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Quantifying the constraint effect induced by specimen geometry on creep crack growth behavior in P92 steel

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ABSTRACT

In this paper, the effect of the specimen geometry on the creep crack growth behavior in P92 steel was quantified and six different types of cracked specimens (including C-ring in tension CS(T), compact tension C(T), single notch tension SEN(T), single notch bend SEN(B), middle tension M(T), and double edge notch bend tension DEN(T)) were employed. Results revealed that the creep crack growth rate against C^* relations varied with changing specimen geometry. For a given C^* value, C(T) and CS (T) showed the highest crack growth rates, which were three times as the lowest crack growth rates in M (T). This revealed that distinctions in specimen geometry influenced the in-plane constraint level ahead of crack tip. Moreover, constraint parameter Q was introduced to quantify the in-plane constraint. During the creep crack propagation, the distributions of Q varied as specimen geometry changed. The specimen order in terms of Q values from high to low was CS(T), C(T), DEN(T), SEN(B), SEN(T) and M(T), which basically represented the constraint level in these specimens.

1. Introduction

Many components servicing at elevated temperatures are continually exposed to high temperatures. Creep crack growth is a principal failure mechanism of components within the high temperature regime due to the detected flaws generated during manufacturing and serving, which usually results in the early failure prior to the designed lives [1–4]. The issue of assessing creep cracks in high temperature components is becoming increasingly important for assuring the reliability of in-service components. Nowadays, extensive experimental works had been performed to study the creep crack growth behavior [5–13], but found that the creep crack initiation and growth characteristics could be affected by the in-plane constraint ahead of crack tip imposed by crack size, specimen geometry, loading model and loading magnitude. Zhao et al. [5] investigated the crack growth behavior using the compact tension (C(T)) specimen with the different crack depths and found that the creep crack growth rates at the same C^* values increased as the crack depth increased. Yokobori et al. [6] studied the effects of component geometry on the embrittling behavior of creep crack growth using C(T) and circular notched specimens and found that the creep crack growth rates were dependent on the stress triaxiality ahead of crack tip. Bettinson et al. [7] performed creep growth tests using ex-service 316H stainless steel and stated that constraint effects were observed in the data, with the C(T) specimens having the fastest crack growth rate and the small middle tension (M(T)) specimens having the slowest. Davies et al. [8] reported that for a given value of C^*, the long-term C(T) data exhibited higher creep crack growth rates and shorter creep crack initiation times, compared to short-term tests on C (T) geometry but the creep crack growth behavior of the long-term double edge notch bend tension (DEN(T)) test was similar to that of the shorter term DEN(T) test. A test result of a low free nitrogen C–Mn steel for the specimens with different loading geometries such as single notch tension (SEN(T)), single notch bend (SEN(B)), M(T) and C (T) specimens showed the similar tendency, but the highest creep crack rates were occurred in C(T) specimens [9]. Matvienko et al. [10] investigated the variations of the crack-front stress field under creep loading with M(T), SEN(B) and C(T) specimens.

The driving force for creep crack growth was dominated by the local elastic–plastic stress in the creep damage zone around a crack tip [14]. Specimen geometry, crack size and microstructure played an important role in the stress state and hence affected the cracking behavior in the creep range. For the aim of quantify the constraint on the crack front, the two parameter approach was introduced in to provide a more accurate characterization of the crack-tip stress fields, such as C^*–T [10], C^*–T_z [15], C^*–Q [16–18], C^*–R [19] and C^*–A_2 [20]. In these approaches, the first parameter C^* integral set the size scale over which high stresses and strains developed, and the secondary parameters T, T_z, Q, R and A_2 were introduced to quantify the crack-tip

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constraint. Among the above mentioned constraint parameters, the parameter Q could be easily obtained and could be incorporated into the creep crack prediction model to give an accurate creep crack growth rate. Combined the C^*–Q two-parameter concept with a NSW model, Budden [16], Nikbin [17] and Yatomi [21] investigated the effect of constraint on the creep crack growth rates. Based on the C^*–Q two-parameter concept and finite element analysis, Bettinson et al. [22] examined the effect of specimen type and load level on the Q from short to long term creep conditions for elastic-creep materials and Zhao et al. [18] predicted the creep crack growth behavior with different crack sizes by considering the constraint effect.

Analogous to J–Q in power law plasticity [23–26], under creep conditions, the stress fields can be given by C^*–Q, which are defined as [16]:

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

$$Q=\frac{\sigma_{\theta\theta}(r,0)-\sigma_{\theta\theta}^{HRR}(r,0)}{\sigma_0} \tag{2}$$

where σ_{ij} is the stress tensor; σ_0 is the yield stress; $\dot{\varepsilon}_0$ is the strain rate at the σ_0; r and θ are polar coordinates centered at the crack tip, which correspond to the radial distance from the crack tip and the angle from the crack plane, respectively; I_n is an integration constant; $\tilde{\sigma}_{ij}(\theta,n)$, $\tilde{\varepsilon}_{ij}(\theta,n)$ are dimensionless functions of n and θ. $\sigma_{\theta\theta}(r,0)$ is the actual crack-opening stress in specimens. $\sigma_{\theta\theta}^{HRR}(r,0)$ is the analytical crack-opening stress determined from the HRR field, which is determined by [27]:

$$\sigma_{ij}=\sigma_0\left(\frac{C^*}{\dot{\varepsilon}_0\sigma_0 I_n r}\right)^{1/(n+1)}\tilde{\sigma}_{ij}(\theta,n) \tag{3}$$

Because creep crack resistance could be affected by in-plane constraint conditions, a proper method should be developed to quantify in-plane constraint. Up to the present, several works on these issues have been reported, but no systematic investigations based on detailed elastic–plastic-creep finite element (FE) analyses to study the in-plane constraint induced by specimen geometries and the variations of constraint during the whole creep crack process have been yet reported.

