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Numerical analysis of the creep crack constraint effects and the creep crack initiation for pressurized pipelines with circumferential surface cracks

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ABSTRACT

The creep crack constraint effects using a load-independent creep constraint parameter Q^* and the creep crack initiation (CCI) times were characterized by 3D finite element method for pipelines with circumferential surface cracks of different geometrical sizes. The results revealed that the distribution regulation of Q^* along the crack front for circumferential internal surface cracks and external surface cracks was similar. The maximum constraint level occurred near the deepest crack front part for cracks with smaller a/c, while it occurred near the free surface for cracks with larger a/c. The constraint values at the same position ($2\Phi/\pi$) increased with the increasing of the crack depth when a/c kept constant. The circumferential internal surface cracks of pipelines were proved more dangerous than the external surface cracks with the same geometrical size. Furthermore, the CCI times were decided by the peak values of constraint, or the CCI firstly occurred at the position where the constraint level was maximum. In addition, the empirical relationships between the CCI times and crack sizes were fitted, which was also verified effectively.

1. Introduction

Many failures occurred in in-service components at elevated temperatures are mainly caused by the creep crack initiation (CCI) and creep crack growth (CCG) [1–3]. Therefore, many investigations about the fracture behavior have been done under high temperature [4–11].

Zhao [12,13] and Tan [14] revealed that the constraint effects could greatly influence the CCI and CCG by accelerating the CCG rate. Budden and Ainsworth [15] first combined C^* and the constraint parameter Q (i.e. the C^*–Q two-parameter method) to characterize the effect of constraint on the stress distribution and proposed an estimation model to calculate the CCG rate. Moreover, Nguyen et al. [16] used a micromechanical model to study the propagation of pre-cracks in a power-law creeping material. Sun et al. [17] analyzed the out-of-plane constraint in the three-dimensional compact tension (CT) specimens by numerical simulation. Zhao et al. [18] also evaluated the constraint effect on the CCG with different CT specimen sizes. Zhao et al. [12] further investigated the constraint effect generated by different crack depths and specimen geometries [13]. Wang et al. [19] proposed a new constraint parameter R, which modified the Hutchinson–Rice–Rosengren (HRR) stress singularity near the crack tip, and also investigated the effect of loading configuration on the constraint [7]. Following that, Sun et al. [20] investigated the effect of constraint generated by crack length on stress distributions and the effect of out-of-plane constraint [17] in CT specimens using the parameter R. Later, Tan et al. [21] proposed the load-independent creep constraint parameter R^* to evaluate the constraint of various specimens throughout the creep time. R^* had also been developed to characterize the in-plane and out-of-plane constraints [22]. Ma et al. [23,24] investigated the unified creep constraint parameter A_c of in-plane and out-of-plane constraint. Zhu et al. [25] introduced a new load-independent parameter Q^* under the elastic-plastic condition to modify the stress field dependent on the J–Q theory. Xu et al. [26] developed Q^* under the creep condition of the crack tip at high temperature, and the load-independence was verified by three-dimensional (3-D) finite element (FE) analyses. However, the constraint level around the cracks of the standard specimen in-

Abbreviations: CCI, creep crack initiation; C3D8R, eight-node linear brick reduced integration elements; CREEP, a user subroutine in ABAQUS for creep analysis; MSF, appropriate multiaxial stress factor; FE, finite element.

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Nomenclature

a	the crack depth
A	coefficient in power-law creep definition
C(t)	transient creep crack tip characterising parameter
C^*	steady state creep crack tip characterising parameter
E	elastic (Young's) modulus
E′	effective elastic (Young's) modulus
n	power-law creep stress exponent
N	power-law plastic stress exponent
P	load
t_{red}	redistribution time
$\dot{\omega}$	damage accumulation rate
Q	constraint parameter
Q^*	load-independent constraint parameter
δ_{ij}	Kronecker delta
σ_{ij}	stress components
$\sigma_{\theta\theta}(r,0)$	analytical crack-opening stress
$\sigma^{FEM}{}_{\theta\theta}(r,0)$	numerical crack-opening stress
$\tilde{\sigma}_{ij}(\theta;n)$	dimensionless functions of n and θ
I_n	dimensionless constant depending on n
$\dot{\varepsilon}_c$	creep strain rate
ω	creep damage parameter
ε_f	uniaxial creep ductility
ε_f^*	multiaxial creep ductility
σ_m	hydrostatic stress
σ_e ($\bar{\sigma}$)	equivalent stress
σ_{22}	opening stress
σ_0	normalizing stress

vestigated above was conservative to measure CCG rates of practical structures, such as shallow surface cracks of pressure pipelines and vessels. Zhao et al. had revealed that the IV type cracks and the incomplete fusion in weld were typical circumferential surface cracks [27]. Hence, the distributions of the constraint ahead of the surface cracks of pressure pipelines were also investigated. Tan et al. [28] characterized and correlated the 3-D creep constraint between axially cracked pipelines and test specimens. R^* had been developed to characterize the constraint of semi-elliptical axial surface cracks in pressurized pipes [29,30], and circumferential surface cracks [31]. Xu et al. [32] had characterized the creep crack-tip constraint levels for pressurized pipelines with axial surface cracks using the load-independent parameter Q^*.

