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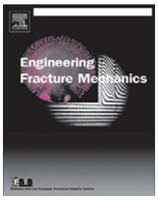

Simulations of creep crack growth in 316 stainless steel using a novel creep-damage model

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ABSTRACT

The paper provides an advanced creep model which gives reasonable descriptions of the effects of damage and stress state from micromechanics viewpoint. A modified creep ductility exhaustion approach is employed to calculate the creep damage. Based on the proposed creep-damage model, numerical analyses of creep crack growth are conducted with a failure simulation technique. The simulated results are compared favorably with available experimental data for compact tension and thumbnail crack specimens for 316 stainless steel tested at 600 °C. The comparisons show the excellent capability of the proposed model in predicting the crack growth rate and progressive crack profiles.

1. Introduction

To improve the efficiency in energy conversion systems such as power plants, aero engines, and chemical reactors, a growing trend towards the use of higher operating temperatures cannot be avoided. Thus, reliable analysis methods to assess the safety of creep-loaded structures containing cracks are required.

Increasing efforts are devoted into numerical simulations since they are cost-effective and time-saving tools. The existing numerical methods to simulate the creep crack growth may broadly be divided into two distinctly different categories. The first category is based on conventional fracture mechanics, in which the rate of crack growth is predicted by correlating it with some fracture mechanics parameters (stress intensity factor, K [1–3], J-integral, or C^*-integral [4,5]). With advances in the computational methods, other methods using damage mechanics, especially local continuum damage concept, are gaining much attention [6]. In this method when the creep damage variable, ω, attains to a critical value, material failure is considered to occur, and thus crack growth can be characterized by a completely damaged element zone ahead of the initial crack tip.

Numerical approaches based on damage mechanics reported in the literature can be further broken down into two groups according to the damage evolution model employed. One group is stress-based while the other is strain-based.

Kachanov [7] and Rabotnov [8] originally devised a stress-based damage model that has been widely used in the conventional creep damage analysis of uncracked structures. As regards its later application to the analysis of creep crack growth, however, it was found to yield solutions with significant mesh dependence. For the purpose of alleviating this problem,

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Nomenclature

a	crack length
A, A'	coefficient in the minimum and average creep strain rate expression, respectively
A_1, A_2, A_3	coefficients in the strain-hardening creep law
B, W	thickness and width of the compact tension specimen, respectively
C, ϕ	material constants in the Kachanov–Rabotnov damage evolution model
C^*	steady state creep fracture mechanics parameter
d	average diameter of cavitated grain boundary facets/micro-cracks
D, q	material constants in the Liu–Murakami damage evolution model
e	creep rate enhancement
E, v	elastic (Young's) modulus and Poisson's ratio, respectively
H, η	geometric function and geometric factor used to calculate C^*, respectively
m_1, m_2, m_3	strain exponents in the strain-hardening creep law
n, n'	stress exponent in the minimum and average creep strain rate expression, respectively
n_1, n_2, n_3	stress exponents in the strain-hardening creep law
N	number of cavitated grain boundary facets/micro-cracks per unit volume
p	rupture stress exponent in stress-based models
P	applied load
P_y/P_x	biaxial stress ratio
r	distance from the Gaussian point to the crack tip
t	time
$\dot{V}_c$	instantaneous load line displacement rate
α	material constant of multiaxiality in stress-based models
β	stress-independent function in the proposed model
$\dot{\varepsilon}^c_{ave}$	average creep strain rate
ω, $\dot{\varepsilon}^c$	creep strain and creep stain rate, respectively
$\varepsilon^c_{ij}(0)$	creep strain rate under the uniaxial condition without damage
$\varepsilon^c_{ij}, \dot{\varepsilon}^c_{ij}$	creep strain tensor and creep stain rate tensor, respectively
ε^e, ε^p, ε^{tol}	elastic, plastic strain components and total strain, respectively
ε_f, ε^*_f	uniaxial and multiaxial creep failure strain, respectively
$\dot{\varepsilon}^c,\ \sigma_0$	reference minimum creep rate and plastic deformation resistance, respectively
Φ	potential function of the stress
θ	angular parameter defining the crack front position
ρ	micro-crack damage parameter
$\sigma_{ij},\ s_{ij}$	stress tensor and deviatoric stress tensor, respectively
σ_{r}	rupture stress
σ_1, σ_{eq}, σ_{m}	maximum principle, equivalent (von Mises) and hydrostatic stress, respectively
ω	damage variable
BCC	body-centered cubic
CDM	continuum damage mechanics
CT	compact tension
FE	finite element

alternative creep constitutive and damage evolution equations were introduced by Liu and Murakami [9–11]. On the basis of Liu–Murakami model, Hyde et al. [12–15] presented a finite element (FE) method to simulate the creep crack growth in compact tension (CT) and thumbnail crack specimens. Good agreement was found between the predicted crack profiles and experimental ones. We should keep in mind that many material parameters in this damage model need to be calibrated very carefully since the FE predictions are greatly sensitive to them.

Alternatively, simple strain-based damage models have been employed in the FE analysis [16,17]. It is assumed that the damage parameter approaches unity when the local accumulated creep strain reaches a critical creep ductility value. Thus, fewer material parameters need to be determined. Ignoring the detailed description of each stage of creep, Yatomi et al. [18–21] and Oh et al. [22] used power-law constitutive equation with the average creep strain as the creep model. In a recent publication by Oh et al. [23], a more accurate strain-hardening creep law representing entire creep curves was employed in the modeling. FE results were consistent with the experimental data of creep crack growth in CT specimens. It is worth mentioning that the creep constitutive and the damage evolution models do not couple each other. Moreover, the multi-axial creep ductility model may be further improved, which will be discussed later.