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MACROSCOPIC CREEP CRACK GROWTH

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1. INTRODUCTION

Large engineering components often contain flaws or develop macroscopic cracks during service. These defects may start to grow at high temperature and thus cause a catastrophic failure even though the nominal strain in the component may be small. This type of creep crack growth has to be distinguished from creep fracture which occurs as the final stage of tertiary creep. In the latter case cavities and/or microcracks are formed more or less homogeneously throughout the whole body and final rupture takes place by linking up of these defects. On the other hand the creep crack growth considered in this paper is due to creep deformation concentrated only near the tip of a macroscopic crack and fracture occurs by creep assisted propagation of this crack. Extensive experimental studies of both these phenomena have been carried out in the last years. However, whilst the mechanisms of creep fracture have been extensively studied theoretically (e.g., [1] - [6]), only some empirical correlations describing macroscopic creep crack growth have been suggested [7 - 15]. In the present paper these correlations are first discussed and their applicability assessed. A recently developed fracture mechanics theory of creep crack growth based on the time dependent Dugdale-Bilby-Cottrell-Swinden type model is then reviewed and suggestions for further experimental studies of creep crack growth are made.

2. EMPIRICAL LAWS DESCRIBING CREEP CRACK GROWTH

The experimental studies show that the process of creep crack growth usually consists of an incubation period and growth period [8, 9, 16, 17]. Depending on the material and testing conditions the incubation period during which creep damage develops ahead of the crack, may represent a substantial part of the specimen life. Nevertheless, the incubation stage has been studied so far very little and most of the authors concentrated on the growth period with the aim to establish a correlation between the rate of crack growth, da/dt, and various macroscopic parameters. The following three correlations have been most commonly pursued:

(i) The rate of crack growth is assumed to be determined at a given temperature by the stress intensity factor, K, [7 - 10] according to the equation

$$\frac{da}{dt} = A\ K^{m}\ , \qquad (1)$$

where A is a constant and m an integer. However, this type of correlation is usually obtained only for rather limited ranges of applied stresses and K values and extrapolation to, for example, a wider range of K values are

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doubtful. There is, of course, no fundamental reason for equation (1).

(ii) The rate of crack growth has been correlated in [11], [12] and [13] with a path independent integral C* obtained from the J integral (which is commonly used in the deformation fracture mechanics) by replacing strains and displacements by their time derivatives. This integral is not the time derivative of J and no physical meaning can be assigned to this quantity. Hence, though C* may perhaps be a useful engineering correlating parameter, it cannot provide any deeper insight into the mechanics of creep fracture.

(iii) Net section stress has been proposed in [14] and [15] to be a suitable correlating parameter. However, if this is so it means that the principle effect of the crack is to modify the stress field in the whole ligament, e.g., by decreasing its cross-section, but not to concentrate the creep strain near the crack tip. This situation does not correspond to the true creep crack growth and it is better described as creep rupture process which occurs under rather complicated stress conditions. The apparent crack growth then corresponds to the necking of the ligament.

In the following we shall consider only the case when crack growth occurs due to localised creep deformation. Hence, the rate of crack growth will principally be determined by the stress intensity factor K, although not necessarily given by equation (1). Since the damage is localised, a fracture mechanics type approach may be developed.

3. FRACTURE MECHANICS TYPE THEORY OF CREEP CRACK GROWTH

The principle problems are (a) to set up macroscopic criteria governing the crack growth and (b) to take into account time dependent stress relaxation ahead of the crack. In the deformation fracture mechanics with a well defined yield stress a very successful model of plastic zone was developed by Dugdale [18] and Bilby, Cottrell and Swinden [19], hereafter called the DBCS model. Recently, a time dependent analogy of this model has been developed by Vitek [20, 21]. The plastic zone has been represented by an array of edge dislocations coplanar with the crack the Burgers vectors of which are perpendicular to the plane of the crack, similarly as in [19]. However, unlike in the DBCS model no fixed friction stress acting upon the dislocations was assumed but the strain rate, $\dot{\varepsilon}$, ahead of the crack was determined by the equation

$$\dot{\varepsilon} = A(\tau/G)^n , \tag{2}$$

where τ is the local tensile stress, A is a constant, n is an integer and G is the shear modulus. It was assumed that equation (2) is the same as the creep law describing the creep behaviour of an uncracked specimen subject to the same tensile stress τ. The time dependent development of the dislocation density, B(x,t), describing the plastic zone, takes place according to the equation

$$\frac{\partial B(x,t)}{\partial t} = - h \frac{\partial \dot{\varepsilon}(x,t)}{\partial x} \tag{3}$$

where t is the time and h a gauge length independent of the applied stress, time and crack length, which has to be introduced if the concept of strain is to be used in the framework of a one-dimensional model.

