Effect of Load Ratio on the Mechanical Field around Crack Front of Dissimilar Metal Weld Joints

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Abstract. Stress corrosion cracking (SCC) of the dissimilar metal weld (DMW) joints in nuclear power equipment has been paid more attention in recent years. Besides the geometric size, load level, multiaxial stress state and mechanical heterogeneity, the relaxation and redistribution of residual stress make it very difficult to directly study the influence of residual stresses on the actual welded components. To study the effect of load ratio on residual stress around the crack front in the weld zone of DMW joints, the distributions of residual stress and stress triaxiality under different load ratios are simulated and discussed. The analyses show that the stress becomes larger with the increasing load ratio. The stress is tensile stress near the crack front. While the stress becomes compressive stress when it is far away from the crack front. The external load ratio has great effect on the stress around the circumferential direction at the crack front. The higher load ratio are more likely to cause the crack propagation. In the region of crack angle $\theta = 80$-120 $^\circ$, the load ratio has little effect on the stress triaxiality.

1. Introduction

In nuclear power equipments such as pressure vessels, there are many similar and dissimilar metal weld joints in the pipeline where the weld zones and geometric discontinuity zones, which are the victim of failure in the nuclear power plants[1]. As a weld filler metal, the high-temperature yield strength induced by the residual stress of Alloy 182 makes it more susceptible to SCC [2]. Under the extreme working conditions of high temperature and high pressure, all kinds of complex loads, the residual stresses introduced in the process of welding, forging and bending, SCC of the DMW joints in nuclear power equipment has been paid more attention in recent years [3]. However, the actual welding, due to the geometric size, load level, multiaxial stress state and mechanical heterogeneity is very complex [4, 5]. It is very difficult to directly study the influence of residual stresses on actual welded components, generally without considering the relaxation and redistribution of residual stresses. By the mechanical pre-compression method, residual stresses were introduced into to predict the propagation of creep crack, and the residual stresses measured by the experiments are in good agreement with the finite element simulation data [6]. The crack initiation and creep relaxation behavior of creep crack were also studied under the influence of residual stress [7, 8]. In the actual welding components, the material properties, specimen geometries and loading modes can affect the...
local residual stress field of the components. Therefore, it is necessary to study the effect of load ratio on the stress field around the crack front in the weld zone of DMW joints under the combined action of residual stresses and applied load [9, 10].

In this paper, the residual stress is introduced into the local crack front of a compact tension (CT) specimen in a DMW joint by the mechanical pre-compression method, the stress-strain fields at the crack front of notched CT specimen under different load ratios are simulated, and the influence of load ratio on the redistribution of residual stress around the crack front is also analyzed.

2. Finite element modelling

2.1. Specimen model

The finite element numerical simulation adopts a high restraint CT specimen, which is cut from the welded zone of a typical nozzle safe-end DMW joint. The geometric size of the CT specimen is shown in Figure 1. The width of the specimen is defined as \( W=20 \text{ mm} \) and crack depth factor as \( a/W=0.5 \). The specimen notch radius is defined as \( r=0.25 \text{ mm} \) and there is a groove with a width of 2.5 mm. \( P \) is a rigid body displacement load, which is used to generate residual stress by pre-compression in the initial stage. In this study, \( P \) is defined to be 0.3 mm. This is modeled by defining the distance between the loading point of rigid body displacement and the left side of the specimen \( d_c \), and the external tensile load \( T \), which is used to simulate the interaction of various complex loads and internal pressure in the FE formulation.

![Figure 1. Geometry of a notched CT specimen (W=20 mm, a/W=0.5)](image)

Due to good strength, toughness and corrosion resistance, many Nickel-based alloys are selected as weld filler metals of DMW joints, and their non linear relationship between stress and strain beyond yield is described by Ramberg-Osgood equation in this simulation:

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

(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 \( n \) is the strain hardening exponent of the material, \( \alpha \) is the offset coefficient of the material[11].

\[
n = \frac{1}{\kappa \ln(1390/\sigma_0)}
\]

(2)

Where \( \kappa=0.163 \).

The mechanical properties data and the Ramberg-Osgood constitutive parameters of Alloy 182 at 343 \(^\circ\)C are listed in Table 1.
Table 1. Mechanical properties of Alloy 182 at 343℃

| Material | Young’s modulus $E$ (MPa) | Poison ratio $\nu$ | Yield stress $\sigma_0$ (MPa) | Hardening exponent $n$ | Hardening parameter $\alpha$ |
|----------|------------------|-----------------|-----------------|-----------------|-----------------|
| Alloy 182 | 193              | 0.288           | 517             | 4.779           | 1.0             |

2.2. Boundary conditions and loading

The symmetrical boundary condition is applied to the ligament area at the crack front and the full constraint is applied to avoid the rigid displacement at the right corner of the specimen. The displacement and rotation in the horizontal direction are limited to the reference point where the displacement load is applied, and only the movement in the upper and lower directions is allowed. The introduction of residual stress is realized by applying a certain compression displacement to the up and down rigid bodys.

In the numerical simulation, a variety of complex loads such as self-weight, internal pressure, tensile stress and bending moment are simplified to a tensile load $T$, which induces the stress intensity factor at the crack front is $30 \text{ Mpa} \cdot \text{m}^{0.5}$. The redistribution of the stress field of the crack tip is studied by changing the load ratio $R$ under the co-action of residual stresses and external load. The variable load process is divided into six stages, as shown in Figure 2. When the period repeats, the stress field distribution has no effect on the stress field distribution. Therefore, three load ratios are selected for the first two cycles and the comparative analysis is carried out. It is assumed that the values of load ratio $R$ is 0.3, 0.5 and 0.7 respectively. The residual stress caused by the pre-compression method is applied at the unloaded stage.

