CREEP DAMAGE AND FRACTURE①

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ABSTRACT Creep damage behavior and creep crack propagation behavior at high temperatures were investigated. The expressions of the resistance to creep damage, stress intensity factor threshold and initiation time were obtained under given conditions. The range of applicability of the characterizing parameter for creep crack growth was analysed by using resistance to creep damage of material. The influence of temperature on stress intensity factor threshold and creep crack growth rate was analysed. Expressions for creep crack growth rate were presented.

1 INTRODUCTION

Macroscopic creep crack growth (CCG) has been studied and reported in the literature for a number of years for various materials. Recent reviews have summarized the different characteristics of CCG from both metallurgical and engineering aspects[1,2]. The characteristics of CCG have been shown to be dependent on both material and microstructure. Several parameters are being used to correlate the CCG data. These parameters are mainly the stress intensity factor K_I and the path-independent integral C^*.

Approaches with which to study the interaction between a macroscopic crack and microscopic damage in a material have been considered by Janson and Hult[3] and Zhang[4,5]. Here, this combination is further investigated by using a new creep damage model.

2 CREEP DAMAGE

From a macroscopic aspect, damage is not directly measurable as strain or plastic strain. However, the damage process is an irreversible process of energy dissipation accompanied by variations of some physical parameters. A new method to establish the evolution equation of damage aided by the introduction of the accompaning parameter was provided by Zhang[5]. Since creep damage is a term coined by engineers to describe the material degradation which gives rise to the acceleration of creep rate known as tertiary creep, we choose creep rate $\dot{\varepsilon}$ as an accompanying parameter and the time of tertiary creep as a damage career Z. If the initiation time of tertiary creep is t_0 at constant stress σ_0, then $Z = t - t_0(\sigma_0)$. According to Zhang[5], the constitution law of creep damage is given by:

$$\mathrm{d}D/\mathrm{d}Z = G\dot{\varepsilon}_m^s Z^{v-1}/(1-D)^n \tag{1}$$

where $\dot{\varepsilon}_m$ is minimum creep rate; n, G, S and v are constants determined by material and test conditions.

For many materials, $s = m/n$, $v = 1$ and

$$\dot{\varepsilon}_m = A_1\sigma^n\exp[-Q/(RT)] \tag{2}$$

so that eq. (1) can be written as:

$$\mathrm{d}D/\mathrm{d}Z = A\sigma^m\exp[-Q'/(RT)]/(1-D)^n \tag{3}$$

where $Q = mQ'/n$, $A = GA_1^{m/n}$, R is Boltzmann's constant and T is the absolute temperature

For three-dimensional problems, the creep damage law may be written as:

$$\left.\begin{aligned}&\mathrm{d}D/\mathrm{d}Z = A\sigma^{*m}\exp[-Q/(RT)]/(1-D)^n \quad (\sigma^* \geqslant \sigma_t)\\&\mathrm{d}D/\mathrm{d}Z = 0 \quad (\sigma^* < \sigma_t)\end{aligned}\right\} \tag{4}$$

where σ^* is the damage equivalent stress.

$$\sigma^* = \bar{\sigma}[2/3(1+\nu_0) + 3(1-2\nu_0)(\sigma_m/\bar{\sigma})^2]^{1/2} \tag{4'}$$

where $\bar{\sigma}$ and σ_m are von Mises' equivalent stress and the hydrostatic stress, and ν_0 is Poisson's ratio.

By integrating eq. (3) and using the con-

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ditions $D(0) = 0$ and $D_c(Z_c) = 1$, the expression for Z_c is:

$$Z_c = \frac{1}{(n+1)A}\sigma^{-m}\exp[Q/(RT)] \qquad (5)$$

If we introduce the Monkman-Grant law:

$$t_f\dot{\varepsilon}_m^p = C \qquad (6)$$

where t_f is the time to failure, and p and C are constants, the expression of the time to failure can be written as:

$$t_f = C\dot{\varepsilon}_m^{-p} = CA_1^{-p}\sigma^{-np}\exp[Q'p/(RT)] \qquad (7)$$

If $p = s$, we obtain:

$$t_f = \frac{CG}{A}\sigma^{-m}\exp[Q/(RT)] \qquad (8)$$

The initiation time of tertiary creep can be obtained by using eq. (5):

$$t_0 = t_f - Z_c = L\sigma^{-m}\exp[Q/(RT)] \qquad (9)$$

where $L = \frac{1}{A}(CG - \frac{1}{n+1})$

Let $t_0 = t_1$, we obtain the expression of the resistance to creep damage as follows:

$$\sigma_t^m = Lt_1^{-1}\exp[Q/(RT)] \qquad (10)$$

3 INITIATION TIME AND THRESHOLD VALUE OF STRESS INTENSITY FACTOR

We consider a two-dimensional problem with a plane crack in plane-stress tension (Mode I). The crack extends in the positive X-direction. Attached to the crack tip is a polar coordinate system(r, θ) with $\theta = 0$ lying directly ahead of the crack. In general, the redistribution of stress due to evolution of demage will take place. In the small invalid zone case the stress field ahead of a crack and the evolution of creep damage can be tested as separate problems. We assume that the near tip stress field is $\sigma(r, \theta, t)$ and the damage equivalent stress field is $\sigma^*(r, \theta, t)$, on the crack propagation line($\theta = 0$), $\sigma^*(r, \theta, t) = \sigma^*(r, t)$, the damage distribution function $D(r, t)$ can be determined by integrating eq. (4):

$$D(r, t) = 1 - \{1 - (n+1) \times \int_0^Z (\sigma^*(r, t))^m A \times \exp[-Q/(RT)]dZ\}^{1/(n+1)} \qquad (11)$$

