Life Prediction at High Temperatures

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ABSTRACT

Models for predicting the lifetimes of uncracked and cracked components subjected to creep are presented. Reference stress methods are employed to determine net section rupture and fracture mechanics concepts to obtain crack growth rates. For cracked components the influence of allowing for net section damage on the crack growth process is considered to produce enhanced crack propagation rates and residual life estimates.

KEYWORDS

Creep, fracture mechanics, crack growth, residual life.

INTRODUCTION

Failure of engineering components by creep at elevated temperatures can occur by net section rupture, crack growth or a combination of both processes. Net section rupture is most likely to occur in structures that are initially defect free and in which damage can develop relatively evenly through the thickness. Failure by crack growth is most likely to be favoured in components which contain an initial defect at a site where the local stress state can cause a sharp crack to be preserved which can propagate readily. In other circumstances crack initiation and growth may take place which is terminated by net section rupture after some amount of crack extension.

Individual procedures have been developed for describing net section rupture in terms of reference stress methods (Penny and Marriott, 1971; Goodall *et al*, 1979) and crack growth using non-linear fracture mechanics concepts (Webster, 1983; Ainsworth and Goodall, 1983; Nikbin *et al*, 1983, 1984).

The procedures have been applied by Webster, Smith and Nikbin (1986) to predict the failure of components by net section rupture and crack growth alone and crack growth followed by net section rupture. When rupture was allowed to terminate the cracking process no influence of damage development in the uncracked ligament ahead of the crack on the crack propagation rate was included in the analysis. The rupture and cracking mechanisms were treated as independent.

In the present paper the earlier analyses are reviewed and extended to allow for crack propagation through previously damaged material. A procedure for making residual life estimates is presented. An example of crack growth in a pressurized cylinder is included to illustrate the influence of interaction between the cracking process and progressive net section damage.

FAILURE BY NET SECTION RUPTURE

Techniques have been developed (Penny and Marriott, 1971; Goodall *et al*, 1979) for describing failure in components by net section rupture in terms of the reference stress concept. Consider Fig 1 which shows a uniaxial creep curve and stress rupture plot. Typically creep strain rate $\dot{\varepsilon}$ can be expressed as

$$\dot{\varepsilon} = \dot{\varepsilon}_o \left\{ \frac{\sigma}{\sigma_o} \right\}^n \tag{1}$$

where σ is stress and $\dot{\varepsilon}_o$, σ_o and n are material constants. Equation (1) can be used to describe the secondary creep rate $\dot{\varepsilon}_s$ or an average strain rate $\dot{\varepsilon}_A$ which can be written in terms of the failure strain ε_f and rupture life t_r as

$$\dot{\varepsilon}_A = \dot{\varepsilon}_f / t_r \tag{2}$$

In addition, for the stress rupture plot illustrated in Fig 1b),

$$t_r = \frac{\varepsilon_{fo}}{\dot{\varepsilon}_o} \left\{ \frac{\sigma_o}{\sigma} \right\}^{\upsilon} \tag{3}$$

where ε_{fo} is the uniaxial creep failure strain at stress σ_o. For $n > \upsilon$ creep ductility will decrease with decrease in stress and when $n = \upsilon$ a constant failure strain is predicted.

The reference stress σ_{ref} for a component can be calculated by limit analysis methods. When σ_{ref} is not constant the life fraction rule can be employed to calculate the fraction of damage ω incurred over a time period t

$$\text{ie} \quad \omega = \int_o^t \frac{dt}{t_r} \tag{4}$$

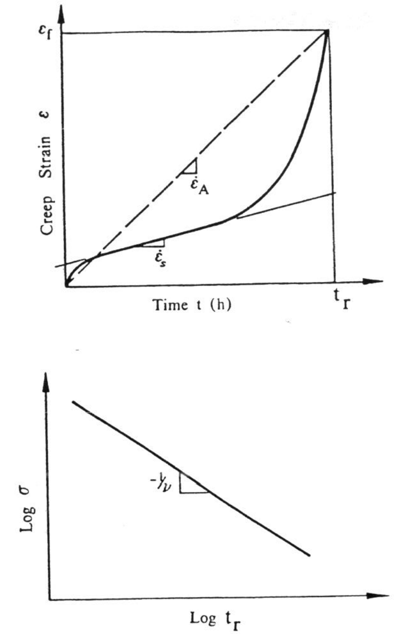

Fig. 1 a) Simplification of primary, secondary and tertiary creep data and b) typical stress rupture plot

