of short cracks (< 1 mm) in various fracture fields involving slow stable crack extension e.g. (creep, fatigue) is of increasing interest. In the development of fracture studies, it provides a link between crack nucleation processes and long crack fracture mechanics analyses. In practice, the life of many high quality components (e.g. nuclear fuel cladding, gas turbine blades) is dependent on the behaviour of small cracks and defects. Now short crack growth often involves high stresses with accompanying plastic straining and the problems of elastic-plastic or fully plastic fracture analyses are well known. However recent developments such as the use of the J contour integral and earlier concepts such as crack tip opening displacement have improved our ability to examine the short crack problem particularly in relation to fatigue [1, 2]. A current problem in water reactor fuel cladding has precipitated a study of the behaviour of short cracks in a stress corrosion situation. The particular cladding alloy, Zircaloy 2 (a zirconium, 1.5% tin alloy), is susceptible at reactor operating temperature (~ 300°C) to failure during a rapid uprating of the fuel power in the presence of gaseous iodine fission products [3]. As the maximum cladding thickness is of order 0.6 mm, failure involves only initiation and short crack growth.

This short paper examines one possibility for the mechanics of the onset of stress corrosion crack extension from a small crack and its subsequent growth. The results are applied to the behaviour of cracked Zircaloy fuel cladding during a power ramp transient.

CRACK TIP OPENING FOR SHORT CRACKS

The crack tip opening displacement (δ) of long cracks in a predominantly elastic field (small scale yielding) is well characterised. For the idealised B-C-S crack model where crack tip plasticity is confined to discrete slip lines radiating from the crack tip it is possible to estimate δ up to general yield (Y), as,

$$\delta = \frac{2AYa}{\pi E} \ln \left[\sec (\beta\sigma)\right] \qquad (1)$$

for an edge crack (of length a) in a semi infinite plate subjected to an applied tensile stress σ. $A \sim 1$ for a plane strain crack with plastic relaxation by two 45° slip lines at the tip, and $\beta = \pi/2Y$. For a work hardening material, it is possible to extend this model for stresses

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exceeding yield if Y is increased to the ultimate stress T and a variable modulus $d\sigma/d\varepsilon$ is used for E [4, 5]. The resulting δ has an elastic and plastic term,

$$\delta = \frac{Aa}{\beta_1 E} \ell n \ [\sec (\beta_1 \sigma)] + Aa\varepsilon_p \left[\frac{\beta_1 \sigma}{(n+1)} + \frac{(\beta_1 \sigma)^3}{3(3n+1)} + \ldots \right]$$

$$\approx \frac{Aa}{\beta_1 E} \ell n \ [\sec (\beta_1 \sigma)] + \frac{Aa\varepsilon_p}{(n+1)} \tan (\beta_1 \sigma) \qquad (2)$$

for small work hardening exponent (n, < 0.1). $\beta_1 = \pi/2T$. For higher n values and $(\sigma/T) > 0.8$, a good approximation is,

$$\delta = Aa \ \ell n \ [\sec (\beta_1 \sigma)] \left[\frac{1}{\beta_1 E} + \frac{2\varepsilon_p}{(n+1)} \right] \qquad (3)$$

Equations (2) and (3) show that any plastic strain (ε_p) contributes approximately twice as much to crack opening as would an equal elastic strain.

Now mechanistically, the achievement of a given crack opening whether by elastic or plastic straining involves the same processes of very localised flow at the crack tip [2]. Hence the crack tip state for a given opening should be the same in terms of dislocation structure and density, and if a critical crack tip situation is involved in a fracture process, it should apply to a whole range of short as well as long crack sizes. In this regard it is becoming increasingly clear that the Stage I/Stage II transition in fatigue crack growth occurs in both low stress and high strain fatigue when the correct crack opening condition is achieved. In stress corrosion crack growth, K_{Iscc} is such a crack state parameter. In terms of the equivalent crack opening.

$$\delta_{Iscc} = \frac{K^2_{Iscc}}{4EY} \qquad (4)$$

$$= \frac{Aa}{\beta_1 E} \ell n \ [\sec (\beta_1 \sigma^*)] + Aa\varepsilon^*_p \left[\frac{(\beta_1 \sigma^*)}{1+n} + \ldots \right] \qquad (5)$$

from equation (2) where σ^* and ε^*_p are the critical applied stress and plastic strain for stress corrosion crack extension from a short crack. The need for a significant degree of plastic straining is consistent with the well known conditions of a high stress (σ^*), of order Y, for the maintenance of stress corrosion failure in smooth specimens.

