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Load-independent creep constraint parameter and its application

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ABSTRACT

A load-independent creep constraint parameter R^* was proposed, and its load-independence was validated using finite element results in previous studies. A fixed distance $r = 0.2$ mm from a crack tip is chosen to define the R^*, and the R^* at steady-state creep can be used to evaluate constraint level with little conservatism for whole creep time. The R^* can be used for ranking constraint levels for different specimens or components, and for predicting constraint-dependent creep crack growth rates. The constraint-dependent creep crack growth rate equations of a Cr–Mo–V steel have been obtained, and it may be used in creep life assessments.

1. Introduction

Many experimental and theoretical evidences have shown that crack-tip constraint state has great influence on the fracture behavior of materials, and the loss of constraint causes the increases in fracture toughness [1]. The quantification of constraint has been widely investigated within the elastic–plastic fracture mechanics frame, and led to the development of two parameter fracture mechanics, such as J–T, J–Q and J–A_2 [2–5]. In these approaches, the first parameter J integral sets the size scale over which high stresses and strains develop, and the secondary parameters T [2], Q [3,4] and A_2 [5] were introduced to quantify the crack-tip constraint. The Hutchinson–Rice–Rosengren (HRR) singular stress field or the small scale yielding (SSY) solution with T-stress = 0 is generally used as the reference field to study the crack-tip constraint [1,3,4,6,7].

Under creep conditions, some experimental and theoretical evidences have shown that constraint can affect creep crack growth (CCG) rate [8–13]. In a recent study, it has been found that there is a significant constraint effect on CCG rate in low C^* region [14], and the CCG rates increase with increasing out-of-plane constraint (specimen thickness). To achieve accurate structural integrity assessment for high temperature components, it is necessary to find a simple and accurate constraint parameter to quantify the creep crack-tip constraint level in specimens or components, and then the correlation of constraint-dependent CCG rates of specimens or components can be obtained. However, the studies for two-parameter characterization of creep crack-tip fields are very limited. The creep crack-tip stress and strain rate fields are usually described by the C^*–Q two-parameter and the Q is used to quantify the constraint [15–17]. The effect of in-plane constraint on CCG using Q parameter was examined [16]. Combined the C^*–Q two-parameter concept with the NSW model, Nikbin [13] investigated the effect of constraint on the CCG rate. Based on the C^*–Q two-parameter concept and finite element (FE) analysis, Bettinson et al. [17] examined the effect of specimen type and load level on the Q from short to long term creep conditions for elastic-creep materials.

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Nomenclature

a	crack length
a_0	initial crack length
$\dot{a}$	creep crack growth rate
$\dot{a}_0$	creep crack growth rate from the standard specimen
A	coefficient in the power-law creep stain rate expression
B	specimen thickness
B_n	net specimen thickness
C^*	C^* integral analogous to the J integral
$C(t)$	$C(t)$ integral
D_0	material constants of CCG rate
E	Young's modulus
I_n	dimensionless constant related to n
J	J-integral
L	characteristic length, usually is set as 1 m
n	power-law creep stress exponent or power-law stain hardening exponent in Ramberg–Osgood relation
q	material constant of CCG rate
Q	constraint parameter under elastic–plastic condition
Q^*	load-independent constraint parameter under elastic–plastic condition
R	creep constraint parameter
R^*	load-independent creep constraint parameter
R^*_{avg}	average value of R^* along 3D crack front
R^*_{z0}	R^* value at specimen center
r	distance from a crack tip
r_c	creep damage zone
t	creep time
t_{red}	creep redistribution time
W	specimen width
z	distance from specimen center along crack front
α	strain hardening coefficient in Ramberg–Osgood relation
δ_{ij}	dimensionless function of n, θ
ε_0	yield strain
$\dot{\varepsilon}_0$	creep strain rate at yield stress
θ	polar coordinate at the crack tip
σ_0	yielding stress
σ_{22}	opening stress
σ_{ij}	deviatoric stress
$\tilde{\sigma}_{ij}$	dimensionless stress function of n, θ
υ	Poisson's ratio

Abbreviations

3D	three dimension
CCG	creep crack growth
CT	compact tension
CT2	compact tension specimen with 2 mm thickness
CT5	compact tension specimen with 5 mm thickness
CT10	compact tension specimen with 10 mm thickness
CT10-SG	compact tension specimen with 10 mm thickness and side grooves
CCT	center-cracked tension
FEM	finite element method
LSC	large-scale creep
LSY	large-scale yield
PE	plane strain
PS	plane stress
SENB	single-edge notched bend
SENT	single-edge notched tension
$\text{SENT}_{\Delta p}$	single-edge notched tension with 0.05 W loading point offset
SSC	small-scale creep
SSY	small-scale yield