Estimation of Creep Crack Initiation Time Considering Initial Plasticity and Constraint Effect

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1. Introduction

The time from the operation to the initiation of crack growth constitutes a large portion of the component's lifetime. It is important to predict creep crack initiation time for the lifetime evaluation of component operating at high temperature. The crack initiation time is defined as the time until micro cracks connect into one major crack or experimentally measurable minimum crack growth [1]. Creep crack initiation is closely related to the stress at the crack-tip. Most of the proposed methods for stress evaluation at high temperature use the steady state creep fracture mechanics parameters C^* as the major factor to characterize the crack-tip stress fields. Davies identified that C^* had a power-law relationship with the crack initiation time, as depicted in Fig. 1 [2-3]. However, the scattering of data is significant and the crack initiation time predicted by C^* does not consider the influence of initial plasticity and the constraint effect.

In this study, the creep crack initiation time is presented in a power-law relationship with the transient elastic-plastic-creep crack-tip opening stress σ_{yy}. C(T) specimens with different geometries and loading conditions, composed of an Austenitic Type 316H stainless steel, were tested at 550℃ under load-controlled loading conditions [2-3]. The crack initiation time is calculated by the method given in ASTM E1457 [4] based on experimentally measured data. The crack-tip opening stress is analytically calculated by the equation given by Lee [5]. The creep crack initiation time and the transient elastic-plastic-creep crack-tip opening stress σ_{yy} are highly correlated.

2. Method

The test material, Austenitic Type 316H stainless steel, is assumed to be described by the Ramberg-Osgood equation for elastic-plastic analysis and the power-law (Norton) for creep properties:

$$\varepsilon = \varepsilon^e + \varepsilon^p = \frac{\sigma}{E} + \alpha\varepsilon_0 \left(\frac{\sigma}{\sigma_0}\right)^m \quad (1)$$

$$\dot{\varepsilon}^c = B\sigma^n \quad (2)$$

Table 1 Summary of elastic, plastic, and creep properties for 316H stainless steel

E (GPa)	σ_0 (MPa)	$\alpha\varepsilon_0$	m	B	N
130	190	0.01	3	9.722E-30	10.47

where ε^e and ε^p are elastic and plastic strain; σ_0 is yield strength and E is Young's modulus; m is strain hardening exponent and α is dimensionless constant; $\varepsilon_0=\sigma_0/E$ is normalizing strain; $\dot{\varepsilon}^c$ is creep strain rate; n is creep exponent and B is creep material constant. The parameters for constitutive models of an Austenitic Type 316H stainless steel are given in Table 1.

The time-dependent crack-tip opening stress at θ=0 under elastic-plastic-creep conditions is expressed as a variable of distance r from crack-tip and time t [5], as given by Eq. (3) using Eq. (4-8):

$$\frac{\sigma_{yy}}{\sigma_{ref}} = \frac{F_{ref}(1+\tau)}{\left[(1+\tau)^{n+1} - \phi_2\right]^{\frac{1}{n+1}}} + \beta_{Q,n} \quad (3)$$

$$\phi_2 = 1 - \left(\frac{F_{ref}}{D_{T=0} + \beta_{Q,m} - \beta_{Q,n}}\right)^{n+1} \quad (4)$$

$$F_{ref} = \left[\frac{C^*}{I_n B \sigma_{ref}^{n+1} r}\right]^{\frac{1}{n+1}} \tilde{\sigma}_{yy}(n) \quad (5)$$

$$D_{T=0} = \left.\frac{(\sigma_{yy})_{T=0}}{\sigma_{ref}}\right|_{t=0} \; ; \quad \sigma_{ref} = \frac{\sigma_0}{L_r} \quad (6)$$

$$\beta_Q = \frac{Q}{L_r} \; ; \quad L_r = \frac{P}{P_L} \quad (7)$$

$$Q = \frac{\sigma_{yy} - \left(\sigma_{yy}\right)_{T=0}}{\sigma_0} \text{ at } r = \frac{2J(0)}{\sigma_0} \quad (8)$$

