ARTICLE IN PRESS

Engineering Fracture Mechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Unified constraint parameter solutions for axial and circumferential surface cracks in pressurized pipes under creep condition

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ARTICLE INFO

Article history:
Received 15 July 2017
Accepted 16 November 2017
Available online xxxx

Keywords:
Unified constraint parameter
Creep
Axial crack
Circumferential crack
Pressurized pipes

ABSTRACT

Unified creep constraint parameter A_c for axial and circumferential surface cracks in pressurized pipes have been calculated and investigated by three-dimensional finite element method. It has been shown that the parameter A_c can effectively characterize in-plane and out-of-plane creep constraints in pressurized pipes. The overall constraint levels of pipe cracks increase with increasing crack depth, length, pipe wall thickness and radius-thickness ratio. The parameter A_c solutions have been obtained for different pipe geometries and crack sizes. In creep life assessments of pressurized pipes, the overall constraint effect can be incorporated by the unified constraint parameter A_c. For shallower and shorter surface cracks in pipes, more benefits can be gained by incorporating constraint effect.

1. Introduction

Creep crack initiation (CCI) and creep crack growth (CCG) are usually the main causes of failure on components operated at elevated temperature, such as pressurized pipes and vessels in power plants and chemical plants [1]. A lot of experiments, theoretical evidences and numerical simulations have shown that the specimen or component geometries, loading configurations and crack size can affect creep crack-tip constraint, which can subsequently influence the CCI time [2–6] and CCG rate [2,7–21] of materials. With increasing creep crack-tip constraint, the CCI time decreases and CCG rate increases. For a given C^* value, the CCG rate increases with increasing crack depth [7] and specimen thickness [8–12]. The CCG rates in M(T)specimens with low constraint are significantly lower than those in C(T) specimens with high constraint for various steels [13–16]. The creep constraint effects on CCG rate were regarded as "structural brittleness" by Yokobori et al. [17]. Recent numerical simulations also have shown that the creep constraints induced by different specimen geometries and crack sizes have significant effects on CCI time [4–6] and CCG rates [18–22].

In the standard for measuring CCI time and CCG rates of materials, the C(T) specimen with high constraint level in plane strain is often recommended to get conservative CCI time and CCG rate data [23]. However, the resultant defects in manufacturing process and service in pressurized pipes and vessels usually are axial or circumferential surface cracks with smaller sizes and lower crack-tip constraint. As a result, the use of the CCI time and CCG rate data from high constraint C(T) specimens in creep life assessment for the shallower surface cracks in pipes or vessels are unduly conservative and overly

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https://doi.org/10.1016/j.engfracmech.2017.11.032
0013-7944/

Please cite this article in press as: Ma HS et al. Unified constraint parameter solutions for axial and circumferential surface cracks in pressurized pipes under creep condition. Engng Fract Mech (2017), https://doi.org/10.1016/j.engfracmech.2017.11.032

Nomenclature

a	crack depth
$\dot{a}$	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
B	specimen thickness
$2c$	crack length
C^*	C^* integral analogous to the J integral
D	inner diameter of pipes
E	Young's modulus
K_{cr}	creep stress intensity factor
n	stress exponent in Norton creep model
p	internal pressure
Q	constraint parameter
R	creep constraint parameter
R_i	inner radius of pipes
R^*	load-independent creep constraint parameter
T_z	out-of-plane constraint parameter
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
ε_c	equivalent creep strain
ε_p	equivalent plastic strain or true plastic strain
σ_0	normalizing stress
σ_ϕ	axial tension stress
υ	Poisson's ratio
ϕ	angular parameter characterizing crack front position

Abbreviations

3D	three-dimensional
CCG	creep crack growth
CCI	creep crack initiation
C(T)	compact tension
CEEQ	equivalent creep strain in ABAQUS code
FEM	finite element method
M(T)	middle tension
SEN(T)	single-edge notched tension

pessimistic [24]. This excessive conservatism caused by the constraint effect can lead to unnecessary repairs or replacement of in-service pipes or vessels at great operational costs. To reduce the excessive conservatism, the constraint effect needs to be incorporated in high-temperature creep defect assessments by using appropriate creep constraint parameters.

Some creep crack-tip constraint parameters have been proposed and studied in the literature. They mainly include the parameters Q [25–27], R [28–32], R^* [33,34], T_z [35,36] and modified parameter Q [7,16,37]. Shlyannikov et al. [38] introduced a creep stress intensity factor K_{cr} to quantify the crack growth resistance and geometry constraint effect. In the creep constraint parameters (Q, R, R^* and T_z) based on crack-tip stress field, the parameters Q, R and R^* can characterize in-plane constraint and partial out-of-plane constraint, and the T_z can characterize out-of-plane constraint [39,40]. In the previous work of authors [41,42], the creep constraint parameter R^* for pressurized pipes with different geometries and axial and circumferential crack sizes have been studied and the parameter R^* solutions have been obtained. Based on the two parameter C^*-R^* concept incorporating constraint effect, the CCG life has been assessed for axially cracked pipes [43]. In the work of Xu et al. [44], the creep constraint effect in pressurized pipelines with axial surface cracks has also been analyzed by using the modified constraint parameter Q.

However, 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