In general, the CCI time occupies the majority of the safe lifetime of structural integrity. Hence, the investigation of CCI is significant for the application of components under the high temperature. In a ductile material when micro-cracks (which may be generated by the nucleation, growth and coalescence of voids ahead of a pre-existing defect) first link up and form the main defect, the elapsed time is defined as the creep crack initiation (CCI) time [33], and the evolution of this process is usually referred to as 'creep damage' [34]. The CCI period is a slow microstructural transition process but not an obvious macroscopic phenomenon, which is sometimes conservatively ignored or neglected in component lifetime calculations. However, it can be important to include CCI, as it often takes up the largest proportion of the lifetime of components operated at high temperature and under high pressure conditions. Holdsworth reviewed the definitions about the CCI and early propagation of cracks from pre-existed defects and explained the phenomenon with 1CrMoV steels [33]. Davies et.al [6] proposed a series of analytical enhancement models to predict the CCI time ahead of a sharp crack tip under the different stress field conditions. Davies et.al [6] also studied the effects of test duration and specimen geometry on CCI times and compared the results with analytical predictions. However, there are few research about the creep crack initiation time of pipeline with the circumferential surface cracks. The circumferential surface cracks have a great effect on the structural integrity evaluation. Besides, the constraint level may significantly influence the process of damage accumulation and creep crack initiation time since it has effect on the stress field ahead of the crack tip. Therefore, the constraint effects on the damage accumulation and creep crack initiation and the CCI times around the circumferential surface crack should be investigated.

British Standards Institution [35] has proposed a method (BS 7910) to assess the CCI times of pipeline with the circumferential internal surface crack under the high temperature and pressure conditions. However, this approach was much conservative, and it would underestimate the CCI times and service life of the pipeline. Hence, an accurate predictive approach of CCI times are also needed.

In this paper, the constraint effects and CCI times of the pressurized pipelines with circumferential surface cracks served at elevated temperature are studied. The distributions of C^* along the crack front in pipelines with internal and external surface cracks are analyzed. Besides, the creep crack-tip constraint effects with different geometrical sizes are characterized using the load-independent creep constraint parameter Q^*. The creep damage accumulations and the CCI times at the positions with the maximum values of C^* or Q^* are also investigated. The empirical relationships between the CCI times and crack sizes are obtained. The effectivity of the empirical equations is verified.

2. The analytical and FE methods

2.1. Load-independent creep constraint parameter Q^*

The stress distribution around the crack tip under the steady-state creep condition is expressed as [36,37]:

$$\sigma_{ij} = \sigma_0 \left(\frac{C^*}{\dot{\varepsilon}_0 \sigma_0 I_n r} \right)^{\frac{1}{n+1}} \tilde{\sigma}_{ij}(\theta; n) \tag{1}$$

where σ_{ij} is the stress component, r is the distance away from the crack tip, and θ is the angle away from the crack line. $\tilde{\sigma}_{ij}(\theta;n)$ is a dimensionless function of n and θ, and I_n is a parameter related to the creep stress-hardening exponent n. As shown in Eq. (1), C^* is the characterization parameter of the crack propagation driving force under steady creep state.

The C^*–Q two-parameter approach is developed under creep conditions. The expression of the stress field is as follows [15,38]:

$$\sigma_{ij} = \sigma_0 \left(\frac{C^*}{\dot{\varepsilon}_0 \sigma_0 I_n r} \right)^{\frac{1}{n+1}} \tilde{\sigma}_{ij}(\theta; n) + Q\sigma_0\delta_{ij} \tag{2}$$

where δ_{ij} is the Kronecker delta. Q is a non-dimensional parameter that measures the constraint conditions around the crack. Moreover, Q is always determined by the difference of σ_{22} between the specimen and the analytical steady-state creep field [16,39]:

$$Q = \frac{\sigma_{22}^{FEM}(r,0) - \sigma_{22}(r,0)}{\sigma_0} \tag{3}$$

where $\sigma_{22}(r,0)$ is the theoretical steady creep stress field calculated by Eq. (6). $\sigma^{FEM}{}_{22}(r,0)$ is the stress distribution predicted by FE simulation.