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ARTICLE

Micro-mechanical State at Tip of Environmentally Assisted Cracking in Nickel-based Alloy

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Abstract: Nickel-based alloys and austenitic stainless steels are widely used in the structures of primary circuit of nuclear power plants. Environmentally assisted cracking (EAC) of these materials is one of the most significant potential safety hazards in the primary circuit of nuclear power plants. Researches show that EAC in nickel-based alloy is a process of oxide film rupture and reform at the tip of EAC in the high temperature water environment of nuclear power plants. To understand the micro-mechanical state at the tip of EAC, the stress-strain in the oxide film and the base metal at the EAC tip was simulated and discussed using a commercial finite element analysis code, which provides a foundation 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.

Key words: nickel-based alloy; environmentally assisted cracking; oxide film; groove-type crack; finite element method (FEM)

With a good corrosion resistance and mechanical property in high temperature water environment, nickel-based alloys and austenitic stainless steels are widely used in the structures of primary circuit in nuclear power plants. But environmentally assisted cracking (EAC) of nickel-based alloys and austenitic stainless steels is an important issue in the safety operation of nuclear power plants [1,2].

To understand the mechanism of EAC, the morphology at the EAC tip was investigated by transmission electron microscopy (TEM) in detail, which indicated that a dense oxide film is covered on the crack surface because of the electrochemical reaction at the EAC tip [3-6]. The further researches also showed that the oxide film at the EAC tip was a dense ceramic material Cr_2O_3 [7,8]. The EAC growing in nickel-based alloys and austenitic stainless steels in high temperature water environment is a process of oxide film forming, rupture and reform at the EAC tip[9].

While quantitative estimating of EAC growth rate in structure materials in the primary circuit of nuclear power plants is an important job, but it is also quite difficult to improve the estimated accuracy of the EAC growth rate in nickel-based alloys and austenitic stainless steels because of the complexity at the EAC tip. Therefore, experiments are still a general investigating approach in the EAC research field. However, it is a great challenge to predict the EAC growth rate of nickel-based alloys and austenitic stainless steels accurately in high temperature water environment of nuclear power plants due to expensive equipments, low experimental accuracy and long period[10-13].

Researches on the theory and numerical simulation could effectively improve the prediction accuracy of the EAC growth rate and assist to analyze experiment data. The oxide film rupture theory at the EAC tip is widely adopted in the safety research field of nuclear power plants[14,15]. Based on this theory, the micro-mechanical state at the EAC tip and its effect on the EAC growth rate in nickel-based alloys were analyzed and discussed in the present paper.

1 Theoretical Basis

The oxide film rupture theory considers that the EAC process in nickel-based alloys and austenitic stainless steels in high temperature water environment can be divided into three

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periods: I-oxide film forming at the crack tip, II-oxide film aging and rupture at the crack tip with a high stress and strain, and III-anode metal separating at the crack tip[9,16], which is shown in Fig.1.

Because the aging and rupture of the oxide film takes most of the time in EAC period, according to the Faraday's law, Ford and Andresen in GE deduced a formula to estimate the EAC growth rate of nickel-based alloys and austenitic stainless steels in high temperature water environment of nuclear power plants[9,17]:

$$\frac{da}{dt}=\frac{M}{z\rho F}\cdot\frac{i_0}{1-m}\cdot\left(\frac{t_0}{\varepsilon_f}\right)^m\cdot\left(\frac{d\varepsilon_{ct}}{dt}\right)^m \quad (1)$$

where, da/dt is the EAC growth rate, M and ρ are the atomic mass and the density of metals, respectively, F is Faraday's constant, i_0 is the bare surface oxidation current density, z is the change in charge due to the oxidation process, m is the exponent in the current decay curve, ε_f is the degradation strain of the oxide film, t_0 is the time before onset of the current decay, and $d\varepsilon_{ct}/dt$ is the strain rate at the EAC tip.

Eq.(1) is the most widely used in prediction equation of the EAC growth rate in nickel-based alloys and austenitic stainless steels in high temperature water environment of nuclear power plants. To investigate the effect of the mechanical state on the EAC growth rate, a geometric model is sketched, as shown in Fig.2.