The material studied in this work is a high strength ferritic steel, P92 steel, which has been widely employed in high temperature components of ultra super critical fossil power plant, i.e. main steam pipes, headers and so on, due to its high creep strength and corrosion resistance at high temperature [28]. The variations of the creep crack growth behavior in P92 steel with different specimen geometries are studied, in which six different types of cracked specimens are employed, i.e. C(T), CS(T), SEN(T), SEN(B), M(T), and DEN(T) specimen. On the basis of the creep crack data from FE and the two parameter approach, the creep crack-tip constraint induced by the specimen geometry during the creep crack growth process has been investigated in detail.

2. Creep crack growth behavior calculation

2.1. Specimen geometry

To investigate the constraint effect induced by the specimen geometry, six cases of creep crack growth testing specimens are considered in numerical analyses, which are depicted in Fig. 1. They respectively are C(T) specimen (see Fig. 1(a)), CS(T) specimen (see Fig. 1(b)), SEN(T) specimen (see Fig. 1(c)), SEN(B) specimen (see Fig. 1 (d)), M(T) specimen (see Fig. 1(e)), and DEN(T) specimen (see Fig. 1(f)). For all cases, the specimen thickness is denoted by B. For M(T) and DEN(T) specimens, the half crack length and half width are denoted by a and W, respectively. For other specimens with an single edge crack such as C(T), CS(T), SEN(T) and SEN(B), the crack length and width are denoted by a and W, respectively. In the present study, for all the specimens, B is 25 mm; W is 50 mm and a/W is 0.5. The detailed conditions for six cracked specimens are shown in Table 1.

2.2. Material model

Creep crack growth simulations are performed using elastic–plastic–creep FE damage analyses. The total strain ε^t is calculated by:

$$\varepsilon^t=\varepsilon^e+\varepsilon^p+\varepsilon^c \tag{4}$$

where ε^e, ε^p and ε^c stand for elastic, plastic and creep strain components, respectively. The deformation theory of plasticity and the von Mises yield criterion are adopted. The elastic–plastic behavior follows the stress–strain relation:

$$\varepsilon^e+\varepsilon^p=\frac{\sigma}{E}+\alpha\left(\frac{\sigma}{\sigma_0}\right)^m \tag{5}$$

where E is the Young's modulus, m is the hardening exponent and α is the strain hardening coefficient. A power law creep model determined by the average creep strain rate is employed to describe entire creep curves for producing more representative deformation rates with longer creep times [1,29]:

$$\dot{\varepsilon}^c_{ave}=\frac{\varepsilon_f}{t_r}=A\sigma^n \tag{6}$$

where $\dot{\varepsilon}^c_{ave}$ is the average creep strain rate; ε_f is the uniaxial failure strain; t_r is the rupture time in a uniaxial creep test; A and n are material constants which can be calculated by plotting the uniaxial minimum creep strain rates against applied stresses (log–log scale). ε_f is the uniaxial creep ductility and depends on the material and the temperature. In this paper, the constant ε_f of 20% is employed, which is the measured value of uniaxial creep tests for the present ASME P92 steel at 650 °C.

On the basis of the creep ductility exhaustion concept, an uncoupled damage model is introduced to calculate the creep damage accumulation and then simulate crack growth during the transient and steady state creep crack growth regimes. Creep damage rate $\dot{\omega}$ is defined by the ratio of average creep strain rate, $\dot{\varepsilon}^c_{ave}$ and multi-axial creep ductility, ε_f^*as follows:

$$\dot{\omega}=\frac{\dot{\varepsilon}^c_{ave}}{\varepsilon_f^*} \tag{7}$$

In this model, multi-axial creep ductility depends on the uniaxial creep ductility of material and the stress triaxiality ahead of crack tip which is the ratio of the principle stress σ_m and the equivalent stress σ_e. In previous study, it was found that the creep crack growth in P92 steel is mainly caused by the nucleation, growth and coalescence of creep voids by investigation the microstructures [5]. Although there are several models to quantify the multi-axial stress effect on creep ductility, the model proposed by Cocks and Ashby on the basis of the void growth and coalescence [27] is employed and is defined as follow:

$$\frac{\varepsilon_f^*}{\varepsilon_f}=\sinh\left[\frac{2}{3}\left(\frac{n-0.5}{n+0.5}\right)\right]\Big/\sinh\left[2\left(\frac{n-0.5}{n+0.5}\right)\frac{\sigma_m}{\sigma_e}\right] \tag{8}$$

The damage accumulated is calculated using a simple time integral rule:

$$\omega=\int_0^t\dot{\omega}dt=\int_0^t\frac{\dot{\varepsilon}^c_{ave}}{\varepsilon_f^*}dt \tag{9}$$

when the accumulated creep damage calculated from Eq. (9) becomes critical (attains 0.999), local failure is considered to occur and progressive creep crack is simulated. Note that within an FE analysis the value of ε_f^* changes for a fixed material point since it depends on the stress triaxiality through Eq. (8), which changes