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A Theoretical Analysis of Time Dependent Ductile Crack Extension in Reactor Pressure Vessel Steels

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Abstract

Recent experimental observations on a reactor pressure vessel steel have shown that time dependent ductile crack extension, below the creep fracture temperature regime, is only significant under load control conditions when there is net-section yield. This viewpoint is substantiated by a theoretical analysis which shows that, for a material with a high ductile crack growth resistance, time dependent ductile crack extension should not occur under load control conditions when yield is contained.

1. Introduction

Nuclear reactor pressure vessel steels, such as A533B, operate at temperatures above their ductile-brittle transition, but below the creep fracture temperature regime. After the initiation of ductile tearing, these steels display a resistance to subsequent crack growth, and it is necessary to increase the load in order for crack growth to proceed, assuming of course that a fatigue or stress corrosion mechanism cannot operate. Garwood [1] has emphasized that there may be circumstances where limited crack extension by stable tearing might occur in a reactor pressure vessel, for example postulated accident conditions, assuming the most severe loading conditions, adverse material properties and with the largest postulated initial defect. This being the case, and if a stable ductile tear is allowed to exist in the structure, it is necessary to address the question as to whether or not further ductile crack extension can proceed as a result of the time dependent deformation behaviour of the material.

Against this background, Ingham and Moreland [2] have observed time dependent ductile crack extension in small-scale specimens of mild steel and A533B that are held at constant load. Their conclusions, which are in accord with Tsuru and Garwood's results [3] for line pipe steels, were:

(a) Time dependent effects are only relevant under fully yielded conditions,

(b) The mechanism can be explained in terms of the rate dependence of the material's deformation behaviour,

(c) Failure due to time dependent crack growth should not be expected in structures where the crack tip yielding is contained.

The results [1] of a recent test programme on A533B wide plate specimens have confirmed that time dependent ductile crack extension is only significant under load control conditions when there is net-section yield. Further support for this viewpoint is provided by the present paper's theoretical analysis which shows that, for a material with a high ductile crack growth resistance, time dependent ductile crack extension should not occur under load control conditions when yield is contained.

2. Theoretical Analysis

This paper's theoretical analysis is based on a Dugdale-Bilby- Cottrell-Swinden (DBCS) strip yield representation [4,5] of plastic deformation in the vicinity of a crack tip. Thus consider the general DBCS model where the tensile stress within the strip yield zone ahead of a crack has the value Y which is representative of the material's tensile yield stress. Irrespective of the plastic zone size and any geometrical parameters, if as a criterion for ductile crack growth it is required that a constant crack tip opening angle CTOA θ, measured with respect to a distance r_m behind the tip (r_m is envisaged to be representative of the fracture process zone size), is maintained during growth, the ensuing differential equation describing crack growth is [6,7]

$$\frac{dJ}{dc} = \theta Y + \frac{4(1-\nu^2)Y^2}{\pi E} \ell n \left[\frac{r_m}{s} \right] \tag{1}$$

where J is the J integral, c is the crack size, E is Young's modulus, ν is Poisson's ratio and s is a parameter which depends on both the extent of yielding and any geometrical parameters in the particular model under consideration. s enters into the expression for the crack opening δ at a distance r behind the tip of a stationary crack of length c:

$$\delta = \Phi_{TIP}(c) + \frac{4(1-\nu^2)Yr}{\pi E} \ell n \left[\frac{s}{r} \right] \tag{2}$$

where Φ_{TIP} is the crack tip displacement in the DBCS model.

