Rare Metal Materials and Engineering
Volume 46, Issue 12, December 2017
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Rare Metal Materials and Engineering, 2017, 46(12): 3595-3600.

ARTICLE

Effect of Film-Induced Stress on Mechanical Properties at Stress Corrosion Cracking Tip

Yang Hongliang, Xue He, Yang Fuqiang, Zhao Lingyan

Xi'an University of Science and Technology, Xi'an 710054, China

Abstract: Oxide film rupture theory has become one of the most popular models to quantitatively predict the stress corrosion cracking (SCC) rate at crack tip of nickel-based alloys in high temperature and high pressure environments, and stress intensity factor has become an important parameter to measure the stress corrosion cracking rate. In order to further understand the fracture mechanism of the oxide film and the driving force of crack growth, film-induced stress intensity factor was proposed. To understand the effect of film-induced stress intensity factor on the micro-mechanical state at the tip of EAC (environmentally assisted cracking), the stress-strain in the base metal at the EAC tip was simulated and discussed using a commercial finite element analysis code. And then the effect of film-induced stress intensity factor on Mises stress, equivalent plastic strain, tensile stress, tensile strain and tensile plastic strain gradient of crack tip was obtained, which provides a parameter to improve the quantitative predication accuracy of EAC growth rate of nickel-based alloys and austenitic stainless steels in the important structures of nuclear power plants. Therefore the oxide film rupture theory was improved.

Key words: stress corrosion cracking; film-induced stress; stress intensity factor; oxide film; nickel-based alloy

Mechanical status at cracking tip of nickel-based alloys and stainless steel SCC for nuclear pressure vessels and steam generators is one of the key factors in the analysis of SCC mechanism and quantitative prediction of crack growth rate[1,2]. In the process of SCC, a layer of oxide film can be formed on the crack tip surface of the nickel base alloy[3]. Researches[4-6] show that an additional tensile stress, which is induced by the oxide of alloys at crack tip, exists at the substrate side of substrate-oxide film interface. The stress could cause the local plastic deformation at crack tip and intergranular film fracture, leading to the formation of deep crack. Corrosion current density increased and the work function decreased with increasing pre-strains, which facilitated anodic dissolution, thereby resulting in an enhancement of the film growth rate and the film-induced stress [7]. Film-induced stress and the residual stress in films deposited by electrolysis are important in the corrosion research and the electrolysis industry[8]. Even in the macroscopic compressive stress zone, film-induced stress at the crack tip can lead to the initiation and propagation of SCC[9-11]. Stress intensity factor, which reflects the stress field near the crack tip, is an important parameter to characterize the driving force and crack growth rate.

In order to understand the effects of stress intensity factor on the stress-strain field of the crack tip induced by the oxide film of the material for nuclear power plants, the stress-strain fields in the SCC crack tip of nickel-based alloys were analyzed by the sub model technology of ABAQUS. The effects of film-induced stress intensity factor on the stress and strain field of the crack tip of nickel-based alloys SCC were obtained.

1 Theory Model

The oxide film at crack tip in the pressurized water reactor was obtained by SEM[12], as shown in Fig. 1.

The area of crack tip is the oxide film formed on the

Received date: August 25, 2016
Foundation item: National Natural Science Foundation of China (51475362, 11502195); Scientific Research Program Funded by Shaanxi Provincial Education Department (16JK1493)
Corresponding author: Xue He, Ph. D., Professor, Xi'an University of Science and Technology, Xi'an 710054, P. R. China, Tel: 0086-29-83856250, E-mail: xue_he@hotmail.com

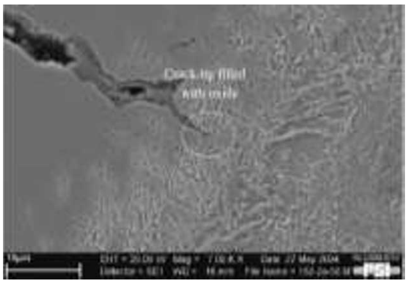

Fig.1 Morphology of oxide film at crack tip

surface of the structural material in the process of corrosion cracking. Fracture mechanism of film-induced stress in stress corrosion cracking can be shown as: Without considering the external load, there is an additional tensile stress at one side of the interface matrix [5]. It makes the local plastic deformation at crack tip, and the stress can cause the dislocation emission, which can cause the oxide film intergranular cracks, then leading to the occurrence and extension of stress corrosion cracking. Thus it can form deep matrix crack, and stress corrosion cracking can be produced [9-11].

