Effects of Temperature Variation on Mechanics Field at Crack Tip of Stress Corrosion Cracking

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Abstract. Creep strain near crack front zone is one of the main driving forces in nuclear structural materials of stress corrosion crack propagation. To understand the effect of temperature variation on mechanical field near crack tip of nuclear structure material in high temperature water environment, compact tensile specimen was taken as an research object and ABAQUS finite element analysis software was also adopted, the Mise stress, plastic strain and creep strain near SCC crack tip region was studied. Results show that the area of the high-stress region decreases gradually with the increasing of the creep temperature, and its declining rate was faster and faster. The effect of temperature variation on the plastic strain is not very obvious. Temperature only has an obvious effect on a small scale near crack tip. With the increase of the distance from the crack tip, the effect of temperature on creep is gradually reduced.

1. Introduction
Stress corrosion cracking (SCC) is a failure mechanism that is caused by environment, susceptible material and tensile strain of nuclear power structural materials under high temperature and high pressure aqueous environments [1-3]. During the process of stress corrosion cracking, creep occurs at high stress area near crack tip of the structural material in the high temperature water environment, which can also induced the rupture of oxide film[4], so it is becoming very important to study the creep phenomenon of nuclear welding materials under high stress conditions. MAO Xueping conducted a high-temperature creep test on the nickel-based alloy C276 as a fuel cladding material, and creep process were studied under different temperatures and stresses [5]. An Junchao studied the creep crack propagation characteristics of P92 steel, and found that the creep crack growth rate in HAZ of welded joint is larger than the creep crack growth rate of base metal [6]. Han Ningning studied the creep behaviour of A508 steel at 450-600 °C, and creep constitutive equation was obtained[7].

Since stress and strain field near crack tip can greatly influence the crack growth, it is necessary to study the influence of temperature variation on crack tip creep stress and strain field in detail. The finite element model was established in this paper, and stress and strain field are analyzed. Research result provides a theoretical basis for predicting the stress corrosion cracking rate of nuclear structural materials in high temperature water environment [8].

2. Finite element modeling
2.1 Specimen model and mesh model
The standard compact tensile test specimens (1T-CT) was adopted in ABAQUS in the paper, the specimen geometry and experimental process was conducted in accordance with ASTM399 standard [9], which was shown in Figure 1, the value of specimen width $W=50$ mm, value of the crack length $a = 0.5W$, and the value of $B/W$ is 0.25. To eliminate the stress singularity caused by the crack tip [10], the blunt circle radius at crack tip is taken as 0.5$\mu$m in numerical simulation. Due to the symmetry of the specimen, half model is adopted, as shown in Figure 2. To improve the analytical precision at the crack tip, the sub-model technique was employed to calculate distribution of the creep mechanical field at crack tip. The 8-node biquadratic plane strain element is adopted in ABAQUS finite element analysis, with a total number of the global number is 24525, as shown in Figure 2. The element type of the sub-model is consistent with whole model, and the minimum size of the element is about 0.5$\mu$m, which is shown in Figure 2.

![Figure 1. The geometry of the compact tensile specimen and the schematic view of the crack tip](image)

![Figure 2. Finite element mesh model of 1T-CT](image)

2.2 Material model
The austenitic stainless steel A508 is a power-hardened material whose constitutive relationship is usually characterized by Ramberg-Osgood relationship [11], and its Common calculation formula form is as follows:

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

(1)
Where $\varepsilon$ is the strain, including elastic and plastic strain. $\sigma$ is the total stress; $\varepsilon_0$ is the yield strain of the material, $\sigma_0$ is the yield stress of the material and its value is 522MPa, and $n$ is the strain hardening exponent of the material and its value is 7.04, $\alpha$ is the offset coefficient of the material and its value is 1.

The creep rate is calculated using the power law model [7] in the FEM calculation:

$$\dot{\varepsilon}_{cr} = A\sigma^n t^m$$

where $\dot{\varepsilon}_{cr}$ is the creep strain rate, $\sigma$ is the applied stress; $A$ is the power law multiplier.

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To understand the effect of creep temperature variation on the stress and creep strain near crack tip, the value of temperature $T$ is 450°C, 500°C, 550°C, respectively. The creep mechanical properties of the material under different temperature is given in Table 1.

| Material | $T/°C$ | $A$  | $n$  | $m$  |
|----------|--------|------|------|------|
| A508     | 450    | 2.81e-6 | 1.47771 | 0.29161 |
|          | 500    | 2.84e-5 | 1.17955 | 0.32799 |
|          | 550    | 7.68e-5 | 1.2052  | 0.42591 |

2.3. Loading and boundary conditions

Loading is applied to the load hole by using the multiple point constraints facility in ABAQUS, which joins the hole centre to the nodes of the hole surface. The concentrated force is applied on the reference point so as to ensure the crack tip stress intensity factor $K_i=8\text{ MPa}\cdot\text{m}^{1/2}$.

Two analysis steps were set up in the analysis process, the first is the process of loading on the specimen, making the sample occur elastic plastic deformation; the second stage is keeping the load constant, set the creep equivalent time 5000h.

3. Results and Discussion

3.1. Effect of creep temperature on Mises stress at SCC crack tip zone

Figure 3. Comparison of Mises stress distribution after creep at different temperatures (MPa)

Mises stress distribution around crack front under different temperatures near crack tip region is shown in Figure 3. Figure 3 shows that the area of the high-stress region increases gradually with the increasing of the creep temperature, this is mainly due to the effect of creep. It can be seen that the different creep temperatures have a great influence on the Mises stress distribution around the crack tip. The higher the creep temperature is, the greater the stress decrease gradient in the crack tip area, and the creep phenomenon becomes more obvious at this moment.
3.2 Effect of Creep Temperature on PEEQ at SCC crack tip zone

Figure 4. Comparison of PEEQ distribution after creep at different temperatures

Figure 4 shows the variation of equivalent equivalent plastic strain PEEQ near crack tip region, which shows that the value of equivalent equivalent plastic strain PEEQ near the crack tip region also increases with the increasing temperature under the same equivalent plastic strain scale range. It can be concluded that the change of temperature change the distribution of crack tip equivalent PEEQ after creep, and temperature also has great effect on the crack tip equivalent plastic strain.

3.3 Effect of Creep Temperature on CEEQ at SCC crack tip zone

Figure 5. Comparison of CEEQ distribution after creep at different temperatures

Figure 5 shows the change of the equivalent equivalent creep strain CEEQ near the crack tip region under different temperatures. It can be seen that the value of equivalent creep strain CEEQ decreases with the increasing distance from the crack tip. Comparison with the cloud distribution of different temperature, equivalent creep strain is mainly concentrated in the crack tip region, and the value of CEEQ decreases with increasing distance ahead of the crack tip. When the distance from the crack tip increases, the effect of temperature on creep gradually weakens, and the variation of equivalent equivalent plastic strain CEEQ is not obvious when the distance is larger ahead from crack tip.

4. Conclusions
(1) The area of high stress zone increases with the increasing of creep temperature, and the rate of descent is faster and faster than previous, that is, the higher the temperature is, the more obvious the creep phenomenon is, Sharp angle change and change.
(2) Temperature has also great effect on the PEEQ distribution of the equivalent plastic strain at the crack tip. The value of PEEQ near the crack tip region also increases with the increasing temperature.
(3) Equivalent creep strain is mainly concentrated in the crack tip region, and the value of CEEQ decreases with increasing distance ahead of the crack tip.

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