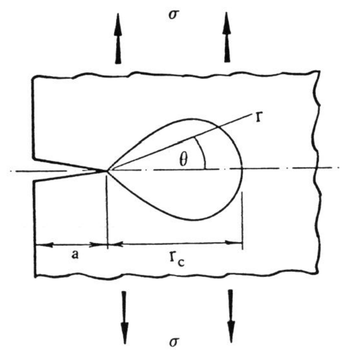

Fig. 2 Zone ahead of creeping crack in which damage accumulates

Substitution of eq (3) into eq (4) allows failure to be calculated at $\omega = 1$ and $t = t_R$ when

$$1 = \int_o^{t_R} \frac{\dot{\varepsilon}_o}{\varepsilon_{fo}} \left\{ \frac{\sigma_{ref}}{\sigma_o} \right\}^{\upsilon} \quad (5)$$

The above analysis can be applied to both cracked and uncracked components provided the appropriate reference stress is calculated (Penny and Marriott, 1971; Goodall *et al*, 1979).

FAILURE BY CREEP CRACK GROWTH

The analysis of the crack propagation process makes use of experimental observations (Webster, 1983; Nikbin *et al*, 1984) that crack growth rate $\dot{a}$ can be correlated most satisfactorily in terms of the creep fracture mechanics parameter C* by an expression of the form

$$\dot{a} = D_o C^{*\phi} \quad (6)$$

where D_o and ϕ are material constants which can be measured experimentally or determined from models of the cracking mechanism. In the approach of Nikbin, Smith and Webster (1983, 1984) a process zone is postulated at the crack tip as shown in Fig 2. It is supposed that the zone encompasses the region over which creep damage accumulates at the crack tip and that crack advance takes place when the creep ductility ε^*_{fo} appropriate to the state of stress at the crack tip is exhausted. The model predicts,

$$D_o = \left\{ \frac{n+1}{n+1-\upsilon} \right\} \frac{\dot{\varepsilon}_o}{\varepsilon^*_{fo}} \left\{ \frac{1}{I_n \sigma_o \dot{\varepsilon}_o} \right\}^{\upsilon/(n+1)} r_c^{(n+1-\upsilon)/(n+1)} \quad (7)$$

$$\text{and} \quad \phi = \upsilon/(n+1) \quad (8)$$

For plane stress conditions ε^*_{fo} is taken to equal ε_{fo} and for plane strain loading to equal $\varepsilon_{fo}/50$. The factor I_n has been tabulated by Hutchinson (1968) as a function of n and state of stress.

When $n = \upsilon$ and failure strain is constant at ε^*_f, eqs (7) and (8) simplify to,

$$D_o = (n+1) \frac{\dot{\varepsilon}_o}{\varepsilon^*_f} \left\{ \frac{1}{I_n \sigma_o \dot{\varepsilon}_o} \right\}^{n/(n+1)} r_c^{1/(n+1)} \quad (9)$$

$$\text{and} \quad \phi = n/(n+1) \quad (10)$$

Close examination of a wide range of experimental data (Nikbin *et al*, 1983; 1984) has revealed that the creep ductility term in eqs (7) and (9) is the most important parameter governing crack growth rates so that eq (6) can be expressed approximately as

$$\dot{a} = \frac{3C^{*0.85}}{\varepsilon^*_f} \quad (11)$$

when $\dot{a}$ is in mm/h, ε_f^* is a fraction and C* is in MJ/m^2h. The plane stress and plane strain bounds of eq (11) are shown plotted in Fig 3 with $\dot{a}\varepsilon_f$ as ordinate to produce a material independent engineering creep crack growth assessment diagram (Nikbin *et al*, 1986). The shaded area represents the spread of all the experimental data examined. It can be seen that the two bounds approximately span the data.

