A 'SIGMA D' APPROACH FOR THE ASSESSMENT OF CREEP CRACK INITIATION IN 316L STAINLESS STEEL CT TEST SPECIMENS

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The 'sigma d' method, based on a design code assessment procedure using the stress at a characteristic distance 'd' from a crack tip, has been used to analyse the initiation of creep crack growth in 316L stainless steel CT test specimens. Test results, taken from the literature, are for both constant and variable applied load and temperature. Comparison of 'sigma d' results with experiment, and assessments based on an R6 type of approach, show the method to be unduly conservative. This conservatism is reduced by a revised method for the calculation of the the characteristic distance 'd', based on an estimate of the position of maximum hydrostatic stress.

INTRODUCTION

Methods for the assessment of fatigue damage in zones containing sharp notches, as described by Langer (1), are based on the understanding that failure, as defined by the initiation of crack growth from the notch, does not occur when the peak stress at the notch tip reaches the endurance limit but rather when the stress at some finite distance 'd' below the surface reaches the endurance limit. The rationale for this hypothesis is that, due to the granular structure of the material, a finite volume of the material must be at a stress equal to the endurance limit in order to cause failure. This approach has been formalised in the French design code RCC-MR, (2), where the stress at a distance 'd' below the surface is designated σ_d (sigma d). The 'sigma d' method has also been extended, by Moulin et al (3), for the assessment of the initiation of growth from pre-existing defects, under creep loading and combined creep-fatigue loading. The specific advantage of the 'sigma d' method, over other methods for the assessment of creep crack initiation, is that materials data required for assessments are available from smooth undefected test specimens.

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The assessment of creep crack growth initiation under conditions of constant applied load and temperature, and variable applied load and temperature has also been described previously, by Hooton et al (4) and Ainsworth et al (5), using an R6 type approach (6). Limited validation of the R6 type approach has also been provided (4,5) by the analysis of Ecole des Mines Paris (EMP) test results from 316 stainless steel CT specimens (7,8).

The present study is focused on the assessment, by the σ_d method, of EMP tests on 316L type stainless steel CT specimens, Fig. 1, tested at 600 and 650°C. In all tests initiation of crack growth was defined by the time corresponding to 0.05 mm crack growth. The only detail of the tests given in this paper is that necessary for the application of the σ_d method, Tables 1 and 2. Further detail is given in (4,5,7,and 8). Results allow comparisons to be made with those of references (4 and 5), and recommendations to be made for amendment of the σ_d method.

INITIATION OF CREEP CRACK GROWTH

Constant Load Creep.

Under creep loading conditions, as for fatigue (3), the elastic stress maintained at at a distance ‘d’ from from the surface of the initial crack, σ_{ed}, is estimated using Creager's approximation, i.e.

$$\sigma_{ed} = \frac{K}{\sqrt{2\pi}} f(\rho/d), \text{ where } f(\rho/d) = \sqrt{\frac{1}{1+\frac{1}{2}(\rho/d)}}\left[1+\frac{\rho/d}{2\left(1+\frac{1}{2}(\rho/d)\right)}\right] \quad \text{..........} \quad (1)$$

K is the linear elastic stress intensity factor, assuming the notch to be a sharp crack, ρ is notch root radius which is equated to zero for crack like defects, and the distance ‘d’ is taken as 50μm, (3). The stress value, σ_{ed} , is then plastically corrected by the application of Neuber’s Rule, using the monotonic stress strain curve, Fig.2, to give the crack opening stress, σ_d.

The reference stress, used in Fig.2, is an estimate of the primary stress in the remaining ligament and is given by,

$$\sigma_{ref} = P\sigma_y / P_L(\sigma_y, a) \quad \text{.................................} (2)$$

where P is the applied load, and P_L is the corresponding value of load at plastic collapse for the body with a crack size a and yield stress σ_y. Monotonic tensile properties have been taken from reference (8), and results for σ_d are compared with creep rupture curves, taken from reference (3), in Figure 3.

Results are also presented in Table 1 in terms of the creep usage factor W, given by $W=t_h/T_a$, where t_h is the hold time and T_a is the allowable time at stress σ_d determined from the stress to rupture curve.

TABLE 1 - EMP Constant Load Creep Test Results at 600°C.

Spec. No.	CT 4	CT 7	CT 10	CT 20	CT 23	CT 24	CT 25
K MPa√m	31.74	26.55	37.60	32.10	18.82	32.81	34.12
σ_{ref} MPa	173	197	196	233	139	233	256
t_i (hrs)	220	212	207	74	296	55	35
$W=t_i / T_a$	17.00	12.91	50.49	19.58	1.14	15.80	17.95

The results, Table 1, show the initiation of creep crack growth is predicted for all cases,(ie W>1). The margins are, however, unduly conservative (>12, apart from CT23).

Variable Load Creep.

Results of EMP two-step loading tests, detailed in reference (7), are given in Table 2. Creep crack growth initiation, in these tests, is defined as 0.05mm total crack growth at the end of step 2.

Results of a σ_d analysis are also given in Table 2, in terms of $W=\Sigma t/T_a$. Again creep damage fractions are high in all cases (in the range 20-50), indicating the initiation of creep crack growth by wide margins.

Comparison with R6 Assessments.

