THE INFLUENCE OF RATE-DEPENDENT DEFORMATION IN PREDICTING DUCTILE FRACTURE IN α - TITANIUM AT 20^{0}C.

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The rate-dependent deformation behaviour of α - Titanium at room temperature is described in terms of a constitutive equation. The ductile fracture properties are also given. The material data is used as input to a post-yield fracture mechanics assessment route to assess the integrity of components containing defects. The assessment route is described and is used to predict the fracture and the fracture instability behaviour of condenser tubes having longitudinal surface defects. The ductile fracture instability conditions are found to be a function of the applied strain rate and the initial defect depth.

INTRODUCTION

In post-yield fracture mechanics it has been demonstrated that for components containing defects, the onset of crack growth and subsequent small amounts of crack extension can be described by parameters such as the J-integral. These parameters have been used in simplified assessment routes to examine whether a component can sustain the loading without the onset of instability. In many cases the assessment routes have been applied to components constructed from materials which are often assumed to exhibit rate independent plastic deformation at room temperature. In some cases this assumption may be appropriate, but it has been widely recognised that many engineering materials do exhibit rate or time dependent effects. The

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importance of this phenomenon, in relation to the assessment of defects in components, is addressed in this paper.

DEFORMATION AND FRACTURE CHARACTERISTICS

The deformation characteristics were obtained from uniaxial tensile specimens tested in closed-loop servo-electrically controlled testing machines. Tests were conducted in strain control, at strain rates, ranging from 1.10^{-7} to 0.57 sec^{-1}. These results (1) have been found to be well described by a single uniaxial constitutive equation, derived by Cernocky and Krempl (2), where

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + \frac{\sigma - g[\varepsilon]}{Ek[\sigma - g[\varepsilon]]} \quad \ldots\ldots [1]$$

E is Young's Modulus, g is the 'equilibrium' stress-strain curve and k is a relaxation function.

Compact tension specimens were tested at a constant displacement rate of 0.15 mm/min and the material's resistance was measured using the J-integral, where

$$J^R = 0.42\ (\Delta a)^{0.74} \quad : \quad \Delta a < 1mm \quad \ldots\ldots [2]$$

with J^R and Δa (= $\{a-a^o\}$), are the measured J-integral and ductile crack extension respectively. An arbitrary value of the J-integral, J^R= 8.1 kJ/m^2, for the initiation of ductile crack growth was used in the following analysis.

ANALYSIS FOR STRUCTURAL INTEGRITY

The route used in this paper to assess the behaviour of a component, utilises the J-integral as the fracture parameter, defined as J^A and crack growth is assumed to take place when $J^A = J^R$. The analysis is applied to the problem of the growth of defects in internally pressurised condenser tubing assumed to contain external longitudinal surface defects, whose length are long compared with the tube wall thickness. The internal radius r is 6.934mm and the wall thickness t is 1mm.

An approach proposed by Ainsworth (3) is adopted, with

$$J^A = \frac{K^2[a]}{E'} \left\{ \frac{K^2\ [a^e]}{K^2\ [a]} + \frac{\mu E'}{E} \left(\frac{E\varepsilon}{\sigma} - 1\right) \right\} \ldots\ldots\ldots\ldots\ldots [3]$$

where K is the elastic stress intensity factor, and ε is the uniaxial strain corresponding to the reference stress σ. For plane stress $E' = E$ and for plane strain $E' = E/(1-\nu^2)$, where ν is Poisson's ratio. The stress intensity factor K[a] is modified to $K[a^e]$ to account for a plastic zone (3).

The stress intensity factor K, is

$$K = \frac{p\ r^2}{R^2 - r^2} \sqrt{\pi a}\ \ F\left[\frac{r}{R}\ ,\ x\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots [4]$$

where R is the outside radius, x = a/t. For x <0.5, the function F is given in a diagram by Rooke and Cartwright (5) for various r/R. For x≥0.5, F is given in ref (6).

The reference stress is (7)

$$\sigma = p / \left\{ \frac{t}{r}\ (1-x)\ /\ \left\{ 1 - \left(x\ /\ \sqrt{(1 + 1.61\rho^2)} \right) \right\} \right\} \ \ldots\ldots [5]$$

where $\rho = c\sqrt{(rt)}$, and c is half the surface length of the defect.

For any applied loading to estimate J^A the uniaxial stress-strain curve was obtained by numerical integration of Eq.[1] together with Eq.[3].