This argument does not indicate why a particular value of crack opening should be required but that once it has been achieved, crack extension can occur. In corrosion fatigue studies, there is some evidence that the threshold for enhanced growth, the equivalent to K_{Iscc}, is the Stage I/Stage II transition i.e. a mechanistic change at the crack tip in the accommodation of a given crack opening [6]. In stress corrosion, δ_{Iscc} could be related to a wider variety of structural sizes (e.g. grain size) or microstructural events (e.g. localised microcracking which occurs at $K \sim 15$ MNm$^{-3/2}$ in high strength steels).

THE GROWTH OF SHORT STRESS CORROSION CRACKS

Because stress corrosion crack extension above K_{Iscc} is stable up to the much higher instability fracture toughness condition (K_{Ic}), it must be possible to exceed or at least maintain the critical crack opening condition δ_{Iscc}. In the long crack low stress situation this is easily achieved because the crack extension force increases with increasing crack length, even for constant end displacement.

However, for a short crack, the maintenance of δ_{Iscc} is dependent on continued plastic straining. From the second half of equation (2) it can be seen that the plastic strain needed decreases in proportion to the increase in crack length for a constant value of σ^*.

An upper limit on plastic strain needed for growth is given by the condition of continuous crack extension where,

$$\Delta a = \Delta\delta/2 \qquad (6)$$

Now, $$\Delta\delta \approx \alpha a \ \Delta\varepsilon_p \qquad (7)$$

Hence for crack extension from a_o to a_f, as ε_p increases from ε_{po} to ε_{pf},

$$(\varepsilon_{pf} - \varepsilon_{po}) = \frac{2}{\alpha} \ell n \left(\frac{a_f}{a_o} \right) \qquad (8)$$

Now, $$\alpha \approx \delta_{Iscc}/\varepsilon_{po} \ a_o \qquad (9)$$

and hence, $$\varepsilon_{pf} = \frac{2a_o \varepsilon_{po}}{\delta_{Iscc}} \ell n \left(\frac{a_f}{a_o} \right) \qquad (10)$$

for $\varepsilon_{pf} >> \varepsilon_{po}$ and $a_f >> a_o$.

Such crack extension would result in large ductility and crack openings comparable with crack length. This is not typical of most stress corrosion cracking failures and certainly not of those which are dangerous in service i.e. low ductility failures. This indicates a discontinuous crack advance process, in which the crack grows by several times the critical crack opening, once the initiation condition has been achieved. A further plastic strain increment is then needed to attain this condition again. A reasonable assumption for such a process is that the increment of crack advance is proportional to the critical crack opening (δ_{Iscc}). This is consistent with the fact that for a crack, the important linear dimensions are proportional to crack length, including δ and the plastic zone size. Then, equation (6) becomes,

$$\Delta a = m \ \delta_{Iscc} \qquad (11)$$

The process is shown schematically in Figure 1. After i steps, the crack length a_i is given by,

$$a_i = a_o + i\, m\, \delta_{1scc} \approx a_o\,(1 + i\, m\, \alpha\, \varepsilon_{po}) \qquad (12)$$

and the increment of plastic strain ε_{pi} needed for the i^{th} step is,

$$\varepsilon_{pi} = \varepsilon_{po}\, a_o/a_i \qquad (13)$$

For failure after r steps, the failure strain ε_{pf} is given from equations (12) and (3) as,

$$\varepsilon_{pf} = \sum_{1}^{r} \varepsilon_{pi} = \varepsilon_{po}\left[1 + \frac{1}{1 + m\alpha\varepsilon_{po}} + \frac{1}{1 + 2\, m\alpha\varepsilon_{po}} + \ldots\right] \qquad (14)$$

Figure 2 shows how $\varepsilon_{pf}/\varepsilon_{po}$ varies with m for a material where $\delta_{1scc}/a_o = 0.5$, $a_o = 10$ µm (a typical initiated crack size) and $a_f = 400$ µm. It can be seen that the ductility is reduced to 2 ε_{po} if m is 5.5.

