PREDICTION OF TRANSIENT EFFECTS DURING EARLY STAGES OF CREEP CRACK GROWTH

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More scatter is usually observed in experimental creep crack growth data in the early stages of a test than later on. This scatter can be attributed to a combination of several factors. In this paper the influences of stress redistribution from the initial elastic state to the steady state creep condition and build-up of damage at a crack tip by creep are each considered. A new definition is proposed for the time needed for the stress distribution to relax from its initial elastic state to some fraction of its steady state creep condition. Also a creep crack growth model, which is based on ductility exhaustion, is examined to account for build-up of damage at a crack tip during the early stages of cracking. It is shown that this build-up of damage is the most likely cause of the increased scatter observed initially in creep crack growth studies on low alloy steels.

INTRODUCTION

Typically more scatter is observed in creep crack growth data during the early stages of an experiment than later on. This often results in a 'tail' when crack growth rate $\dot{a}$ is plotted against the creep fracture mechanics parameter C^* as shown in Figure 1 for two low alloy steels (1, 2). Previously (3) this behaviour has been attributed to stress redistribution from the initial elastic state, primary creep and the development of damage at a crack tip.

In this paper, the relative effects of stress redistribution and build-up of damage at a crack tip are examined. Bounds on the transition time for stress redistribution are calculated. An expression for the dependence of crack growth rate on the build-up of damage at a crack tip is presented. Finally comparisons are made with the experimental data shown in Figure 1.

STRESS REDISTRIBUTION TIME

The elastic stress distribution ahead of a crack tip is described in terms of the stress intensity factor K by;

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$$\sigma = K/\sqrt{2\pi r} \quad (1)$$

where σ is the stress at distance r ahead of the crack tip. For a material which deforms in secondary creep according to the expression;

$$\dot{\varepsilon}^c = B\sigma^n \quad (2)$$

where $\dot{\varepsilon}^c$ is secondary creep rate, and B and n are material constants, the steady state creep stress distribution is;

$$\sigma = \left(C^*/I_n Br\right)^{1/(n+1)} \quad (3)$$

In this expression, I_n is a non-dimensional function of n and state of stress.

On initial loading, in the absence of plasticity, the stress distribution will be elastic and will gradually redistribute to its steady state creep condition with time t as illustrated in Figure 2. At a distance r^* from the crack tip, a stress σ^* can be defined where the stress remains approximately constant and the elastic and creep stresses have the same magnitude.

The value of r^* can be calculated from equations (1) and (3) as;

$$r^* = \left[K^2/(2\pi)\right]^{(n+1)/(n-1)}\left[I_n B/C^*\right]^{2/(n-1)} \quad (4)$$

Equation (4) identifies the region $r < r^*$ in which stress relaxation takes place at the crack tip because of creep. Substituting typical values of crack length a = 25 mm and W = 50 mm for tests on standard compact tension specimens gives $r^* \approx 3$ mm. Since the size of the creep process zone r_c shown in Figure 3 in which creep damage accumulates is nominally of the order of a material's grain size, this implies that creep damage develops well within the region where stress relaxation takes place during the redistribution period.

An estimation of the time t_w of this redistribution period can be determined as the time taken for the creep strain ε^c to equal the elastic strain ε^e at $r = r^*$ such that;

$$\varepsilon^e_{r=r^*} = \varepsilon^c_{r=r^*} \quad (5)$$

For plane stress conditions, solution of equations (1) to (5) gives the transition time t_w as;

$$t_w = \frac{I_n}{2\pi}\frac{K^2}{EC^*} \quad (6)$$

This expression can be compared with the characteristic time t_1 proposed by Riedel and Rice (4) for the time to achieve steady state creep conditions;

$$t_1 = \frac{K^2}{(n+1)EC^*} \quad (7)$$

The relationship between t_w and t_1 is obtained from equations (6) and (7) as;

$$t_w/t_1 = (n+1)I_n/2\pi \quad (8)$$

The value of I_n is relatively insensitive to n and is around 3 for plane stress and n is in the range of 3 and 10. Therefore, in general, t_w is between about 2 and 5 times larger than t_1. It therefore provides a more conservative estimate of the time to reach a steady state condition.