Therefore, film-induced stress plays an important part in the crack growth driving force. Mechanical factor is one of the three factors that affect the crack growth (mechanics, materials, environment). The concept of stress and strain field at crack tip was proposed by Japanese expert Shoji, and the theoretical calculation formula of strain rate at crack tip was proposed according to the crack tip strain gradient theory and the strain redistribution in the crack growth [13].

$$\frac{\mathrm{d}\varepsilon_{\mathrm{ct}}}{\mathrm{d}t}=\left(\frac{\mathrm{d}\varepsilon_{\mathrm{ct}}}{\mathrm{d}a}\right)\cdot\left(\frac{\mathrm{d}a}{\mathrm{d}t}\right) \tag{1}$$

$$\left(\frac{\mathrm{d}\varepsilon_{\mathrm{ct}}}{\mathrm{d}a}\right)=\frac{\partial\varepsilon_{\mathrm{ct}}}{\partial a}-\frac{\partial\varepsilon_{\mathrm{ct}}}{\partial r} \tag{2}$$

$$\varepsilon_{\mathrm{ct}}=\beta\cdot\left(\frac{\sigma_{\mathrm{y}}}{E_0}\right)\cdot\left[\ln\left(\frac{R_{\mathrm{P}}}{r_0}\right)\right]^{1/(n-1)} \tag{3}$$

where, β is constant, σ_{y} is the yield strength of the material, E_0 is Young's modulus of the material, r_0 is distance from the crack tip to the front of the crack tip, K is stress intensity factor, n is the hardening exponent for the plastic, R_{p} is plastic zone size; $R_{\mathrm{p}}=\lambda(K/\sigma_{\mathrm{y}})^2$, λ is constraint factor.

Due to the change of r_0 and K in the process of crack propagation, the change of strain at crack tip can be induced. Therefore, the strain rate at crack tip is modified as follows:

$$\frac{\mathrm{d}\varepsilon_{\mathrm{ct}}}{\mathrm{d}t}=\beta\cdot\frac{\sigma_{\mathrm{y}}}{E_0}\cdot\frac{n}{n-1}\cdot\left(2\frac{\dot{K}}{K}+\frac{\dot{a}}{r_0}\right)\cdot\left[\ln\left(\frac{R_{\mathrm{P}}}{r_0}\right)\right]^{1/(n-1)} \tag{4}$$

The crack growth rate of EAC can be expressed as Eq. (5) by adopting to crack tip strain rate calculation Eq. (4).

$$\begin{cases}\dfrac{\mathrm{d}a}{\mathrm{d}t}=k_{\mathrm{a}}\cdot\left\{\beta\cdot\dfrac{\sigma_{\mathrm{y}}}{E_0}\cdot\dfrac{n}{n-1}\cdot\left(2\dfrac{\dot{K}}{K}+\dfrac{\dot{a}}{r_0}\right)\cdot\left[\ln\left(\dfrac{R_{\mathrm{P}}}{r_0}\right)\right]^{1/(n-1)}\right\}^m\\ k_{\mathrm{a}}=\dfrac{M}{Z\rho F}\cdot\dfrac{i_0}{1-m}\cdot\left(\dfrac{t_0}{\varepsilon_{\mathrm{f}}}\right)^m\end{cases} \tag{5}$$

Eq.(5) is the FRI model which combines together mechanics factors, electrochemical environment parameters and material parameters together. This model is based on slip dissolution theory. The crack growth rate of nickel-based alloys in high temperature water environment is quantitatively predicted, and the stress intensity factor K is an important parameter to characterize the fracture of the material.

The stress intensity factor K can be divided into external load stress intensity factor K_{a} and film-induced stress intensity factor K_{f}:

$$K=K_{\mathrm{a}}+K_{\mathrm{f}} \tag{6}$$

when $K_{\mathrm{a}}+K_{\mathrm{f}}=K_{\mathrm{IC}}$, the SCC is to nucleating and extending. Under constant load stress corrosion, the film-induced stress is increased, the effective stress of the crack is also increasing, and the plastic strain is developed, and the critical condition causes the nucleation and expansion of the micro crack, which leads to the stress corrosion cracking.

It is usually considered the external load, while ignoring the film-induced stress using of Shoji's equation to predict the crack growth rate. Although K_{f} is relatively less, it is not negligible in short cracks. According to Eq.(6), K is easier to reach K_{IC} because of the existence of K_{f}, and the SCC is easier to nucleate and crack.

It can be assumed that the stress intensity factor of rack tip remains unchanged, because the film-induced stress change is relatively small, and the FRI model Eq.(5) can be simplified as Eq. (7). The K increases with the increasing of K_{f}, and the crack growth rate increases according to Eq.(7).

$$\frac{\mathrm{d}a}{\mathrm{d}t}=k_{\mathrm{a}}^{1/(1-m)}\cdot\left[\frac{\beta\sigma_y n}{E(n-1)}\cdot\frac{1}{r_0}\cdot\left[\ln\left[\frac{\lambda}{r_0}\cdot\left(\frac{K}{\sigma_y}\right)^2\right]\right]^{1/(n-1)}\right]^{m/(1-m)} \tag{7}$$

In the small plastic zone of crack tip, the film-induced stress is more obvious in short crack, the greater the K_{f}, the easier the crack growth, and the main effect is K_{a} in the long crack. If the crack is long enough, K_{f} can be ignored. Therefore, K_{f} is more suitable for short crack propagation.

2 Finite Element Modeling

2.1 Specimen model

Half inch compact tension specimen (0.5T-CT) was used in this numerical calculation with virtual experiment process according to American Society for Testing and Materials Standard[14]. The geometric shape and size of 0.5T-CT specimen are shown in Fig.2.