The time taken for a crack to advance from an initial value a_o to a is obtained by integrating eq (6) to give

$$t = \int_{a_o}^{a} \frac{da}{D_o C^{*\phi}} \quad (12)$$

The dependence of C* on crack length and component geometry can be obtained in non-dimensional form from numerical estimates of the J-contour integral (Kumar *et al*, 1981).

An illustration of the predictions of eq (12) for a centre cracked plate (CCP) of width W, with D_o and ϕ given by eqs (9) and (10), is shown in Fig 4 (Webster et al, 1986) where t_r is the uncracked plate rupture life and

$$\lambda = \frac{(n+1)}{I_n^{n/(n+1)}} \cdot \frac{\varepsilon_f}{\varepsilon^*_f} \left\{ \frac{r_c}{W} \right\}^{1/(n+1)} \quad (13)$$

The figure indicates that crack propagation rate increases more rapidly with increase in n for a given state of stress. For a given value of n it is apparent that crack growth is more rapid in terms of non-dimensional time for plane stress conditions than it is for plane strain loading. This is a consequence of the normalizing parameter λ and a faster crack propagation rate is predicted for plane strain conditions in real time consistent with experimental experience. Similar trends have been observed for cracked bending components (Webster et al, 1986).

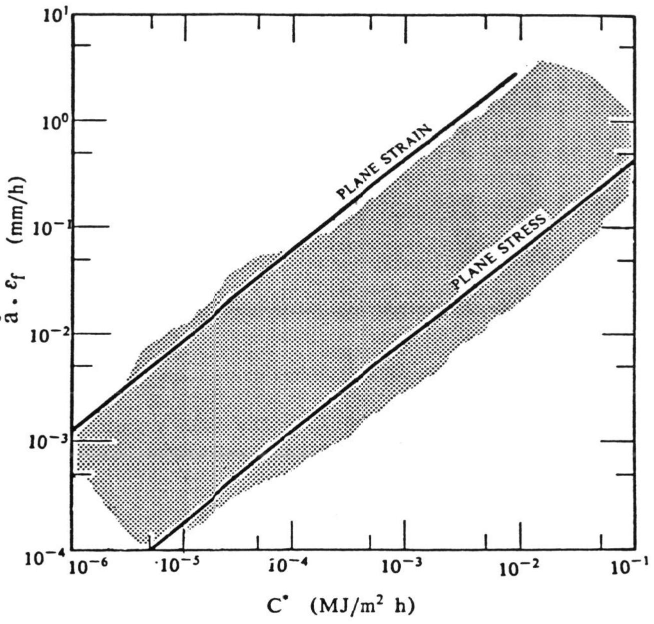

Fig. 3 Material independent engineering creep crack growth assessment diagram

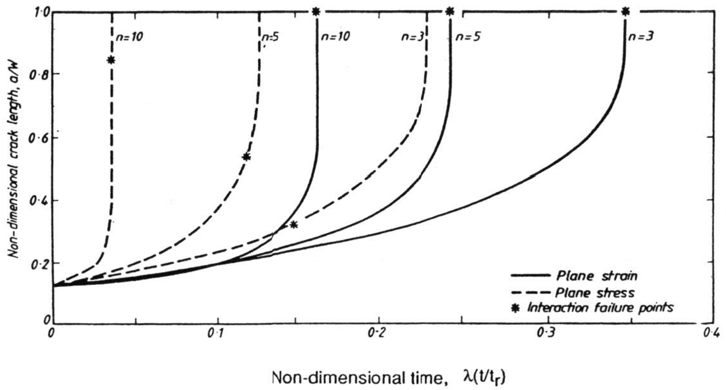

Fig. 4 Creep crack growth v. non-dimensional time for CCP specimen

TERMINATION OF CRACK GROWTH BY RUPTURE

During crack growth, in addition to damage accumulation local to the crack tip, damage will develop in the uncracked ligament as indicated by eq (4). The crack length a_R at which rupture of the ligament will take place is obtained by substituting eq (6) into eq (5) to produce

$$1 = \int_{a_o/W}^{a_R/W} \cdot \frac{\dot{\varepsilon}_o}{\varepsilon_{fo}} \left\{ \frac{\sigma_{ref}}{\sigma_o} \right\}^{\upsilon} \cdot \frac{W}{D_o C^{*\phi}} \cdot d(a/W) \qquad (14)$$

The predictions of this equation for the case of the CCP geometry for a typical value of $r_c/W = 0.001$ and $n = \upsilon$ is shown in Fig 4. It is clear that for plane strain conditions that rupture does not intervene until approximately $a/W = 1$. For plane stress loading rupture can terminate the cracking process after relatively short amounts of crack growth but because of the rapid acceleration in cracking that occurs this has little influence on failure times for $n > 3$. The effect of ligament rupture becomes more pronounced with decrease in initial crack size (Webster *et al*, 1986).