STRESS REDISTRIBUTION MODEL

The redistribution behaviour is analysed in more detail in this section. The stress at $r = r^*$ is constant during the redistribution so that the strain rate $\dot{\varepsilon}^*$ at distance r^* is also constant because there is no elastic strain change. If the strain rate at a distance r is α times larger than $\dot{\varepsilon}^*$, the following relation can be obtained.

$$\alpha\dot{\varepsilon}^* = \dot{\varepsilon}^e + \dot{\varepsilon}^c \quad \text{......} \quad (9)$$

where the $\dot{\varepsilon}^e$ and $\dot{\varepsilon}^c$ are respectively the elastic strain rate and creep strain rate at distance r. When equation (2) is employed, equation (9) becomes;

$$\alpha B\sigma^{*n} = \frac{1}{E}\frac{d\sigma}{dt} + B\sigma^n \quad \text{......} \quad (10)$$

The factor α will in general be a function of time as well as distance r. When elastic conditions apply, its elastic value α_e from equation (1) is given by;

$$\alpha_e = \dot{\varepsilon}/\dot{\varepsilon}^* = \left(r^*/r\right)^{1/2} \qquad \text{for } t = 0 \qquad (11)$$

and when creep conditions predominate, its creep value α_c from equations (2) and (3) becomes;

$$\alpha_c = \dot{\varepsilon}/\dot{\varepsilon}^* = \left(r^*/r\right)^{\frac{n}{n+1}} \qquad \text{for } t \to \infty \quad \text{......} \quad (12)$$

Equation (10) has been solved numerically using these values. The results are shown in Figure 4 for different n values for $r/r^* = 0.01$. In this figure σ_e is the initial elastic stress and σ_c the steady state creep stress. It is evident that little difference is obtained between using α_e or α_c except near the steady state creep condition. At long times, creep strain is dominant so that equation (12) is expected to give a closer approximation to the actual α. Taking $\alpha = \alpha_c$ also predicts a longer time for stress redistribution and will therefore give a more conservative estimation. The rate of stress redistribution is dependent on the creep exponent n and is faster with increase in n. However, even for the slowest case ($n = 3$), the stress redistribution at $r/r^* = 0.01$ is within 10% of its steady state value in less than 10% of the transition time t_w.

Figure 5 shows the stress redistribution behaviour for several values of r/r^* for $n = 5$. It is clear that redistribution occurs more quickly as the crack tip is approached. For a typical creep process zone size ($r_c/r^* \approx 0.1$), the stress redistribution is within 10% of being complete in less than 10% of t_w.

Table 1 lists the material creep properties and the transition times t_w for the 1CrMoV and 2¼CrMo steels shown in Figure 1. In most cases t_w is less than 10 hours and in view of the above discussion it is expected that stress redistribution will be almost complete at $t_w/10$. As the region of extensive scatter in Figure 1 extended over a much longer period than this, its cause cannot be attributed predominantly to stress redistribution.

TRANSIENT CRACK GROWTH

A prediction of steady state creep crack growth has been proposed by Nikbin, Smith and Webster (5) in terms of ductility exhaustion in the process zone at a crack tip. It gives the steady state creep crack growth rate $\dot{a}_{ss}$ as;

$$\dot{a}_{ss} = \frac{(n+1)B}{\varepsilon_f^*}\left(\frac{C^*}{I_n B}\right)^{\frac{n}{n+1}} r_c^{1/(n+1)} \quad \text{...} (13)$$

where ε^*_f is creep ductility appropriate to the state of stress at the crack tip. The model has also been extended to the prediction of the transient period of crack growth at the beginning of a test (6, 3). In the transient model, creep damage ahead of a stationary crack is accumulated from the damage free state, and the effect of stress redistribution is ignored. This gives the transient crack growth rate as;

$$\dot{a} = \frac{1}{\varepsilon_f^* - \varepsilon_u^*} B\left(\frac{C^*}{I_n B}\right)^{\frac{n}{n+1}} (dr)^{1/(n+1)} \quad \text{...} (14)$$

where ε^*_u is the ductility already used up in a ligament dr ahead of the crack prior to arrival of the crack at the ligament as shown in Figure 3.

The predictions of equations (13) and (14) for the 1CrMoV and 2 1/4CrMo steel data presented in Figure 1 are shown in Figure 6. For both steels, the transient behaviour of each test is well characterised by the transient crack growth model. Therefore, it is argued that this type of scatter in the early stages of a creep crack growth test is mainly caused by the build-up of damage ahead of a crack tip well after the generation of the steady state creep stress distribution.

CONCLUSIONS

Transient effects during the early stages of crack propagation have been examined and attributed to stress redistribution and the build-up of damage at a crack tip. A transition time t_w has been defined for characterising the time for stress redistribution, and it has been shown for low alloy steels that stress redistribution in these materials is too rapid to be the main cause of the transient crack growth behaviour which is observed. A model for the build-up of damage at a crack tip during the early stages of cracking has been applied to two low alloy steels and been found to give a satisfactory prediction of the transient crack growth behaviour observed.

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TABLE 1- Creep properties and transition times

Material	B	n	ε_f	Test No.	t_w (hr)	Duration t_r (hr)	t_w/t_r
1CrMoV steel	1.30×10^{-20}	6.5	0.15	BD3	58.	752	0.077
				BE31	2.94	55	0.053
				BE32	6.17	167	0.037
$2^1/_4$CrMo steel	1.19×10^{-19}	7.4	0.45	EP3	0.165	31	0.0053
				EP5	0.075	241	0.0003

Note: Creep constant B is defined to give creep strain rate in hr $^{-1}$ with stress in MPa.

