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Prediction Model of EAC Growth Rate of Nickel-based Alloy under Low Temperature and High Stress

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One of the recognized quantitative calculation models of crack growth rate is the Ford and Andresen model for predicting the crack growth rate of environmentally assisted cracking (EAC) based on oxide film rupture theory. In the Ford–Andresen model, the crack tip strain rate is the core mechanical parameter needed to obtain the quantitative calculation of crack growth rate, but obtaining an accurate calculation is difficult. To obtain a more simplified quantitative model of environmental crack growth rate, the nickel-based alloy 600, a nickel-based alloy commonly used in structural material for nuclear power, was used as the research object, and its mechanical properties, low-temperature/high-stress creep curve, and creep rate were obtained in experiments. Based on the creep characteristics of alloy 600 under low temperature and high stress, a quantitative calculation of its creep rate was obtained. The creep rate can be used to replace the strain rate at the crack tip in the EAC growth rate prediction model, and a quantitative prediction model for the crack growth rate based on using the creep rate at the crack tip as the mechanical parameter can then be established, which simplifies the crack growth rate prediction model based on using the crack tip strain rate as a mechanical parameter. The relationship between stress and the stress intensity factor at the crack tip obtained by finite element simulation, as well as a quantitative calculation model of creep rate, is established, which is characterized by the stress intensity factor of the crack tip. Moreover, experiments establish a quantitative calculation model of creep rate characterized by stress at the crack tip so that different quantitative prediction models of crack growth rate characterized by crack tip creep rate can be established. Then the effect of the mechanical parameters, creep parameters, and electrochemical parameters of alloy 600 on the prediction model is analyzed, providing a basis for the application of the prediction model.

INTRODUCTION

The commonly used materials in nuclear power pipelines and pressure vessels are nickel-based alloys and stainless steel, and environmentally assisted cracking (EAC) induced by stress corrosion cracking (SCC) often occurs during service (Ke et al., 2010; Du et al., 2020). Structural materials of nuclear power primary water circuit must work in an environment with temperatures of 288°C–320°C and 16 MPa of pressure for a long time; the crack tip especially must withstand higher stress. Notably, these features are consistent with the characteristics of metal creep. However, the creep of metal occurs in a high-temperature environment, above 0.5 times of metal melting point especially, and the diffusion process of thermodynamics has an exponential relationship with temperature. In key structural materials such as nuclear power pressure vessels, the working temperature is relatively low, significantly lower than the temperature at which the material occurs significant creep. However, experimental studies in nuclear power primary water circuits show that not only does creep occur in nickel-based alloys but is also closely related to the SCC of the metal (Gras, 1992; Angeliu et al., 1995). The research results of Hua and Rebak (2008) show that microcavities on the surface of the intergranular fracture of environmentally assisted cracking have the morphological characteristics of creep, and the creep rate is basically the same as the SCC expansion rate. The factors that increase SCC, such as small grain size, high carbide precipitation at grain boundaries, and cold working, will also accelerate creep. Both SCC and diffusion creep in nuclear power primary water circuits are thermally activated processes, and the activation energies of intergranular fracture and creep are basically the same. Both creep and SCC in a primary water circuit are hindered by impurity segregation at the grain boundary.

Although experimental studies have shown that the SCC crack growth rate is numerically greater than the creep rate, there is a relationship between creep and SCC, and SCC is affected by creep. Therefore, people try to establish the relationship between strain rate, creep rate, and intergranular fracture behavior in intergranular fractures. The creep failure mechanism proposed by Angeliu et al. (1995) suggests that intergranular fracture is caused by the formation and expansion of intergranular voids caused by creep and also points out that water is not a necessary condition for grain boundary fracture, but water can increase the crack growth rate by increasing the dislocation movement at the grain boundary. In the model proposed by Vaillant et al. (1999), the

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