The boundary point of the damage zone is determined by the following equation:

$$\sigma^*(r, t) = \sigma_t \qquad (12)$$

Creep fracture involves an incubation period followed by a period of crack growth that left unchecked can result in a loss of structural integrity. During the incubation period creep deformation devolops in the creep zone emanating from the crack tip until sufficient accumulative damage has occurred to produce crack growth. In order to relate initiation of crack growth to applied load a fracture criterion is required. Zhang[4] has proposed the following fracture criterion: crack extension will occur when the creep damage at a small structural distance, r_d, from the crack tip attains its critical value D_c. Both the critical value of creep damage and structural distance are considered as material properties to be determined from experiments. By eq. (11), the fracture criterion can be written as:

$$D(r, t)|_{r_d = D_c} = 1 - \{1 - (n+1) \times \int_0^Z [\sigma^*(r_d, t)]^m A \times \exp[-Q/(RT)]dZ\}^{1/(n+1)} \qquad (13)$$

As an example, we consider a material which exhibits both elastic and nonlinear viscous response (for uniaxial tension, it has the form $\dot{\varepsilon} = \dot{\sigma}/E + B\sigma^n$). The asymptotic stress fields near tips of both stationary and propagating cracks, have the HRR type:

$$\sigma_{ij}(t) = [c(t)/(BIr)]^{1/(n+1)}\hat{\sigma}_{ij}(\theta, n) \qquad (14)$$

and $t < t_m$, $c(t) = K_1^2/[(n+1)tE]$ (15)

$t > t_m$, $c(t) = C^*$ (16)

$$t_m = K_1^2/[(n+1)EC^*] \qquad (17)$$

where t_m is the transition time and C^* is the path-independent integral.

In the $t_0(\sigma(r_d)) < t_m$ case, the crack tip stress field is characterized by the stress intensity factor K_1. From eqs. (4′), (14) and (15), we can obtain:

$$\sigma^* = \{K_1^2/[BI(n+1)Etr]\}^{1/(n+1)}H \qquad (18)$$

where $H = (\hat{\sigma}_\theta + \hat{\sigma}_r - 2\nu_0\hat{\sigma}_r\hat{\sigma}_0)^{1/2}$ (19)

If $\sigma^*(r_d, t) < \sigma_t$, no creep damage occurs at r_d during the test. As a criterion, we have the threshold value of stress intensity factor, K_{1t}, which can be solved from the following equation:

$$\sigma^*(r_d, t) = \sigma_t = \{K_{1t}^2/[BI(n+1) \times Etr_d]\}^{1/(n+1)}H \quad (20)$$

therefore

$$K_{1t}^2 = BI(n+1)Etr_d\sigma_t^{n+1}/H^{n+1} \quad (21)$$

The result shows, if $K_1 < K_{1t}$, not crack growth takes place. This is in agreement with the results reported earlier[6,7].

Substituting eq. (9) into eq. (21) we now obtain:

$$K_{1t}^2 = BI(n+1)EH^{-(n+1)}L \times \exp[Q/(RT)]r_d\sigma_t^{(n+1)/m} \quad (22)$$

From this equation, we know that K_{1t} depends upon temperature and increases with decreasing temperature.

If $\sigma^*(r_d, t) > \sigma_t$, creep damage will occur at r_d. By using eqs. (18) and (4), we have

$$dD/dZ = AH^m\exp[-Q/(RT)] \times \{K_1^2/[BI(n+1) \times Etr_d]\}^{m/(n+1)} \quad (23)$$

By integrating this equation and using the condition $D_c = 1$, the expression for Z_c is:

$$Z_c = (n+1)^{-1/(n+1)}A^{-1}H^m\{\exp[Q/(RT)] (BIEt_1r_d)\}^{m/(n+1)}K_1^{-2m/(n+1)} \quad (24)$$

and then initiation time t_i is

$$t_i = Z_c + t_0 \quad (25)$$

The result shows $t_i \propto K_1^{-2m/(n+1)}$, and is in agreement with the empirical relationship[8,9].

In the $t_0(\sigma^*(r_d)) > t_m$ case, the crack tip stress field is characterized by C^*-integal. By using eqs. (14) and (16), the expression for $\sigma^*(r, t)$ is

$$\sigma^*(r, t) = [C^*/(BIr)]^{1/(n+1)}H \quad (26)$$

Similarly, by eqs. (26) and (4), the expression for t_i is obtained under a long-term creep condition:

$$t_i = t_0 + A^{-1}H^{-1}(n+1)^{-1} \times \exp[Q/(RT)](BIr_d)^{m/(n+1)} \times C^{*-m/(n+1)} \quad (27)$$

4 CREEP CRACK GROWTH RATE

Let the polar coordinate move with the crack, under steady-state crack growth; the variation of the stress field is small and can be neglected when viewed by an observer fixed to the moving crack tip.

