Influence of Yield Stress Mismatch on the Creep Stress Field around Crack Tip of Stress Corrosion Cracking

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Abstract. To understand the influence of yield stress mismatch on the creep stress field around crack tip in safe-end dissimilar metal welded joints at primary circuit, the influences of different mismatch coefficients on the creep stress field around the crack front were analyzed using ABAQUS software. Results show that the Mises stress distribution is not very different after the creep under different mismatch coefficients. The equivalent plastic strain (PEEQ) in the Nickel based 182 near crack tip is basically remain unchanged and the PEEQ of HAZ is decreasing with the increasing of the mismatch coefficient. The creep strain is mainly concentrated in the crack tip area and there is little change in creep strain under different mismatch coefficients.

1. Introduction
Stress corrosion cracking (SCC) is a failure mechanism which is caused by environment, susceptible material and tensile stress of nuclear power structural materials under high temperature and high pressure water environments[1-2].

As a key component of the primary circuit of nuclear power plant, the structural integrity of welded joints of dissimilar metal safety terminals has become a key issue affecting the long-term safe operation of pressurized water reactor power plants[3]. SCC also occurs in the welded joints of the primary circuit of pressurized water reactor[4]. The particularity of the welding process makes it easy to produce residual stresses in welded joints, and residual stress in welding process is one of the key factors leading to stress corrosion cracking in nuclear power plant[5]. There is a high degree of heterogeneity in mechanical properties of dissimilar metal welded joints, and the yield stress of the weld area varies very high[6]. At the same time, owing to the significant difference between the welded metal parts of the dissimilar metal welded joint components[7], a series of mechanical problems will arise after welding and after welding heat treatment[8]. Recently many researches have focused on the research of mechanical properties of welded joints. It is believed that the failure of the yield strength of the material at the welded joint will cause the change of the crack tip mechanical field and have a great influence on the SCC crack growth[9-10].

In order to provide some help for the safety evaluation of dissimilar metal welded joints, this paper takes the dissimilar metal welded joints at the safe end as the research object. The creep stress and strain field under different yield stress after creep was established using ABAQUS in this paper, and stress and strain field are analyzed under different yield stress.
2. Finite element modeling

2.1. Specimen model

The compact tensile(1T-CT) specimen was adopted in this paper using finite element software ABAQUS and its geometrical dimensions are confirmed to the ASTM399 standard [11], which as shown in Figure 1(a). Because the welded joints is including three parts, named as welded zone(WZ), heat affected zone(HAZ) and base metal(BM), respectively, and its material distribution is shown in Figure 1(b).

![Geometry and dimensions model](image)

(a) Geometry and dimensions model

![Sandwich model of welded joint](image)

(b) Sandwich model of welded joint

**Figure 1.** Geometry and dimensions of 1T-CT model

To eliminate the stress singularity generated at the crack tip [12], the crack tip radius was taken as 0.5μm in the finite element simulation. The CPE8R was adopted in the global mesh type, as shown in Figure 2(a). In order to improve the accuracy of computation, sub-model technique is adopted. To obtain more detailed and accurate crack tip stress and creep strain, the mesh around crack tip was refined and its number was 15027, the sub-model mesh type is kept consistent with the global mesh model type, which is shown in Figure 2(b), and the total mesh number of sub-model is 3620.

![Global mesh model](image)

(a) Global mesh model

![Mesh around the notch](image)

(b) Mesh around the notch

**Figure 2.** Finite element mesh model of 1T-CT

2.2. Material model

The research object of this paper is the safe-end dissimilar metal welded joints in primary circuit of nuclear power plants, and which is composed of for different type materials, which is low carbon steel A508, heat affected zone material, welded zone material Alloy182 and austenitic stainless steel 316L, respectively.

To derive the creep property around crack tip of Alloy182, Creep constitutive relation is adopted power law model to describe the creep law in the simulation [13-14]. The constitutive relationship and its forms is as below.
\[ \dot{e}_{cr} = A \sigma^n t^m \]  

(1)

Where \( \dot{e}_{cr} \) is the creep strain rate. The \( \sigma \) is the applied stress; \( A \) is the power law multiplier, and its value is \( 3.77 \times 10^{-19} \), \( n \) is the creep exponent, and the value is 6.71 [15].