![Figure 2. The loading changed with calculation and analysis steps](image)

2.3. FE Model

To reduce the computation time, half of the actual CT specimen is selected to establish the finite element model. A symmetry constraint is set on the symmetry line of the CT specimen. Figure 3 gives the mesh of the notched CT specimen (global model and the area around the crack front), where X-axis is the crack growth direction and Y-axis is the direction perpendicular to the crack growth direction. 17260 4-node bilinear plane strain elements are adopted in the global model. A more refined mesh is adopted near the crack front, in order to obtain a more detailed and accurate data. The minimum size of the element is about 0.025 mm in the area around the crack front.
3. Results and discussion

3.1. Effect of load ratio on the mechanical field

A set of specimens with passivated circular radius \( r=0.25 \) mm were selected and subjected to the mechanical pre-compression. Before unloading, the compression displacement \( P=0.3 \) mm was applied at the point where the rigid body compression position \( dc=15 \) mm. Thus, the residual stresses introduced at the front end of the crack and the external tensile load \( T=274.98 \) N \((K_{CL}=K_{I}=30 \text{ MPa} \cdot \text{m}^{0.5})\) are able to work together.

Figure 4 shows the residual stress distributions around the crack front of the CT specimens. Under the function together with residual stress and applied load, the high-stress zone around the crack front is much larger under constant loading. With the increase in the load ratio of the applied load, the stress becomes larger. The stress is tensile stress near the crack front. While the stress becomes compressive stress when it is far away from the crack front.

Figure 5(a) shows the residual stresses along the ligament length at the crack front with different load ratios of trapezoidal loading. The stress increases to the peak of a tensile stress, then drops gradually and finally becomes a compressive stress. At the same time, the larger of the load ratio, the higher the tensile stress peak is.

The residual stress at the characteristic distance \( d=0.125 \) mm ahead of the crack front is shown in Figure 5(b). The crack angle \( \theta \) varies from 0º to 180º around the crack front. The maximum stress occurs when the crack angle \( \theta=90º \), which leads to the crack propagates at \( \theta=90º \) firstly. The larger of the load ratio, the greater the stress around the circumferential direction is. The external load ratio has great effect on the stress around the circumferential direction at the crack front.
3.2. Effect of load ratio on stress triaxiality

Figure 6(a) shows the stress triaxiality along the ligament length at the crack front. The peak value appears at about 0.25 mm away from the notch tip and the stress triaxiality is negative, which is due to the fact that the stress triaxiality is mainly controlled by the residual tensile stresses. The value of stress triaxiality increases with the increasing load ratio, which indicates the higher load ratio are more likely to cause the crack propagation.

As shown in Figure 6(b), the peak of stress triaxiality at the characteristic distance (d=0.125 mm) ahead of the crack front occurs when the crack angle θ=90°. In the region of θ=80-120 °, the load ratio has little effect on the stress triaxiality, which can influence the crack morphology. The effect of external load on the stress along the ligament length at the crack front is more obvious than that around the circumferential direction.

4. Conclusions

Finite element analyses have been conducted for notched CT specimen with the combined action of residual stress and external load. The distributions of residual stress and stress triaxiality under different load ratios are simulated and analyzed. The main results are as follows:
With the increase in the load ratio of the applied load, the stress becomes larger. The stress is tensile stress near the crack front. While the stress becomes compressive stress when it is far away from the crack front.

The maximum stress occurs when the crack angle $\theta=90^\circ$, which leads to the crack propagates at $\theta=90^\circ$ firstly. The external load ratio has great effect on the stress around the circumferential direction at the crack front.

The higher load ratio are more likely to cause the crack propagation. In the region of crack angle $\theta=80$-$120^\circ$, the load ratio has little effect on the stress triaxiality, which can influence the crack morphology. The effect of external load ratio on the stress along the ligament length at the crack front is more obvious than that around the circumferential direction.

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References
[1] Li G and Congleton J 2000 Corros. Sci. 42 1005
[2] Lim Y, Kim D, Kim S and Kim H 2019 Nucl. Eng. Technol. 51 228
[3] Li G, Li G, Fang K and Peng J 2011 Acta. Metall. Sin. 47 797
[4] Kim W, Park J, Lee H, Hong S, Kim Y and Kim S 2013 Int. J. Pres. Ves. Pip. 110 66
[5] Sugiura R, Jr A, Suzuki K, Yokobori T, Suzuki K, Tabuchi M 2010 Eng. Fract. Mech. 77 3053.
[6] Turski M, Bouchard P, Steuwer A and Withers P 2008 Acta. Mater. 56 3598
[7] Chen L, Wang G, Tan J, Xuan F and Tu S 2013 Eng. Fract. Mech. 97 80
[8] Song X, Wang G, Xuan F and Tu S 2015 Eng. Fract. Mech. 149 45
[9] Chen B, Spindler M and Smith D 2010 ASME 2010 PVP K 357
[10] Bray D, Dennis R and Smith M 2010 ASME 2010 PVP K 387
[11] Xue H and Shi Y 1998 Int. J. Pres Ves. Pip. 75 575.