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ARTICLE

Effects of Stress Intensity Factor on Electrochemical Corrosion Potential at Crack Tip of Nickel-Based Alloys in High Temperature Water Environments

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Abstract: Stress will enhance the local anodic dissolution rate of nickel-based alloys at crack tip and accelerate the crack propagation in high temperature water environments. The relationship between stress and corrosion was studied by the elastic plastic finite element method. The effects of stress intensity factor on the surface electrochemical corrosion potential (ECP) at the crack tip of alloys 600 with a 1T-CT specimen in simulated boiling water reactor environment were analyzed. The effects of plastic deformation and elastic deformation on the changes of the electro-chemical corrosion potential around the crack tip were also discussed. The results indicate that the effects of stress intensity factors on ECP changes of the crack tip surface have the maximum values in the front of the crock propagation, and they decrease gradually towards the sides of the crack. The values of ECP changes increase with the increase of stress intensity factor. The effect of plastic deformation is more obvious than that of elastic deformation.

Key words: stress intensity factor; electrochemical corrosion potential (ECP); crack tip; finite element method; high temperature water

Stress corrosion cracking (SCC) is the degradation of materials under combined actions of load, material and corrosive medium, neither of which alone would cause the failure[1]. Nickel-based alloys are widely used in the critical components and the structures in nuclear power plants, these alloys are susceptible to SCC in many environments, especially in chloride environments. Many SCC failures of components, made of nickel-based alloys, have been reported during the storage or service in nuclear power plants. Since the failures caused by SCC, which could occur without any significance and warning, would lead to cost breakdowns of the operating system[2], many researches have been carried out to explore the SCC mechanisms and predictive models[3-7].

It was found that the stress would enhance the local anodic dissolution of alloys at crack tip and accelerate the crack propagation[8-10], the crack propagation rate increases with the increasing of stress intensity factor, and the crack growth rate predictive models considering the stress intensity factor were carried out. Further researches found that the applied stress will change the chemical potential of metal surface and affect the electrochemical corrosion potential (ECP) of metals[11,12]. Since SCC occurs only in specific potential range, its change caused by different stress may affect the crack propagation rate significantly in high temperature water environments. In this paper, the ECP value changes around crack tip of alloy 600 affected by stress intensity were investigated with the finite element method.

1 Theory Model

1.1 Effect of mechanochemical on elastically deformed metals

In the system with positive ions, the mechanochemical activity of metals is related to external pressure, so the change of equilibrium electrical potential, which equals to the change of standard electrical potential, is affected by external excess pressure. It is defined as Eq.(1) [11]:

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$$\Delta \varphi_{\mathrm{E}} = -\frac{\Delta P V_{\mathrm{m}}}{zF} \tag{1}$$

where $\Delta\varphi_{\mathrm{E}}$ is the change of equilibrium electrical potential caused by elastic deformation; ΔP is external excess pressure experienced by the metal, and it will be denoted with the absolute value of the hydrostatic part of stress tensor, and equals to hydrostatic pressure in Abaqus calculations; V_{m} is the mole volume of metal; z is ion valence and F is Faraday's number.

1.2 Phenomena of mechanochemical in metal plastic deformation

The additional chemical potential of atoms caused by dislocation in plastic metals will change the standard potential of metals [11] and expressed as Eq (2):

$$\Delta \varphi_{\mathrm{P}} = -\frac{RT}{zF} \ln \frac{\varepsilon}{\varepsilon_0} \tag{2}$$

where $\Delta\varphi_{\mathrm{P}}$ is the change of equilibrium electrical potential caused by plastic deformation; R is gas constant; T is absolute temperature; ε is the strain of material, and will be instead by equivalent plastic strain in Abaqus calculation; ε_0 corresponds to the onset of strain hardening.

The local change of standard potential caused by plastic strain calculated via Eq. (2) is without the account of applied macroscopic stresses. In case of simultaneous plastic deformation, the overall value of mechanochemical effect is defined by the standard potential shift which represents a sum of Eq. (1) and Eq. (2), expressed as Eq.(3):

$$\begin{aligned} \Delta \varphi &= \Delta \varphi_{\mathrm{E}} + \Delta \varphi_{\mathrm{P}} \\ &= -\frac{1}{zF}\left[\Delta P V_{\mathrm{m}} + RT \ln \frac{\varepsilon}{\varepsilon_0}\right] \end{aligned} \tag{3}$$

1.3 Distinguishing of elastic zone and plastic zone

It is known that a plastic zone exists at the crack tip, and the elastic deformation and plastic deformation have different effects on equilibrium potential, so it is necessary to distinguish the elastic zone and the plastic zone of crack tip. The Irwin's approximation is reasonable for solving practical engineering problems, so the Irwin's approximation corrected by power-lawer materials was introduced to calculate the plastic zone size[13], and expressed as Eq.(4):

$$r = \frac{1}{2\sqrt{2}\pi} \frac{m-1}{m+1} \left[\frac{K_{\mathrm{I}}}{\sigma_0}\right]^2 \tag{4}$$

where r is the plastic zone size at crack tip; m is hardening exponent; K_{I} is stress intensity factor at crack tip; σ_0 is the yield stress of material.

The Eq.(3) will be used in plastic zone, and Eq.(1) will be used to calculate the ECP change in elastic zone in contrary.

2 FEM Simulations

2.1 Material and specimen model

One inch compact tension (1T-CT) was used in this numerical simulation calculation with the virtual experiment process according to the American Society for Testing and Materials (ASME) Standard E399[14], and the geometric shape and the size of 1T-CT specimen are shown in Fig.1.

The Ramberg-Osgood equation is used to describe the nonlinear relationship between stress and strain in this simulation. Ramberg-Osgood equation is written as Eq.(5)[15]:

$$\varepsilon = \frac{\sigma}{E} + \alpha \frac{\sigma_0}{E} \left[\frac{\sigma}{\sigma_0}\right]^m \tag{5}$$

where ε is strain, σ is stress, E is Young's modulus of the material, σ_0 is the yield strength of the material, α is the yield offset and m is the hardening exponent for the plastic, the hardening behavior of the material depends on the material constants α and m.

According to the slip-dissolution model, a crack growth occurs by extremely localized anodic dissolution. The sides of the crack are protected by the film, and the crack growth proceeds by a cyclic process of the film rupture, the dissolution, and the film repair of the crack tip[3]. To investigate the effect of stress intensity factor on the crack tip surface electrochemical corrosion potential, the cracks with a completely dissolved film at crack advance and a complete film at sides of crack were adopted in this simulation. The alloy 600 at high temperature (288 °C) was used as base metal, the film at sides of crack was simplified as Cr_2O_3 considering that only a thin chromium oxide layer is continuous of the triple layer formed at alloy 600 surface in PWR primary water[16]. The mechanical properties of alloy 600 and film are given in Table 1, and other parameters used in simulation are listed in Table 2.

2.2 Load condition

The hoop stress σ_θ and radial stress σ_{m} for thin-walled cylinder subject to internal pressure are shown in Eq. (6) and Eq. (7).

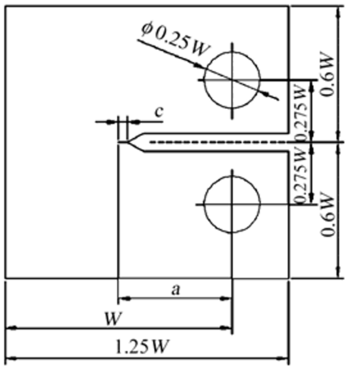

Fig.1 Geometric size of 1T-CT specimen (W=50 mm, a=0.5W, c=1.5 mm)