In Fig.2, the effect of the micro-mechanical state at the crack tip on EAC growth process can be illustrated as: Fig.2a denotes the surface oxide film forming at the crack tip of nickel-based alloys and austenitic stainless steels, which is corresponding to period I in Fig.1; Fig.2b denotes a groove-type crack extends into the base metal and the surface oxide film aging and rupture at the crack tip because of an anodic electrochemical reaction at the crack tip, which is corresponding to period II in Fig.1; Fig.2c denotes the oxide film reform as the actual crack tip propagates, which is corresponding to periods III and I in Fig.1. This cycle occurs again and again, which leads to the damage of structures in nuclear power plants. Thus, the simulation and the study on micro-mechanical state of oxide film before and after rupture are important.

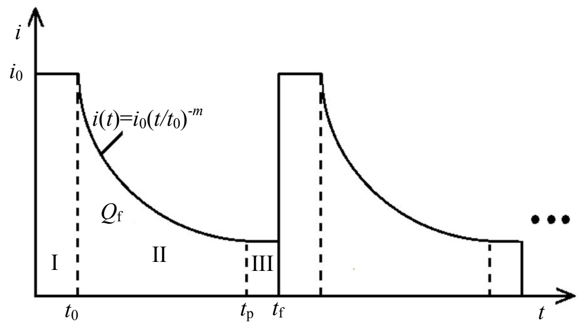

Fig.1 Schematic illustration of the oxidation current density transients at the crack tip

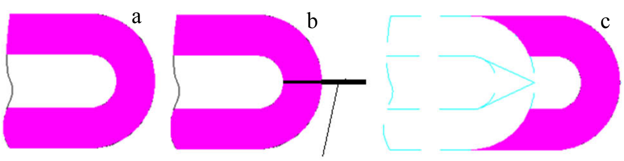

Fig.2 Sketch diagram of oxide film rupture and reform process: (a) oxide film form, (b) groove-type crack form and oxide film rupture, and (c) oxide film reform

2 Finite Element Model

2.1 Material model

Ramberg-Osgood equation was used in the present simulation as the material mechanical relation for the nickel-based alloy at the EAC tip, which is written as follows:

$$\frac{\varepsilon}{\varepsilon_0}=\frac{\sigma}{\sigma_0}+\alpha\left(\frac{\sigma}{\sigma_0}\right)^n \quad (2)$$

where σ is the stress, σ_0 is the yield strength of the material, ε is the strain, ε_0 is the yield strain of the material, α is the dimensionless material constant, and n is the strain hardening exponent of the material.

The material mechanical parameters of nickel-based alloy 600 are adopted as: σ_0=436 MPa, α=1, n=5.29 and E is Young's modulus of the material and E=190 GPa. The oxide film is a dense elastic material, whose mechanical parameters are set as E=19 GPa, Poisson's ratio υ=0.3, respectively[1].

2.2 Geometry model and mesh

One inch compact tension (1T-CT) specimen was used in the present numerical calculation with the numerical experiment process according to the American Society for Testing and Materials Standard (ASTME399-90). The geometric shape and size of 1T-CT specimen are shown in Fig.3a. Constant concentrated loads were applied on the up and down pin holes, which kept the stress intensity factor K_I of 20 MPa·m$^{1/2}$.

The thickness of the oxide film at the EAC tip was assumed to be 2 μm in the present simulation[18,19]. The groove-type crack length was assumed as 1, 2 and 3 μm[10]. Three preset lines in the oxide film were used as the observation paths at the EAC tip, which are shown in Fig.3b. Where, path 1 is nearby the base metal, path 2 is nearby the oxide film surface and path 3 is along the cracking direction.

15421 CPE8 (8-node biquadratic plane strain quadrilateral) elements were adopted in the model. Because the stress concentration appeared nearby the boundary between the base metal and oxide film at the crack tip, the refined mesh was used in the crack tip region, which is shown in Fig.3c.

3 Results and Discussion

3.1 Stress and strain at the crack tip

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