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Characterization of creep crack-tip constraint levels for pressurized pipelines with axial surface cracks

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ABSTRACT

Through extensive 3D finite element analyzes, the creep crack-tip constraint levels were characterized using a load-independent creep constraint parameter Q^* for pipelines with axial surface cracks of different geometrical sizes, which involved in various crack depths and crack shapes. The Q^* distribution along the crack front for axial internal surface cracks and axial external surface cracks exhibited the same distribution tendency. However, the constraint level of internal surface cracks was higher than external surface cracks. In addition, the constraint level was improved as the crack depth became deep; in contrast, the constraint level showed a reduction tendency as the crack shape ratio a/c increased from 0.2 to 1.0. The highest constraint levels for the axial surfaces cracks in pipelines approached to that of single-edge notched tension specimen. Finally, two empirical equations for estimating the constraint level were established as a function of crack depth ratio and crack shape ratio for axial surface cracks in pipelines.

Abbreviations

3D	three-dimensional
CCG	creep crack growth
CCI	creep crack initiation
CCT	center-cracked tension
CST	C-shaped cracked tension
CT	compact tension
DENT	double-edge notched tension
FEM	finite element method
HRR	Hutchinson–Rice–Rosengren
SENB	single-edge notched bend
SENT	single-edge notched tension

1. Introduction

Creep crack initiation (CCI) and creep crack growth (CCG) have been the main failure mechanism for components operated at elevated temperature, and this will lead to the early failure for components before the design life [1–4]. For assuring the component integrity, a majority of works have been conducted to investigate the fracture behavior of materials under high temperature. Zhao et al. [5] focused on the creep crack growth properties of the welded joint and the microstructure evolution during crack propagation. Webster et al. [6] paid attentions on the effect of stress relief on the high temperature structural integrity for defected components. Davies et al. [7] revealed the role of the duration time and the specimen geometry on the creep crack initiation. Yokobori and Sugiura [8] investigated the influences of microstructure and aging on the embrittling behavior of creep crack growth.

Besides the creep facture mechanics of materials, Zhao et al. [9,10] and Tan et al. [11] reported that the constraint effects ahead of crack tips had a great influence on the crack initiation and would significantly affect the crack growth rate through creep crack growth tests of different steels. In general, in standards for measuring CCG rates of materials, in order to ensure that the crack tip has relatively high constraint so as to get conservative CCG rate data, the compact tension (CT) specimen with deep crack (a/W = 0.5) under plane strain condition is usually recommended [12]. As well known, it is unavoidable for defects to be produced in the manufacturing process and servicing stage, such as welding defects, erosion corrosion cracks on the inner surface of pipelines and so on. Moreover, the cracks presented in engineering pressure pipelines and vessels are mainly surface shallow cracks and the constraint levels of them may be lower than that of standard CT specimens employed in tests. In addition, investigated results had showed that crack depths, specimen widths, loading configurations and sample thicknesses had a great influence on the constraint effects ahead of crack tips [9,13,14]. Nikbin et al. [15] revealed that the CCG rates of specimens in plane strain state were obviously

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Nomenclature

a	crack depth
A	coefficient in the power-law creep strain rate expression
A_2	constraint parameter
$2c$	crack length
C^*	contour integral for characterizing crack-tip stress field at steady-state creep
E	Young's modulus
J	J-integral
L	characteristic length
n	power-law creep stress exponent
p	internal pressure of pipeline
Q	constraint parameter
Q^*	load-independent constraint parameter
r	distance from the crack tip
R	creep constraint parameter
R^*	load-independent creep constraint parameter
R_i	inner radius of pipeline
t	wall thickness of pipeline
T	constraint parameter
T_z	creep constraint parameter
θ	polar angle at the crack tip
Φ	angular parameter
$\dot{\varepsilon}_c$	creep strain rate
$\dot{\varepsilon}_0$	creep strain rate at normalizing stress σ_0
ν	Poisson's ratio
σ_0	yield stress
σ_{22}	opening stress ahead of crack tips
σ_{ij}	deviatoric stress
$\tilde{\sigma}_{ij}$	dimensionless function of n, θ
σ_e	equivalent stress
σ_m	hydrostatic stress

