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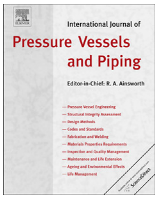

Unified correlation of in-plane and out-of-plane creep constraints with creep crack growth rate

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ABSTRACT

In this paper, the equivalent creep strain distributions ahead of crack tips in SEN(B), SEN(T) and M(T) specimens with different in-plane and out-of-plane constraints were calculated by extensive finite element analyses, and the creep crack growth (CCG) rates of these specimens were simulated over a wide range of C^* by using stress dependent creep ductility and strain rate model in a ductility exhaustion based damage model. The capability and applicability of the constraint parameter A_c based on crack-tip equivalent creep strain for characterizing both in-plane and out-of-plane creep crack-tip constraints and establishing a unified correlation with CCG rate of a steel were investigated. The results show that with increasing constraints, the CCG rate increases, and the effect of out-of-plane constraint on CCG rate is more obvious than that of in-plane constraint. The CCG rate of high constraint specimen geometry (such as SEN(B)) is more sensitive to the out-of-plane and in-plane constraints than that of low constraint specimen geometry (such as M(T)). The parameter A_c is a unified characterization parameter of in-plane and out-of-plane creep constraints for the different specimen geometries. Base on the parameter A_c, the unified correlation formulas of in-plane and out-of-plane constraints with CCG rate of the steel have been obtained, and they are independent on the choices of the standard specimen. The unified correlation formulas may be used in constraint-dependent CCG life assessments of high-temperature components (such as pressure vessels and pipes) with any in-plane and out-of-plane constraint levels.

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 constraint contains in-plane and out-of-plane constraints. The in-plane constraint is directly affected by specimen dimension in the direction of growing crack, that is, the length of the un-cracked ligament, while the out-of-plane constraint is affected by the specimen dimension parallel to crack front, that is, the specimen thickness. Because the constraint can dramatically alter the material's fracture toughness, it is important to develop a clear understanding of its effect on the fracture behavior of materials.

The characterization of constraint has been widely investigated within the elastic-plastic fracture mechanics frame, and leading to the development of two-parameter or three-parameter fracture mechanics, such as two-parameter concepts K-T [2], J-Q [3], J-A_2 [4], J-T_Z [5], J-h [6] and three-parameter concept J-T_z-Q [7] etc. Most of these parameters are only used to quantify the in-plane or out-of-plane constraint separately, but not the interaction between them and the overall level of constraints. However, in the actual engineering structures, both in-plane and out-of-plane constraint exist simultaneously. In order to describe their interaction and the overall level of constraints, a unified constraint parameter which can characterize both constraints together is required [8,9]. Mostafavi et al. [9,10] have suggested a unified constraint parameter φ which was defined as the size of plastic region at the onset of fracture normalized by the plastic region size of a standard test:

$$\phi = \frac{A_s}{A_{ssy}} \tag{1}$$

where A_s is the plastic region area at fracture and A_{ssy} is the reference plastic region area at fracture for a standard specimen in plane strain condition. They argued that there is no evident difference on the plastic zone size at fracture between in-plane and out-of-plane

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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_1, A_2	constants in 2RN creep model, and A_2 also is a constraint parameter
A_s	area of the plastic region at fracture
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_{PEEQ}	area surrounded by equivalent plastic strain isoline
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
A_{ssy}	area of reference plastic region at fracture measured in a standard test
B	specimen thickness
B_N	net specimen thickness
c_1, c_2	constants in stress dependent creep ductility formula
C^*	C^* integral analogous to the J integral
$C(t)$	$C(t)$ integral
E	Young's modulus
F	applied load
h	stress triaxiality factor or factor to estimate C^* in experiment using load line displacement
J	J-integral
K	stress intensity factor
Kcr	creep stress intensity factor
K_{in}	initial stress intensity factor
m	constant in stress dependent creep ductility formula
n	stress exponent in Norton creep model
n_1, n_2	stress exponents in 2RN creep model
P_L	limit load
Q	constraint parameter
R	creep constraint parameter
R^*	load-independent creep constraint parameter
T	T-stress constraint parameter
Tz	out-of-plane constraint parameter
t	creep time
t_{red}	creep redistribution time
t_T	creep transition time
$\dot{V}_C$	creep load line displacement rate
$\dot{V}_t$	total load line displacement rate
W	specimen width
θ	polar coordinate at the crack tip
$\dot{\varepsilon}_0$	creep strain rate at normalizing stress
$\dot{\varepsilon}_c$	creep strain rate
$\dot{\varepsilon}^c_{ref}$	uniaxial creep strain rate at reference stress
ε^*_f	multiaxial creep ductility
ε_f	uniaxial creep ductility
ε_{f1}	lower shelf creep ductility
ε_{f2}	upper shelf creep ductility
ε_c	equivalent creep strain
ε_p	equivalent plastic strain
ϕ	a unified constraint parameter defined by plastic region area
σ_0	normalizing stress
σ_e	von Mises equivalent stress
σ_m	mean normal stress
σ_{ref}	reference stress
σ_y	yield stress
ω	damage parameter
$\dot{\omega}$	damage rate
η	factor to estimate C^* in experiment using load line displacement
$\dot{\Delta}$	load line displacement rate

Abbreviations

2D	two-dimensional
2RN	two-regime Norton
3D	three-dimensional
CCG	creep crack growth rate
C(T)	compact tension
CEEQ	equivalent creep strain in ABAQUS code
FEM	finite element method; HRR Hutchinson–Rice –Rosengren
M(T)	middle cracked tension
PEEQ	equivalent plastic strain in ABAQUS code
SEN(B)	single edge-notched bend
SEN(T)	single-edge notched tension

constraints, and the parameter φ is equally sensitive to in-plane and out-of-plane constraints. However, finite element method (FEM) calculations by Yang et al. [11,12] show that the constraint parameter φ has its limitation in characterizing constraint at higher J-integral for the ductile material with higher fracture toughness due to the extension of the plastic zone size to the specimen boundaries. Thus, they defined a new unified constraint parameter A_p by modified the parameter φ as follows [11,12]:

$$A_p = \frac{A_{PEEQ}}{A_{ref}} \tag{2}$$

where A_{PEEQ} is the area surrounded by the equivalent plastic strain (ε_p) isoline ahead of a crack tip and A_{ref} is the reference area surrounded by the ε_p in a standard specimen. It has been shown that the parameter A_p can characterize both in-plane and out-of-plane constraint for ductile materials with higher fracture toughness, and based on the A_p the unified correlation of in-plane and out-of-plane constraint with ductile fracture toughness of A508 steel [11,12] and a dissimilar metal welded joint [13] were obtained. In a recent study of authors [14], it has been shown that the parameter A_p also can characterize both in-plane and out-of-plane crack-tip constraint under brittle fracture conditions.

Under creep conditions, a lot of experimental and theoretical evidences have shown that crack-tip constraint can affect creep crack growth (CCG) rate [15–23]. For a given C^* value (creep fracture mechanics parameter), the model predications showed that the CCG rates in plane strain are significantly greater than those in plane stress [17]. Some experimental results have shown that there is an effect of specimen thickness on the CCG rate [16,20], and the specimens with larger thickness exhibit higher CCG rate. It also has been found that at the same C^* value the creep crack growth rates measured in the middle tension (M(T)) specimens are lower than those obtained from deep crack compact tension (C(T)) specimens