The damage distribution near the crack tip is shown as Fig. 1 and the boundary point of the damage zone is r_0. During the time interval $t_2 - t_1$ for the crack to extend an increment r_0, the crack growth rate $\dot{a}$ is assumed to be constant; the damage of r_0 has undergone an evolution from zero to D_c. The stress history of the current crack tip is assumed to be $\sigma(Z)(Z = t - t_1)$.

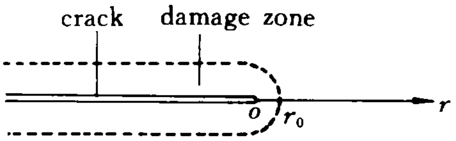

Fig. 1 Damage distribution ahead of crack tip on crack propagation line

In this case, $\sigma_t > \sigma_n$ (net section stress), the creep damage would be confined to the vicinity of the crack tip. By using eq. (14) the stress history of r_0 may be written as:

$$\sigma_{ij}(Z) = \{c(t_1 + Z) / [BI(r_0 - Z\dot{a})]\}^{1/(n+1)} \times \sigma_{ij}(\theta, n) \quad (28)$$

In the short-term creep case, $t_1 < t_m$, the damage equivalent stress at r_0 can be written as:

$$\sigma^*(Z) = [K_1^2/BI(n+1) Et_1(r_0 - \dot{a}Z)]^{1/(n+1)}H \quad (29)$$

and the creep damage evolution of r_0 is:

$$(1-D)^n dD = AH^m\exp[-Q/(RT)] \times [K_1^2/BI(n+1)Et_1 \times (r - \dot{a}z)]^{m(n+1)}dZ \quad (30)$$

By integrating this equation and using the conditions $D(0) = 0$ and $D_c = 1$, the expression for $\dot{a}$ is:

$$\dot{a} = (n+1)^2r^{1/(n+1)}AH^m\exp[-Q/(RT)] \times \{K_1^2/[BI(n+1)Et_1]\}^{m(n+1)} \quad (31)$$

The result shows that $\dot{a} \propto K^{2m/(n+1)}\exp[-Q/(RT)]$, which is in agreement with the empirical relationship of Kawasaki and Horiguchi[10] and Nazmy and Wuthrich[11]. According to Dawasaki, for austenitic stainless steel at temperatures of 600, 650, and 700 ℃, the empirical equation is:

$$\dot{a} = A_1K^\delta\exp[-Q/(RT)]$$

In the constant temperature case, from

eq. (31) we have $\dot{a} \propto K^{2m/(n+1)}$, which is in agreement with the results reported earlier[12, 13]. It is clear that, for material with high RCD, the stress intensity factor is a characterizing parameter for CCG rate under short-term-creep($t_1 < t_m$) and a low value of applied stress condition, CCG rate increases with increase of temperature T at constant K_I.

In the long-term creep case, $t_1 > t_m$, the damage equivalent stress at r_0 may be written as

$$\sigma^*(Z) = \{C^*/[BT(r_0 - \dot{a}Z)]\}^{1/(n+1)}H \qquad (32)$$

By substituting eq. (32) into eq. (4), we have:

$$(1-D)^n dD = AH^m \exp[-Q/(RT)] \times \{C^*/[BT(r_0 - \dot{a}Z)]\}^{m/(n+1)} dZ \qquad (33)$$

Similarly, the crack growth rate $\dot{a}$ may be obtained by integrating eq. (33):

$$\dot{a} = (n+1)^2 r^{1/(n+1)} AH^m \times \exp[-Q/(RT)] \times [C^*/(BT)]^{m/(n+1)} \qquad (34)$$

If temperture T is a constant, $\dot{a} \propto C^{*\,m/(n+1)}$, which is in agreement with Nikbin[14].

For materials with high RCD, under long-term creep conditions, C^* is a characterizing parameter for CCG rate.

5 CONCLUSIONS

(1) The resistance to creep damage is an important parameter for describing the creep fracture quality of material. RCD may be expressed in the following form:

$$\sigma_t^m = L^{-1} t_1 \exp[Q/(RT)]$$

(2) For material with high RCD under a low value of applied stress, a threshold value of K exists at a given time, below which no crack growth takes place. K_{It} increases with decreasing temperature:

$$K_{It} \propto \sigma_t^{-(n+1)/m} r_d \exp[Q/(RT)]$$

(3) The expressions of initiation time have been obtained under short-term and long-term creep times.

(4) The influence of temperature on CCG rate has been investigated under high RCD and a low value of applied stress. The result shows that CCG rate increases with increasing temperature.

(5) The fracture mechanics parameters applicable to its correlation with CCG rate depend on both the RCD of the materials and the stress history of the current crack tip. For materials with high RCD, the stress intensity factor and the C^* integral are the appropriate characterizing parameters under short-term creep and long-term creep conditions, respectively.

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