RESULTS AND DISCUSSION

Effect of Crack Length

Representative J^A versus p curves are plotted in Fig.1. For each initial crack length, the chain dotted curve represents the locus of points of J^A versus p for continuous crack growth after initiation. For an initial crack length ratio of 0.2, there is a limit to the amount of crack growth. This is because the pressure reaches the pressure p_u (corresponding to the ultimate tensile strength) before J^A attains the corresponding value of $J^R[\Delta a]$. At longer crack length ratios the crack growth is more extensive after reaching a peak pressure. The peak pressure corresponds to the point where the slope $\partial P/\partial J$ of the chain dotted curve is zero as shown in Fig.1. It is assumed that ductile fracture instability takes place at the peak pressure, p_{inst}.

Effect of Strain Rate

Results are shown in Fig.2. The chain dotted line represents the locus of points of J^A versus p for continuous crack growth. Initiation of crack growth occurs at a pressure closer to the yield pressure p^L at high rates. Subsequently the instability pressure is closer to p^L at high strain rates than at low strain rates. At the strain rate corresponding to the 'equilibrium' stress-strain curve, the instability pressure is close to p_u.

In Fig.3 the pressures p_u, p_{inst} and p^L at initial crack length to thickness ratios in the range $0 < a^o/t < 1.0$ are shown for strain rates of 10^{-7}, $5.1.10^{-4}$ and $-.57$ sec^{-1}. At each strain rate p_{inst} is bounded from below by p^L and from above by p_u.

At strain rates close to the 'equilibrium' curve (i.e. 10^{-7} sec^{-1}) p_{inst} coincides with p^L for $a^o/t > 0.85$. As the strain rate increases, it can be seen from Fig.3 that p_{inst} coincides with p^L for a^o/t less than 0.85. At smaller crack lengths, and a strain rate of 10^{-7} sec^{-1}, $p_{inst} = p_u$ at about $a^o/t = 0.15$.

It is considered that the results of the above study are representative of the behaviour of a number of engineering materials which exhibit rate-dependent deformation. The results have illustrated that account should be taken in cracked components of the sensitivity of the material behaviour to the rate of loading. Further work is underway to investigate the behaviour of components under sustained load or creep conditions.

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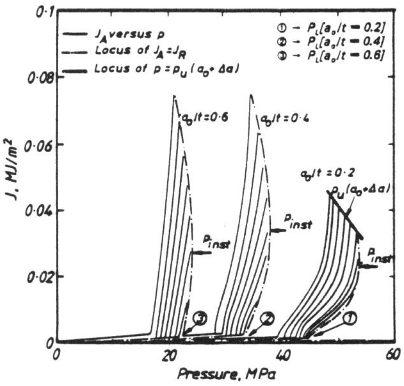

Figure 1 Driving force curves for $\dot{\varepsilon}$=5.1 $10^{-4}s^{-1}$

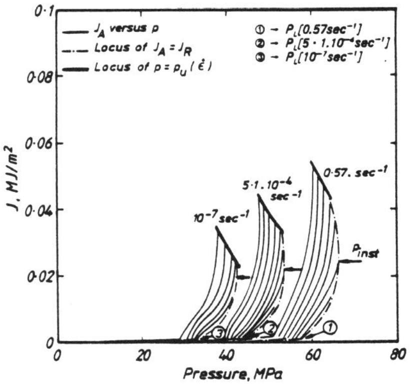

Figure 2 Driving force curves for a/t=0.2

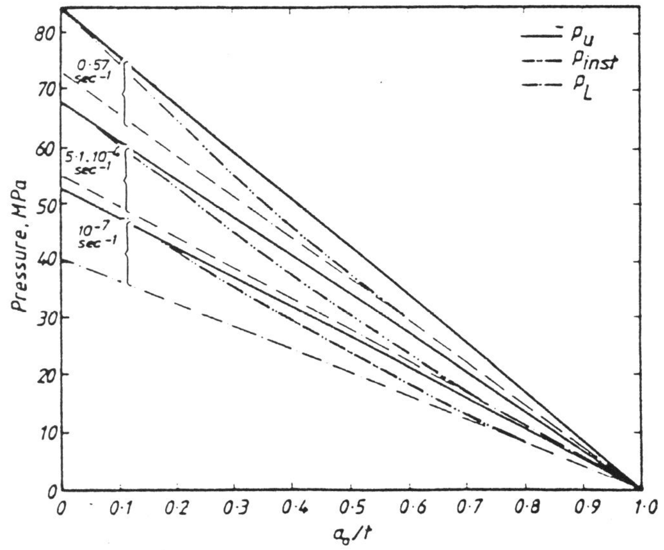

Figure 3 Influence of strain rate on yield, instability and ultimate pressures