APPLICATION TO ZIRCALOY-2 CRACKING IN IODINE VAPOUR

The failure of Zircaloy-2 water reactor fuel cladding by stress corrosion in the presence of fission product iodine vapour is a good example of a displacement limited failure involving only short crack growth. Cladding thickness is of the order 0.6 mm and failures are known to occur following rapid power upratings (time period ~ 30 mins) involving cladding stresses of order Y (~ 480 MN/m^2). The cladding is forced out by the oxide fuel during the uprating to a total hoop strain of order 1% (i.e. a plastic strain of order 0.6%). Immediately after the uprating stress relaxation will result in a further plastic strain increment of approximately 0.25%. Assuming an initial crack of 10 µm, can such strain increments overcome the initiation condition given by δ_{1scc}? At present it is difficult to know what the effective value of σ/T is as $\sigma \to Y$, but it will $\to 1.0$. Therefore, although equation (2) cannot be used without knowing σ/T, it is clear that a bound on the problem is penetration of the flow zones across the section. In this case, the simpler equation

$$\delta \approx 2\varepsilon_p \,.\, t \qquad (15)$$

can be used where t is the clad thickness. When combined with equation (4), this gives

$$\varepsilon_p^* = \frac{K_{1scc}^{\;2}}{8\ ETt} \qquad (16)$$

and taking current values for K_{1scc} (32 MNm$^{-3/2}$ - ref (7)) and T (550 MN/m^2), $\delta_{1scc} = 4.2$ µm and $\varepsilon_p^* = 0.35\%$. This plastic strain is well within the values expected during the uprating.

However, for failure to occur a further increment of strain is needed. Figure 2 indicates that an initiated crack could be pushed to 2/3t by an additional 0.5% plastic strain if m = 4, i.e. the crack advance increment averages 16.8 µm. This is 2-3 times the typical grain size for Zircaloy-2 and is therefore consistent with the cleavage mechanism observed.

SUMMARY

This initial study of the crack opening displacement of short cracks in a high stress field has indicated that it provides a means of comparing low stress, long crack extension with short crack behaviour. Early calculations in relation to the Zircaloy-2 cladding problem indicate that its failure is consistent with a K_{1scc} concept.

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REFERENCES

1. DOWLING, N. E., in "Cracks and Fracture", ASTM STP 601, 1976, 19.
2. TOMKINS, B., Phil. Mag., 18, 1968, 1041.
3. COX, B. and WOOD, J. C., in "Corrosion Problems in Energy Conversion", (ed. C. S. Tedman, The Electrochemical Soc.), 1974, 275.
4. HEALD, P. T., SPINK, G. M. and WORTHINGTON, P. J., Materials Science, 10, 1972, 129.
5. TOMKINS, B., Trans. ASME - J. Eng. Matls. and Tech., 97, No. 4, 1975, 289.
6. TOMKINS, B., Proc. Conf. on the Influence of Environment on Fatigue, I. Mech. E., May 1977.
7. WOOD, J. C., J. Nucl. Mat., 45, 1973, 105.