Previous investigations, (4) and (5), have demonstrated that creep crack growth initiation under constant load creep and non-constant creep loadings of variable stress and/or temperature can be described using an R6 type approach. For these assessments, the failure assessment diagram (FAD) and 'yield' stress are determined using isochronous stress-strain data corresponding to the assessment time. The conventional fracture toughness used in low temperature assessments is replaced by a time-dependent toughness. For two-step loading, assessments are

TABLE 2 - EMP Two-step Loading Tests

	Step 1				Step 2				
Spec. Number	Temp (T°C)	σ_{ref} (MPa)	K MPa√m	t (hr)	Temp (T°C)	σ_{ref} (MPa)	K MPa√m	t (hr)	W
CT 42	600	162	20.95	170	650	162	20.95	190	31.2
CT 45	600	153	20.10	231	650	153	20.10	177	21.4
CT 47	650	183	22.40	83	600	183	22.40	716	38.9
CT 46	600	150	19.77	259	600	265	34.98	77	47.4
CT 48	600	271	35.55	21	600	149	19.53	6291	46.4

based on an average reference stress, $\overline{\sigma}_{ref}$, defined such that the accumulated creep strain at this reference stress for the total time is equal to the accumulated creep strain at the reference stress history.

Results of these assessments are compared with the R6 option 1 FAD in Figure 4. (Note: for the times of the EMP tests the FAD is little dependent on time). Clearly R6 assessments indicates far less conservatism than the above σ_d method.

Proposed Amendments to the σ_d method.

The present σ_d method assumes the crack tip stays sharp during creep loading. Whereas, for creep ductile materials, crack tip blunting will occur. A first approximation to include this effect, in the calculation of σ_{ed} , would be to include an estimate of notch tip blunting radius, ρ, in equation (1). However, in the range of interest, the value of the function f(ρ/d) appoximates to unity and depends only weakly on the value of ρ/d. The value of σ_{ed}, therefore, for a given geometry and loading is dependent only on the value of 'd'.

In consideration that the relevant dimension relating to creep damage may be dependent on the stress value, rather than grain size as for fatigue, it is proposed that the distance 'd' should be taken as that corresponding to the position of maximum hydrostatic stress. Detailed finite element calculations of time-independent crack tip stresses, reported by O'Dowd and Shih (9), indicate that the blunted crack opening, given roughly by J/σ_0, sets the size scale over which large stress triaxiality and large strain develop, and consequently the size scale on which microscopic ductile fracture processes may be presumed to act. For cases of widespread creep, as in EMP tests, a time-dependent value of J is given by reference (4) as,

$$J = R'\left(\varepsilon^{c}_{ref}\sigma_{ref}\right) \qquad (3)$$

where $R' = \left(K / \sigma_{ref}\right)^2$ and ε^{c}_{ref} is the creep strain corresponding to the reference stress. Hence, $d = J/\sigma_0$, where σ_0 is a normalising stress which may be taken as the $\sigma_{0.2}$ proof stress, taken from the isochronous stress strain curve.

Results for σ_d determined for the tests of Tables 1 and 2, using 'd' values calculated in the above manner, are shown in Figure 3. Results for two-step loading are based on an equivalent K defined as $\overline{K} = K\overline{\sigma}_{ref} / \sigma_{ref}$. Clearly results based on the revised definition of characteristic distance 'd' show far less conservatism than those based on a constant d = 50μm.

CONCLUSIONS

The assessment of creep crack growth initiation in 316L stainless steel CT test specimens has shown the 'sigma d' method, based on a constant characteristic distance of 50μ, to be unduly conservative compared with both experiment and assessments using an R6 type of approach. This conservatism is reduced when the characteristic distance is based on an estimate of the position of the maximum hydrostatic stress in the region of the blunted crack tip, given by $d = J/\sigma_o$.

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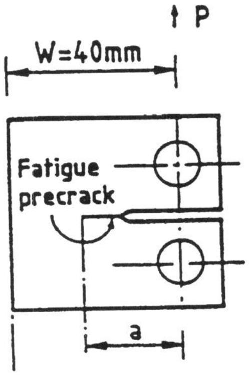

Figure 1 Geometry of EMP CT Specimens

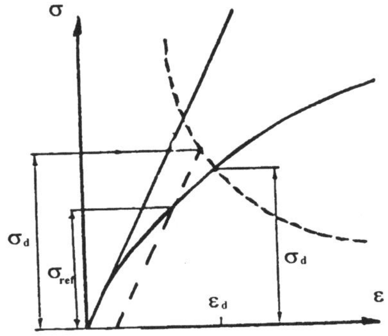

Figure 2 Application of Neuber's Rule

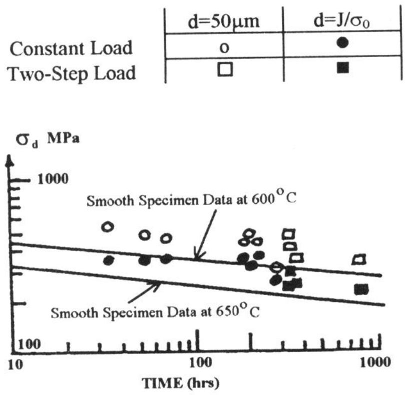

Figure 3 Comparison of σ_d results with time to rupture curves

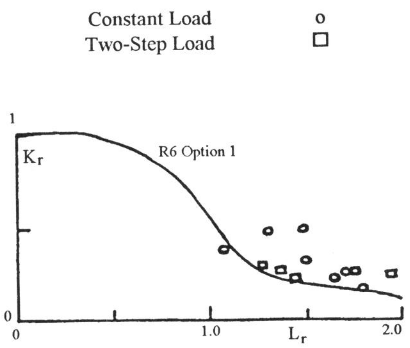

Figure 4 FAD + Assessment Points