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Creep constraint analysis and constraint parameter solutions for circumferential surface cracks in pressurized pipes

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ABSTRACT

Creep crack-tip constraints for inner circumferential surface cracks in pressurized pipes have been analyzed by three-dimensional finite element method and the constraint parameter R^* solutions have been obtained for different pipe geometries and crack sizes. It has been shown that the constraint level of circumferential cracks is lower than that of axial cracks, and the constraint effects need to be considered in creep life assessments of pressurized pipes. The benefits from incorporating constraint effects are greater for the circumferential cracks than for the axial cracks and for the shallower and shorter cracks than for the deeper and longer cracks.

1. Introduction

It has been well known that crack-tip constraint state has significant influence on fracture behavior of materials, and the loss of constraint causes the increases in fracture toughness [1]. The constraint effect is usually caused by specimen or structure geometry, crack size, loading configuration, etc. To improve accuracy in structural integrity assessments, the crack-tip constraint effect requires to be incorporated by suitable constraint parameter. 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, 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] are introduced as constraint parameters to quantify the crack-tip constraint levels of specimens or actual components. However, the studies on creep crack-tip constraint effect is still limited, and in the present codes of high-temperature creep defect assessments, the constraint effect still has not been incorporated. To incorporate the constraint effect in creep life assessments, the creep crack-tip constraint parameter needs to be developed, and the constraint parameter solutions for typical high-temperature components, such as pressurized pipes, and vessels, should be investigated and provided for practical applications.

A lot of experimental and theoretical evidences have shown that constraint can affect creep crack growth (CCG) rate [6–23]. For a given C^* value (creep fracture mechanics parameter), the model predications showed that the CCG rates in plane strain (PE) are significantly greater than those in plane stress [7–11]. Zhao et al. [12] investigated creep crack growth behavior using the compact tension (C(T)) test specimens with different crack depths and found that the creep crack growth rates at the same C^* values increased as the crack depth increased. The experimental results of Tabuchi et al. [13] and Tan et al. [14,15] have shown that there is an effect of specimen thickness on CCG rate, and the specimens with larger thickness exhibit

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Nomenclature

a	crack depth
$\dot{a}$	creep crack growth rate
$\dot{a}_0$	creep crack growth rate of the standard specimen
A	coefficient in the power-law creep strain rate expression
$2c$	crack length
C^*	C^* integral analogous to the J integral
$C(t)$	$C(t)$ integral
D	inner diameter of pipes
E	Young's Modulus
L	characteristic length
n	power-law creep stress exponent
p	internal pressure
Q	constraint parameter under elastic–plastic condition
Q^*	parameter for correlating creep crack growth rate
r	distance from a crack tip
R	creep constraint parameter
R_i	inner radius
R^*	load-independent creep constraint parameter
R_1^*	R^* value at the deepest point along crack front
R^*_{avg}	average value of R^* along crack front
t	creep time or pipe thickness
t_{red}	stress redistribution time
W	specimen width
$\dot{\varepsilon}$	creep strain rate
$\dot{\varepsilon}_0$	creep strain rate at normalized stress
θ	polar coordinate at the crack tip
σ_0	normalized stress
σ_ϕ	axial tension stress
σ_{22}	opening stress
$\sigma_{22,CT}$	opening stress of C(T) specimen under plane strain
$\Delta\sigma$	opening stress difference
υ	Poisson's ratio
Φ	angular parameter characterizing crack front position

Abbreviations

3-D	three-dimensional
CCG	creep crack growth
C(T)	compact tension
DEN(T)	double edge-notched tensile
FEM	finite element method
M(T)	middle tension
PE	plane strain
SEN(B)	single edge-notched bend
SEN(T)	single edge-notched tensile

faster creep crack growth rate. Zhao et al. [16] and Yamamoto et al. [17] have also reported that the experimental creep crack growth rates of thick specimens are 3–5 times faster than those of thin specimens for P92 steel and weld joint, respectively. Ozmat et al. [18] tested 304 austenitic steel and showed a tendency for M(T) specimens to produce a lower CCG rate than the C(T) and double edge-notched tensile (DEN(T)) specimens. The compact tension (C(T)) and middle tension (M(T)) specimen tests of Bettinson et al. [19,20] for the 316H austenitic steel showed the CCG rate data of the M(T) specimen lie below those of the C(T) specimen by a factor of about 3. Data on P91 and P122 high chromium steels done by Takahashi et al. [21] showed a significantly lower creep crack growth rate for M(T) specimens compared with C(T) specimens. Davies et al. [22] found that the long-term C(T) data exhibited higher CCG rates, for a given value of C^*, compared to short-term tests on C(T) geometry. However, the CCG behavior of the long-term double edge notch tension (DEN(T)) test was similar to that of the short term DEN(T) tests. A test result of a low free nitrogen C–Mn steel for the specimens with different loading configurations showed that the CCG rates in the single edge-notched tensile (SEN(T)), single edge-notched bend (SEN(B)) and M(T) specimens are generally lower than those in C(T) specimens [23]. Yokobori et al. proposed a parameter Q^* for correlating creep crack growth rate [24–27], and their work showed that the creep crack growth rate for a thick specimen is higher than that of a thin