where $\tau=t/t_{red}$ denotes normalized time; ϕ_2, F_{ref}, and $D_{T=0}$ refer to initial plasticity correction factor, the steady state creep stress field from the RRss fields, and the small-scale-yielding stress field for T=0, respectively; I_n is an integration constant and $\tilde{\sigma}_{yy}$ is dimensionless function; $J(0)$ is J-integral at t=0. To remove the load magnitude dependence of the constraint effect parameter Q, β_Q was introduced. To determine stress field σ_{yy} and $(\sigma_{yy})_{T=0}$, elastic-plastic analysis of specimen and modified boundary layer analysis [6] are needed, respectively. Abaqus v2018 was used for these FE analyses to define σ_{yy} and $(\sigma_{yy})_{T=0}$. The values of β_Q for the plastic hardening exponent (m) and creep exponent (n) are 0.38 and 0.19.

In this study, the creep crack initiation time is defined as the time when the crack propagation amount is 0.2mm, $t_{0.2}$. using The crack-tip opening stress is calculated at $t=t_{0.2}$ and r=0.05mm.

3. Results

The twenty-one creep crack growth tests (CCG) [2-3] with C(T) specimens having various dimensions are analyzed. The ratio of the plastic limit load P_L to the applied load P ranges from about 0.67~1.18.

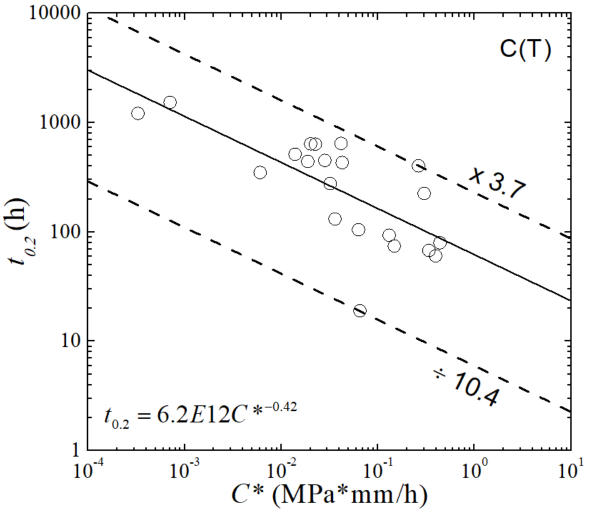

Fig.1 Correlation between $t_{0.2}$ and C*

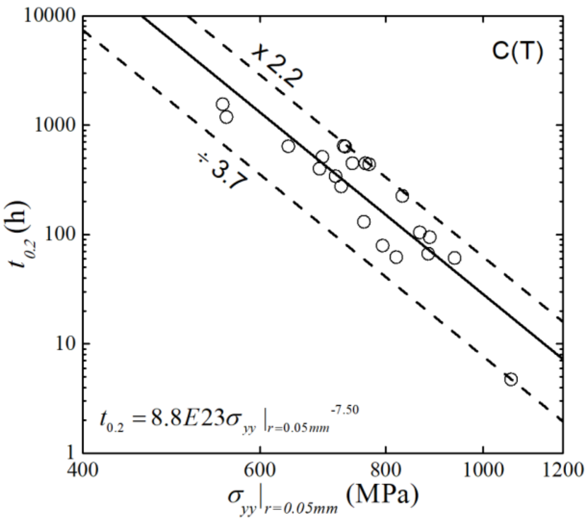

Fig.2 Correlation between $t_{0.2}$ and $\sigma_{yy}|_{r=0.05mm}$

The crack initiation time and the crack-tip opening stress were plotted in Fig. 2 on a logarithmic scale. The initiation time and the opening stress range from 4~1550 hours and 550~1070 MPa. Their power-law distribution is specified in the graph. The scatter of the data is reduced compared to Fig. 1. Particularly, the degree of lower bound decreased from 10.4 to 3.7.

4. Conclusions

In this study, crack initiation time is correlated with the crack-tip opening stress derived from elastic-plastic-creep transient stress field formula considering initial plasticity and constraint effect. The crack initiation time is well described by power-law expression of the crack-tip opening stress. As a future work, various type of cracked specimens will be considered.

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