The yield strength mismatch coefficient of the heat affected zone is defined as the following formula 2

\[ M_Y = \sigma_{HAZ}/\sigma_{A182} \]  

(2)

In the formula (2), \( \sigma_{HAZ} \) and \( \sigma_{A182} \) represent as the yield stress of heat affected zone and Alloy182, respectively. The mechanical properties of the material in different part of welded joints is shown in Table 1 [16].

| Material | E/GPa | \( v \) | \( \sigma_0/\text{MPa} \) | Material | E/GPa | \( v \) | \( \sigma_0/\text{MPa} \) | \( M_Y \) |
|----------|------|------|-----------------|----------|------|------|-----------------|------|
| A508     | 183  | 0.30 | 476             | A182     | 204  | 0.33 | 337             | 674  | 2   |
|          |      |      |                 | HAZ      | 204  | 0.33 |                 | 1011 | 3   |

2.3. Loading and boundary conditions

Two analysis steps are set in the finite element simulation analysis. The first one is the loading process, and loading is applied to the load hole by using the reference point of the rigid body in the Y direction. And the specific value of the concentrated force is applied to the reference point to ensure the crack tip stress intensity factor \( K_I \) is \( 30 \text{MPa.m}^{0.5} \) in the tensile direction [17]. The second step is the creep process, and creep time is set as 1000h.

In order to eliminate the rigid body displacement during the experiment period, two points in the right side of the CT specimen was constrained in rotation and movement of X direction, so that they can only move and rotate along the Y direction. The centre position on the right side of the specimen was also fixed along the Y direction, so that the specimen does not have rigid body displacement.

3. Results and Discussion

3.1. Effect of yield stress mismatch on the Mises stress at crack front

The Mises stress distribution around the crack front under different mismatch coefficient after creep is shown in Figure 3, which shows that when the welding material around crack tip equal-matches the yield strength of the material in the heat affected zone, the crack tip Mises stress distributes symmetrically along the material interface between HAZ and Alloy182. The Mises stress gradually decreases with the increasing distance from the crack front under any mismatch coefficient. And when the welded material occurs mismatch, the Mises stress in the HAZ is less than the Mises stress in the Alloy182, which indicating that the yield stress of the HAZ will increase, which also will offset the high stress zone to the welding material. And the Mises stress distribution under different mismatch coefficients change very little after the creep.
3.2 Effect of yield stress mismatch on the PEEQ at crack front

The equivalent plastic strain (PEEQ) distribution around notch front under different mismatch coefficient after creep is shown in Figure 4, which shows that the PEEQ also distributes symmetrically along the material interface under the equal mismatch between HAZ and Alloy182. Equivalent plastic strain in the Nickel based 182 near crack front is basically remain unchanged under different mismatch coefficient after creep, but the PEEQ of HAZ is gradually decreasing with the increasing of the mismatch coefficient.

3.3 Effect of yield stress mismatch coefficient on the CEEQ at crack front

The equivalent creep strain (CEEQ) is also an important crack growth driving force parameter in the stress corrosion cracking tip, and its distribution around the crack front notch under different mismatch coefficient after creep is shown in Figure 5. Figure 5 shows that the creep strain is mainly distributed around the crack tip region, and its value is becoming less and less with the increasing distance from crack tip. The value of CEEQ is becoming larger and larger when the mismatch coefficient of HAZ is increasing.
4. Conclusions
(1) When the welding material and HAZ material mismatches, the Mises stress will decrease to a same level after creep, and the Mises stress mutation will appear on the interface between HAZ and Alloy182.
(2) The equivalent plastic strain(PEEQ) around crack front in HAZ will decrease with the increasing of mismatch coefficient, but equivalent creep strain(CEEQ) increases with the increasing of mismatch coefficient.
(3) The PEEQ, Mises stress and CEEQ also distributes symmetrically along the material interface when HAZ and Alloy182 is in the equal mismatch.

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