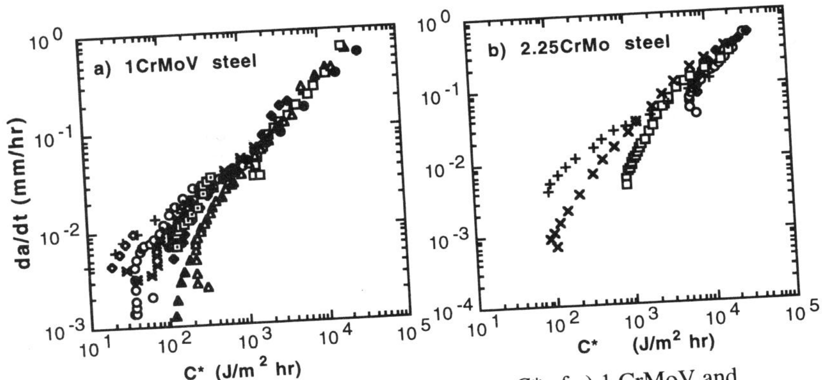

Figure 1. Creep crack growth rate versus C^* of a) 1 CrMoV and b) $2^1/_4$ CrMo steel at 550°C

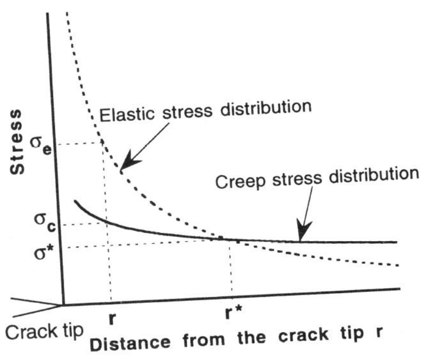

Figure 2. Elastic and steady state creep stress distributions ahead of a crack tip

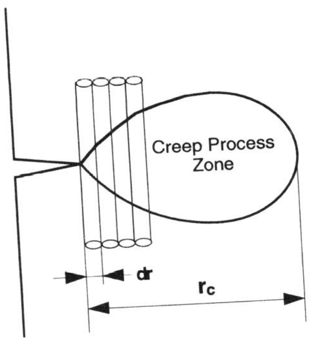

Figure 3. Creep cracking process zone

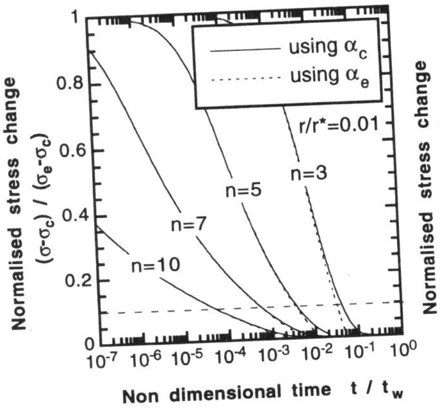

Figure 4. Effect of n on the stress redistribution time

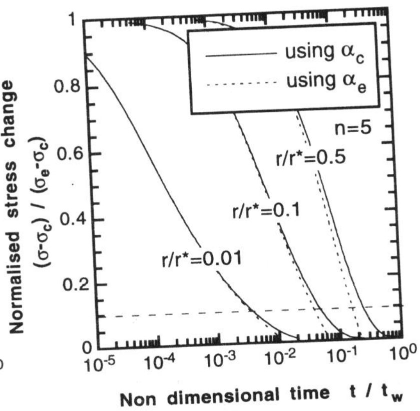

Figure 5. Stress redistribution at different distances r

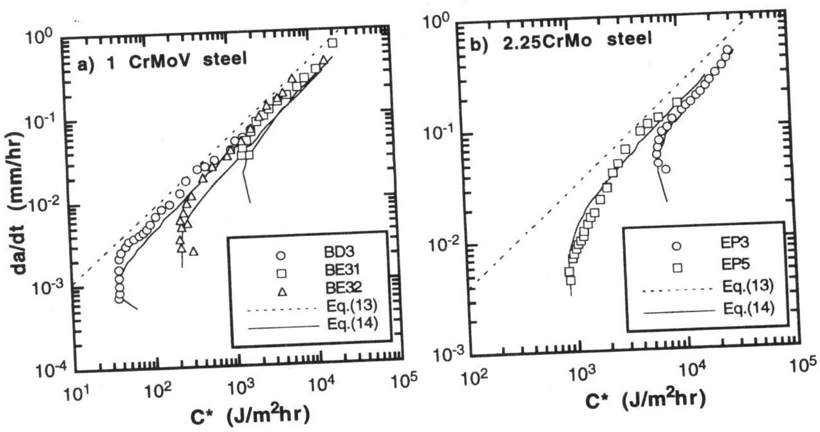

Figure 6. Comparison between predictions of transient crack growth and experiments for a) 1 CrMoV and b) 2 1/4CrMo steels