The numerical solutions of equation (3) for a given applied tensile stress, σ, and different values of n have been presented in [20] and [21]. With increasing time a region of uniform stress develops ahead of the crack. This region extends with time and the stress decreases. Thus at any time the stress distribution is similar to that assumed in the DBCS model. Furthermore, the dislocation distributions found by solving equation (3) are very similar to those given in (19) if the uniform stress ahead of the crack is taken as an apparent friction stress. Owing to this result all the analytical formulae of the DBCS model can be readily used replacing the friction stress, σ_1, by the apparent friction stress σ_1^F which is a function of both time, t, and applied tensile stress σ. In particular the crack opening displacement can be written as

$$\phi = \frac{4(1-\nu)}{\pi} a \left(\frac{\sigma_1^F}{G}\right) \ln \sec \frac{1}{2} \pi \frac{\sigma}{\sigma_1^F} , \tag{4}$$

where ν is Poisson's ratio. The dependence

$$\sigma_1^F = \sigma_1^F(t,\sigma) , \tag{5}$$

is, of course, obtained as a result of the numerical calculation and approximate analytical expressions for equation (5) have been given in [20] and [21]. However, the time does not figure out in equation (5) explicitly but always as the dimensionless quantity

$$T = A \frac{h}{a} 10^{4-2n} t . \tag{6}$$

It has been suggested by Wells [22] and Cottrell [23] that attainment of a critical crack opening displacement (COD), ϕ_c, is a condition for the onset of crack propagation. It has been shown in [21] that this condition is also applicable to the initiation of creep crack growth. The incubation time is then the time needed for accumulating ϕ_c.

If the critical COD, ϕ_c, is known the incubation time, t_i, can be calculated by inverting equations (5) and (4). The result of this calculation is, however, the dimensionless time T_i, related to t_i by equation (6), and to calculate t_i the gauge length h has to be chosen. Hence, the present theory possesses two semi-empirical parameters, the critical COD, ϕ_c, and the gauge length, h, the determination of which will be discussed later.

In order to describe the crack propagation we assume that both the COD and h are constant during this process. The crack propagation can then be regarded as a sequence of repeated initiations and the following three possibilities have been studied in detail [24, 25]:

(i) The crack always travels a fixed length, d, when the critical COD is reached, eliminating the whole of plastic zone during this extension. This may correspond to cavity growth on an inclusion or to formation of a microcrack on the most favourably oriented grain boundary and subsequent linking of these defects with the main crack. d can then be identified with the average separation of inclusions or with average grain size.

(ii) The crack always extends by a distance equal to the length of the plastic zone eliminating the plastic zone during this extension. This may correspond to the case when cavities and/or microcracks form throughout the whole of the plastic zone.

(iii) The crack extends by the amount equal to the plastic opening at the crack tip, i.e., Φ_c, and only this part of the plastic zone which was contained inside this length is eliminated. This corresponds to continuous crack growth by plastic tearing.

In all three cases the rate of crack growth was found [24, 25] to be strongly dependent on K but for a given K a substantially weaker, but not negligible, dependence on σ always exists. The rate of crack growth can conveniently be expressed as

$$\frac{da}{dt} = B\ K^{\alpha}\ , \tag{7}$$

where both B and α are functions of the applied stress σ and their numerical values have been given in [24]. Furthermore α is different in three different ranges of values K and generally decreases with increasing K. Hence, although equation (7) is similar to equation (1) it is not the same because of the above mentioned functional dependences of B and α.

In order to apply the present theory we have to determine the two semi-empirical parameters Φ_c and h. This can be done on the basis of the following measurements:

(a) The incubation time, t_i, measured as a function of the initial crack length a_o and applied stress σ.
(b) The rate of crack growth as a function of the current crack length, a, and of σ.

If the mode of the crack propagation has been identified a combination of measurements (a) and (b) for a limited range of a_o and σ provides sufficient data for determination of Φ_c and h [24] when using equations (4), (5) and (7).

4. CONCLUSIONS

In the case of true creep crack growth the rate of crack propagation is principally governed by the stress intensity factor, i.e., the crack growth is due to the accumulation of the creep damage near the crack tip. However, the rate of the crack growth is not generally described by equation (1). On the other hand when the rate of crack growth can be correlated with the net section stress the main effect of the crack is to modify the stress field and thus the creep strain rate, in the whole specimen. The latter case should then be treated using a creep rupture theory.

The fracture mechanics type theory of the creep crack growth the principle results of which have been reviewed in this paper, enables both the calculation of the incubation period and of the rate of crack growth if the creep behaviour of the material described by equation (2) is known.

However, the theory contains two semi-empirical parameters - the critical COD, Φ_c, and the gauge length, h. These have to be determined experimentally as described above. Once these two parameters have been determined from measurements for a limited range of applied stress, σ, and crack length, a, the theory may be used for extrapolation to different ranges of σ and a. In particular, the measurements are usually done for relatively high stress levels so that they can be carried out in a reasonably short time. However, the application is often needed at much lower loads and the theory may be used to carry out this extrapolation provided the same mechanism of creep crack growth operates at both high and low loads.

However, most experimental data on creep crack growth cannot be analysed using the present theory. For example when K appears to control creep crack growth the measurements are usually presented as plots of da/dt vs. K but variation of this dependence with σ and the incubation period have usually not been studied. In order to use the present theory the following information is needed and has to be obtained from experiments:

(i) Creep behaviour of uncracked specimens giving the relation (2).

(ii) Mode of creep crack growth as defined in paragraph 3.

(iii) The incubation time as a function of the initial crack length a_o and the applied stress σ.

(iv) Rate of creep crack growth as a function of the current crack length a and of the applied stress σ but not only of the stress intensity factor K.

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