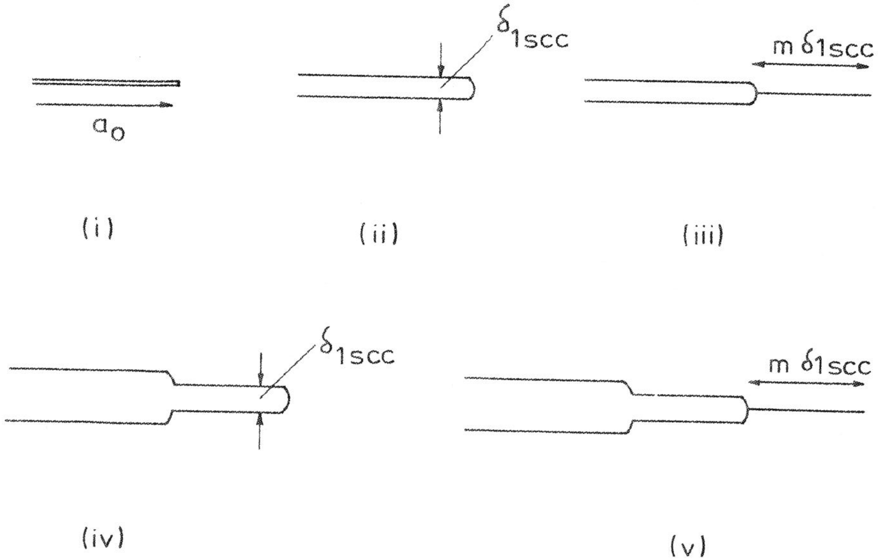

Figure 1 - The discontinuous crack advance process for stress corrosion crack growth

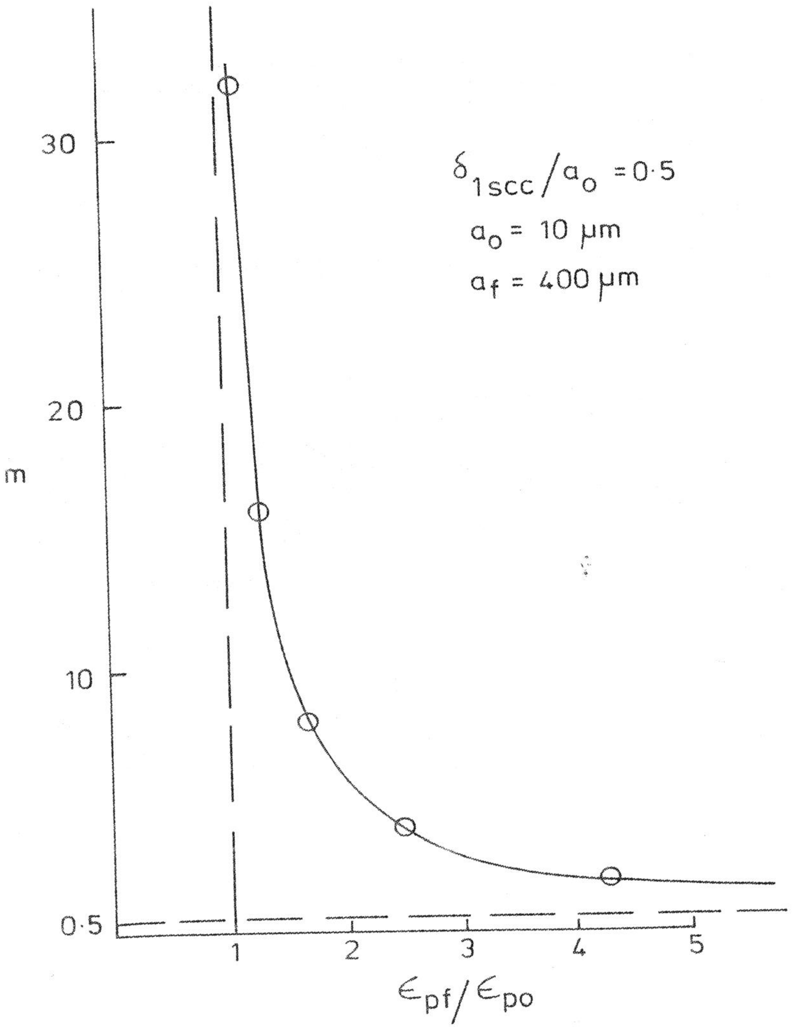

Figure 2 - Ratio of fracture strain to initiation strain as a function of crack advance coefficient