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In-plane and out-of-plane unified constraint-dependent creep crack growth rate of 316H steel

H.S. Ma, G.Z. Wang *, S. Liu, S.T. Tu, F.Z. Xuan

Key Laboratory of Pressure Systems and Safety, Ministry of Education, East China University of Science and Technology, Shanghai 200237, China

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ABSTRACT

The unified characterization parameter A_c of in-plane and out-of-plane creep constraints along three-dimensional crack front in different specimen geometries has been analyzed. Based on the parameter A_c and the experimental creep crack growth rate data of different specimen geometries in the literature, the in-plane and out-of-plane unified constraint-dependent creep crack growth rate equation of 316H steel has been obtained. The predicted creep crack growth rate by using the equation for each specimen agrees well with the experimental data. Based on the two-parameter $C^* - A_c$ concept, the equation may be used in creep crack growth life assessments incorporating in-plane and out-of-plane constraint effects.

1. Introduction

Under creep conditions, a lot of experimental and theoretical evidences have shown that the crack-tip constraint can affect creep crack growth (CCG) rate [1–11]. The constraint includes in-plane and out-of-plane constraints. The in-plane constraint is directly affected by crack depth, length of the un-cracked ligament and loading configuration of specimens, while the out-of-plane constraint is affected by the specimen thickness. To accurately predict creep life and achieve structural integrity assessments for high temperature components, it is important to quantify the creep crack-tip constraint levels. The creep crack-tip stress and strain rate fields are often described by the $C^* - Q$ two-parameter under plane strain or plane stress conditions and the Q was used to quantify the constraint [12–14]. The effect of in-plane constraint on CCG has been examined by using Q parameter [13]. Combined the $C^* - Q$ two-parameter concept with the NSW model, Nikbin [3] investigated the effect of constraint on the CCG rate. Based on the $C^* - Q$ two-parameter concept and finite element analysis, Bettinson et al. [14] examined the effect of specimen type and load level on the Q from short to long term creep conditions for elastic-creep materials. Recently, Zhao et al. [8] quantified the constraint effect induced by specimen geometry on creep crack growth behavior in P92 steel by using the parameter Q. The two-parameter $C(t) - T_Z$ and the three-parameter $C(t) - T_Z - Q$ descriptions for crack-tip fields were proposed by Xiang et al. [15] and Xiang and Guo [16] for small and extensive creeping, respectively. The T_Z is an out-of-plane constraint factor, and the in-plane constraint is characterized by the parameter Q. In the definition of the Q parameter above, the HRR stress field is usually taken as the reference field.

In the previous work of authors [17], it has been suggested that the HRR stress field may not be suitable to be used as a reference field for defining the constraint parameter under creep condition due to larger crack-tip blunting and creep damage. Based on the reference field of the standard C(T) specimen in plane strain with deep crack ($a/W = 0.5$) and high

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* Corresponding author. Tel./fax: +86 21 64252681.
E-mail address: gzwang@ecust.edu.cn (G.Z. Wang).

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Nomenclature

a	crack length
$\dot{a}$	creep crack growth rate
$\dot{a}_0$	creep crack growth rate of the standard specimen
A	constant in Norton creep model
A_c	unified characterization parameter of in-plane and out-of-plane creep constraint
A_{CEEQ}	area surrounded by equivalent creep strain isoline
A_p	unified characterization parameter of in-plane and out-of-plane constraint
A_{ref}	area surrounded by equivalent plastic strain isoline at fracture measured in a standard test, or the area surrounded by equivalent creep strain isoline in a standard specimen
B	specimen thickness
B_N	net specimen thickness
C_1, C_2	constants in constraint-dependent CCG rate equations
$C(t)$	$C(t)$ integral
C^*	C^* integral analogous to the J integral
E	Young's modulus
h	stress triaxiality factor
L	half length of the test specimens.
n	stress exponent in Norton creep model
P	applied load
Q	constraint parameter
R	creep constraint parameter
R^*	load-independent creep constraint parameter
Tz	out-of-plane constraint parameter
t	creep time
t_{red}	creep redistribution time
v	Poisson's ratio
W	specimen width
z	distance along the crack front
$\dot{\varepsilon}_0$	creep strain rate at normalizing stress
$\dot{\varepsilon}_c$	creep strain rate
ε_c	equivalent creep strain
σ_0	normalizing stress

Abbreviations

2D	two-dimensional
3D	three-dimensional
CCG	creep crack growth
C(T)	compact tension
CS(T)	C-shaped cracked tension
CEEQ	equivalent creep strain in ABAQUS code
DE(T)	double-edge notched tension
FEM	finite element method
HRR	Hutchinson–Rice–Rosengren
M(T)	middle cracked tension
SE(B)	single edge-notched bend
SE(T)	single-edge notched tension
TF	stress triaxial factor

constraint, a constraint parameter R was proposed to characterize the creep crack-tip constraint, and the constraint effects induced by the crack depths [17,18], specimen thicknesses [19] and loading configurations [20] have been investigated in detail. For the convenience of application, a load-independent creep constraint parameter R^* has been defined by modifying the parameter R [21]. Based on the parameter R^*, the characterization and correlation of two-dimensional and three-dimensional creep constraint between axially cracked pipelines and test specimens were studied [22,23], and the constraint-dependent CCG rate equations were established for Cr–Mo–V steel [21].

The creep constraint parameters described above only can quantify the in-plane or out-of-plane constraint separately, and they may not characterize both of them and overall level of constraints. In actual high-temperature components, there exist both in-plane and out-of-plane constraints. In order to describe their interaction and the overall level of constraints, a unified creep constraint parameter which can characterize both in-plane and out-of-plane creep constraint together is