INTERACTION BETWEEN CRACK GROWTH AND RUPTURE

Material deterioration and damage can occur during service. Residual life assessments involving crack growth require an estimate of how the constants in eq (6) are affected. If ductility exhaustion only takes place during exposure it is possible to replace D_o in eq (6) by a value for exposed material D_e given by

$$D_e = D_o/(1 - \varepsilon_o/\varepsilon_f) \qquad (15)$$

where ε_o is the creep strain used up during prior service (Webster, 1987). An illustration of how service exposure influences crack propagation rates in a stainless steel is shown in Fig 5 (Buchheim *et al*, 1986). Component remanent lifetimes can then be determined, using the above procedures, with D_o replaced by D_e.

The above methods make no allowance for progressive damage in the uncracked ligament on crack propagation rates. This can be achieved by replacing the constant D_o by a variable D in eqs (6), (12) and (14). An approach which is consistent with eqs (4) and (15) is to express D as,

$$D = D_o/(1 - \omega) \qquad (16)$$

An example of how this cumulative damage model influences crack growth in a $^1/_2$CrMoV steel pressure vessel is shown in Fig 6 (Nishida and Webster, 1988). The main effect is to cause an increased crack growth rate towards the end of life.

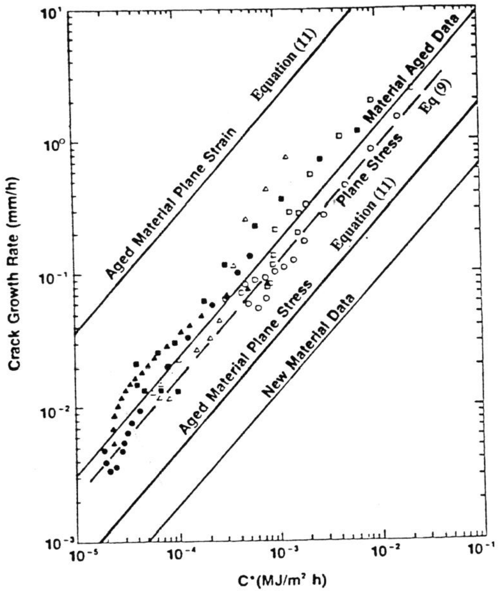

Fig. 5 Creep crack growth data for service exposed 304H stainless steel at 760°C

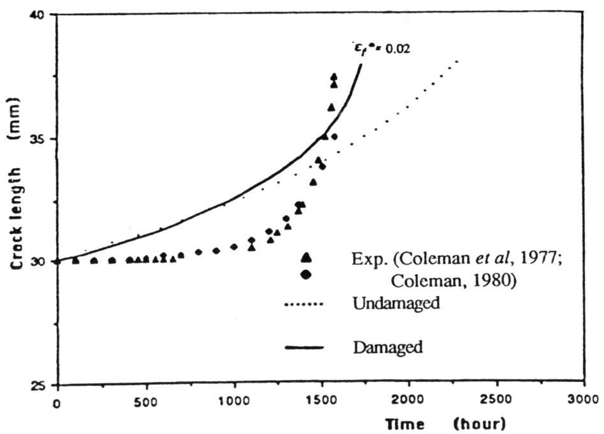

Fig. 6 Experimental and predicted crack growth from a circumferential crack in a $^1/_2$ CrMoV pressure vessel

CONCLUSIONS

Separate models for predicting the failure of uncracked and cracked components in terms of net section rupture, crack growth, crack growth terminated by rupture and interaction between crack propagation and ligament damage have been presented. For cracked components and plane strain conditions, net section rupture has little influence on failure times. Allowance for cumulative damage on crack propagation rates causes accelerated cracking towards the end of life.

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