higher than those under plane stress condition at the same C^* values. The CT specimen with deeper crack length would exhibit a lower CCI time and a higher CCG rate than that of shallow cracks under a given C^* value [9]. These phenomena were confirmed to be caused by different crack-tip constraint levels of these specimens. Bettinson et al. [16] found that the CCG rates of CCT specimens were always lower than that of CT specimens. Through wide-ranging numerical simulations, Xu et al. [17] had revealed that CT specimens had higher crack-tip constraint than CCT specimens while the constraint of CST, SENB, SENT and DENT specimens was in the middle between them. Therefore, the constraint discrepancy between defected components and tested specimens may result in overestimated or underestimated prediction results. An excessive pessimism would lead to unwarranted repairs or replacement of in-service pipelines at extra costs. Contrarily, an underestimated estimation would greatly affect the reliability of structures. Therefore, understanding and characterizing the constraint levels for different tests specimens should be studied to assure that the data determined in laboratory can be applied to real cracked structures. Furthermore, the constraint effects in the real cracked structures should be evaluated and accounted for in order to solve the transferability problem. These factors play a vital role in providing an accurate remained life for high temperature components with various cracks.

Up to now, the quantification and characterization of constraint effects has been extensively investigated in elastic-plastic fracture mechanics and has stimulated the development of two-parameter fracture mechanics, such as J-T [18], J-Q [19,20] and J-A_2 [21]. In these methods, the first parameter J integral is used to set the dimensions over which high stresses and strains develop, while the secondary parameters T, Q and A_2 are introduced to quantify the crack-tip constraint level. However, at high temperatures, creep deformation is time-dependent and very complex. As a result, the research progress of creep crack-tip constraint effects under high temperature is far behind studies on the constraint effect under elastic-plastic condition. To effectively characterize the creep crack-tip constraint effect ahead of crack tip, two-parameter fracture mechanics are also introduced. Budden and Ainsworth [14], Nikbin [13] and Zhao et al. [9] employed C^*-Q two parameter approach to represent the stress and strain field in creep regime. Chao et al. [22] proposed C^*-A_2 to determine the higher-order asymptotic crack-tip fields in a power-law creeping material. Using the stress field in deep cracked CT specimen as a reference filed, Wang et al. [23] and Sun et al. [24] developed the C^*-R two parameter for characterizing the stress filed field for specimens with different crack depths and specimen thicknesses. Furthermore, a C^*-R^* solution for creeping solid were proposed by Tan et al. [25] and Liu et al. [26] to characterize creep constraint between axially cracked pipelines and specimens. Ma et al. [27,28] proposed a C^*-A_c unified characterization parameter to demonstrate the in-plane and out-of-plane together based on equivalent creep strain presenting ahead of crack-tip. Moreover, Xiang et al [29] considered that C^*-T_z could efficiently represent the three dimensional stress fields ahead of a through-thickness crack under small scale creep conditions while for extensive creep conditions C^*-T_z-Q could better described the stress filed in crack border. Similar to the two-parameter fracture mechanics approaches in elastic-plastic regime, the first parameter C^* integral is used to characterize the strength of mechanical field ahead of crack tips, while the above mentioned secondary parameters Q, A_2, R, R^*, A_c and T_z and are introduced to characterize the creep crack-tip constraint level ahead of crack tips. Our previous studies [9,17] had successfully adopted the C^*-Q two parameter approach to demonstrate the stress and strain filed ahead of crack tip in creep regime and found that although the constraint level could be represented by the parameter Q, the values of Q were related to component geometries, crack depths, loading configurations and load levels [30]. For eliminating this phenomenon, a load-independent creep constraint parameter Q^* was introduced by modifying the creep constraint parameter Q, and the creep crack-tip constraint effects induced by various specimen geometries were effectively quantified using the Q^* parameter [17].

In this paper, the constraint levels in the real cracked structures which were represented by pressurized pipelines with axial surface cracks served at elevated temperature were studied, which would be beneficial to transferring creep crack growth data determined from standard ASTM procedure to real flawed structures. The creep crack-tip constraint effects for internal and external surface cracks with different crack shapes and crack depths were characterized using the load-independent creep constraint parameter Q^*. Moreover, the empirical equations to correlate the typical values of constraint and the dimensions of presented cracks in components were developed.

2. Load-independent creep constraint parameter Q^*

The J-Q two-parameter theory has been widely used in constraint analysis in elastic-plastic fracture mechanics [19,20]. However, it has been confirmed that the parameter Q depends on structure geometry, crack depth and load level, and cannot remain constant during crack growth process. Thus, it is inappropriate to describe the constraint effect on J-R curves in ductile crack growth [31,32]. To resolve this problem, Zhu et al. [31] proposed a modified crack-tip stress field of the J-Q theory for power-law hardening