Against the preceding general background, consider the specific model of the plane strain deformation of a solid with two symmetrically situated deep cracks, and with tension of the small remaining ligament, a sustained load P being applied at a point a great distance from the ligament (Figure 1). B is the solid thickness, 2L is the ligament width and there is a line plastic zone of size R_p at each tip. This model is a special case of the more general model of a periodic system of coplanar cracks in an infinite solid, which is cut along vertical surfaces so as to give the model in Figure 1 (this cutting procedure will be exact for the analogous Mode III model). It has been shown elsewhere [8], that the values of the J integral and the parameter s are given by the expressions:

$$J = \frac{4(1-\nu^2)Y^2L}{\pi E} \left[(1+\lambda)\ell n(1+\lambda)+(1-\lambda)\ell n(1-\lambda) \right] \tag{3}$$

and $$s = 2eL\lambda^2 \tag{4}$$

with $$\lambda = \frac{P}{2BLY} = \sqrt{2t\left[1 - \frac{t}{2}\right]} \tag{5}$$

and where t is the ratio of the plastic zone size (R_p) at each tip to half the ligament width (L). Thus for small-scale yielding, t, $\lambda \to 0$ while t, $\lambda \to 1$ as the general yield state is approached.

In applying these results, we are interested in the situation where there has been same crack growth due to an increase in the load P. This load is then maintained at a constant value and to simulate the rate dependence of material deformation, the yield stress is assumed to decrease below its initial value Y to some slightly lower value Y_*. The question then arises as to whether or not there will be any further crack growth. To address this question, we use relations (1), (3), (4) and (5), with Y replaced by Y_*. With the load P constant, and $dJ/dc = -dJ/dL$, relation (5) shows that $d\lambda/dL = -\lambda/L$, whereupon relations (1), (3) and (4) give the condition for further crack growth as

$$\lambda = \frac{P}{2LBY_*} = \left[1 + \frac{2eL}{r_m \exp\left\{ \dfrac{\pi E\Theta}{4(1-\nu^2)Y_*} \right\}} \right]^{-1/2} \tag{6}$$

Now r_m, as mentioned earlier, is regarded as a measure of the fracture process zone size which, for a ductile material that fractures by a hole coalescence mechanism, will approximate to δ_{IC}, the critical crack tip opening displacement associated with the onset of fracture at the tip of a stationary crack in a fracture mechanics test. $\delta_{IC} \equiv J_{IC}/Y$ with the DBCS model, where J_{IC} is the critical value of the J integral at the onset of plastic fracture. Now L/r_m will at most be of the order 10^3, and noting that T_{MAT} ($\equiv E\Theta/Y \cong E\Theta/Y_*$) for a high crack growth resistant material is >100, then relation (6) clearly shows that further (time dependent) crack extension will not occur unless the general yield state is approached.

3. Discussion

The results of the preceding section's analysis clearly demonstrate that with a material, such as a reactor pressure vessel steel, that has a high resistance to ductile crack growth, time dependent ductile crack extension should not occur under load control conditions (and therefore quite obviously should not occur under displacement control conditions) when yield is contained. It is worth noting that this conclusion is based on the same results that have been used to reach the conclusion [9] that when a crack grows slowly by, for example, a stress corrosion mechanism, in a component that is subject to constant applied loads, then (unstable) ductile crack growth should not occur when yield is contained, if the material has a high crack growth resistance. Though this paper's analysis is based on a very specific model, there is no reason to suspect that a different conclusion would be reached if other models were analysed.

The theoretical results complement experimental results, obtained notably by Ingham and co-workers [2] and Garwood and co-workers [1,3], and which are referred to in the Introduction. Taking the experimental observations and theoretical predictions together, it would seem that time dependent ductile crack extension in reactor pressure vessel steels should not be a problem in practice if yield is contained.

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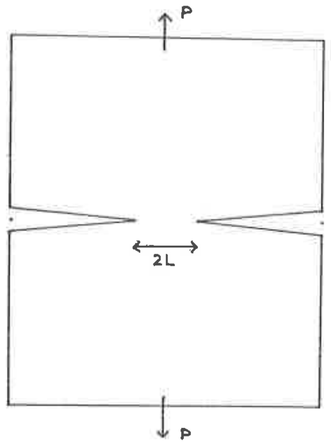

FIGURE 1. The plane strain tension model of a solid containing two symmetrically situated deep cracks, and with tension of the small remaining ligament.