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ARTICLE

Anomalous Mechanical Behavior in Stationary Small Crack Tips about EAC for Nickel-Base Alloy

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Abstract: The crack tip mechanical characteristic and crack propagation rates are influenced by crack length, but the current research of environmentally assisted cracking (EAC) focuses on long crack, and small crack is usually ignored. The mechanical characteristics of small crack tips for single-edge crack panel specimens during the EAC in high temperature water were studied. The specimens were made of nickel-base alloy and the finite element method (FEM) was adopted. The results show that the stress and the strain are much higher for small crack compared to long crack, and this leads to a higher crack propagation tendency of small crack. A corrected method has been introduced to calculate the plastic zone size of small crack. The Irwin correction method can improve the accuracy of J integral of long crack, but errors still exist for small crack. So the numerical method with elastic plastic fracture method has been recommended to calculated J integral for small crack under larger load condition considering the lack of mature theoretical guidance about the small crack. The crack propagation process of the EAC of structure materials serviced in nuclear power plants is suggested to divide into small crack propagation and long crack propagation owing to their anomalous mechanical behaviors.

Key words: environmentally assisted cracking (EAC); small crack; stress; strain; J integral

It is well known that the environment, the material, and the mechanics near to the crack tip are the most important factors affecting the growth rate of the environmentally assisted cracking (EAC) crack in high-temperature aqueous environments[1]. Since Person found small-crack effect in studying the aluminum alloy crack growth behavior[2] in 1975, he pointed out that the service life of components, especially for high strength alloy materials, was mainly controlled by the initiation and the propagation behavior of small fatigue cracks with the scale usually identified from 0.1 to 1 mm[3,4] in engineering. This means that the effective life of components takes most of the service life that is small crack period[5]. The mechanical behavior of short crack is obviously discriminated with long crack, which can't be explained by the traditional theories[6]. Therefore, many researches have been performed to understand the so-called anomalous behavior of the small fatigue cracks.

The pressure vessels of nuclear reactor are usually designed based on the norms of boilers and pressure vessels of ASME, which is defined by linear elastic fracture mechanics (LEFM)[7]. However, the fracture failure of components has large plastic deformation when the service temperature of components is far above the brittle-ductile transition temperature in most cases. This is because the components serve in a corrosive environment, and the failure of components exhibits an EAC behavior[8], which is the interaction among tensile stress, corrosive environment and susceptible material, such as the EAC failure of pipes made of nickel base alloy used in light water reactor environments. The continuum assumption and linearly elastic hypothesis are not valid upon calculating the stress and strain field nearby the small crack tip of EAC, so it will be a great security risk if the stress intensity factor (K_I) is associated with small crack propagation. However, it is

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difficult to obtain sufficient experimental data because of the slow propagation rate of EAC, and a lack of mature theoretical guidance about the small crack, the stress and strain field nearby small crack tip of EAC condition is almost completely ignored in practice[9,10].

In the present paper, the results of a detailed elastic plastic fracture mechanics (EPFM) of the stress and strain field nearby small crack under EAC condition of nickel-base alloy were reported. It is necessary to use the local stress, plastic strain and plastic zone in the stationary crack tips upon quantitative predicting the crack propagation rate and remained life of components, and the stress and plastic strain nearby small crack tip were also discussed under constant K_I and changed K_I.

1 Specimen and Calculation Model

The single-edge crack panel model was adopted during the change of the crack length in the simulated experiments, which was expected to represent the crack tip stress and strain conditions in the entire EAC experimental process. The geometric shape and size of the panel are shown in Fig.1a.

As the crack front along the thickness of a specimen is mainly dominated by the plane strain condition in EAC experiments, the specimen could be simplified as a plane strain model[11]. The finite element mesh of the model is shown in Fig.1b, where the biquadrate plane strain quadrilateral elements were adopted in the whole model, and the mesh of the crack tip region was refined in order to obtain more detailed crack tip stress-strain data. Here X-axis is the opposite direction of the crack growth, and Y-axis is the normal direction of the crack growth in the coordinate system.

The alloy 600, widely used as structural materials in nuclear power plants, was adopted in this numerical simulation. The mechanical properties of the alloy are shown in Table 1. The stress-strain relation beyond yielding is represented as the Ramberg-Osgood equation at the loading stage, and the stress (σ)-strain (ε) relation is simply regarded as a linear elastic relation at the unloading stage in this simulation. The Ramberg-Osgood equation is written as Eq.(1)[12]

Table 1 Properties of alloy 600 in PWR primary water at 340 °C[12]

Properties	Value
Yield strength, σ_0/MPa	436
Yield offset, α	3.075
Hardening exponent, n	6.495
Young's modulus, E/GPa	189.5
Poisson's ratio, v	0.286

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n \tag{1}$$

where σ_0 is the yield strength of the material, ε_0 is the yield strain, α is the yield offset and n is the strain hardening exponent of the material. The stress-strain curve of alloy 600 calculated by Eq.(1) are shown in Fig.2.

The diameter and the wall thickness of RVP (reactor vessel plant) used in pressurized water reactor (PWR) were 4400 and 225 mm, respectively. The hoop stress and radial stress were 147 and 73.5 MPa when the internal pressure was equal to 15 MPa under service condition, and the range of stress intensity factor calculated were from 5 to 10 MPa·m$^{1/2}$. Thus the stress intensity factor K_I with 10 MPa·m$^{1/2}$ was adopted to study the stresses and plastic strains nearby a stationary crack tip[13], and the effects of K_I on the stress and strain distribution nearby crack tip was studied with K_I changing from5 to 10 MPa·m$^{1/2}$.

2 Results and Discussion

2.1 Stress and strain distribution nearby small crack tip

The distribution of the tensile stress (σ_{22}) and equivalent plastic strain (ε_p) in front of a stationary crack tip are shown in Fig.3. It can be seen from Fig.3a that σ_{22} declines with the increase of the distance away from the crack tip at a constant crack length, but the change gradient decreases.

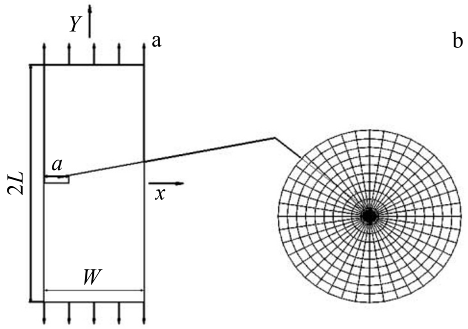

Fig.1 Single-edge crack panel model (L=25 mm, W=20 mm): (a) unilaterally cracked specimens and (b) FEM of the crack tip

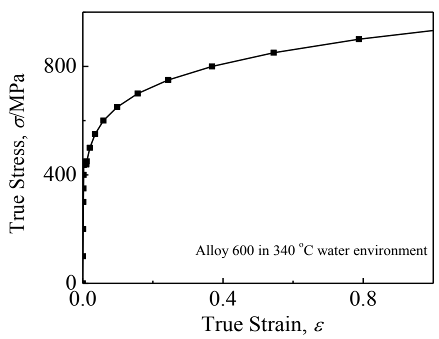

Fig.2 Stress-strain relationship of alloy 600