Study on the Rate of Elastic-plastic Crack Propagation of Heterogeneous Metal Welded Joints in Nuclear Power

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Abstract. In the high-temperature water environment of nuclear power, austenitic stainless steel, nickel-based alloy materials and welded joints composed thereof are the key locations for environmental cracking (EAC) problems such as stress corrosion cracking (SCC). In order to understand the crack propagation behavior and expansion rate of welded joints under the condition of abrupt and heterogeneous material properties of welded joints, this paper uses the extended finite element technique (XFEM) in the large nonlinear finite element software ABAQUS, based on the elastoplastic material model. Under the condition of welding residual stress field, the effects of different initial crack length and strength mismatch ratio on the crack growth rate of stress corrosion crack under constant load were studied. The results show that the SCC crack growth rate increases with the increase of the initial crack length. When the crack length of the initial welded joint is constant, different mismatch ratio has a certain effect on the crack growth rate. In the low ratio range (less than 1), the crack growth rate also increase if the strength mismatch ratio increase. but the crack growth rate is gradually reduce in high ratio range (more than 1). This indicates that the mismatch ratio of 1 is favorable for crack propagation, and the larger the mismatch ratio, the crack propagation is hindered.

1. Introduction

The welding process uses a lot of processes in nuclear voltage vessels and pipes, so there are many welded joints on equipment such as nuclear voltage vessels, which are the most dangerous parts [1]. Due to the very complicated internal structure of the welded joint, mechanical properties and the residual stress generated during the welding process, various defects may occur, such as cracks, inclusions, etc., the welded joint is the main area that causes structural failure which are EAC occurrence and crack propagation[2]. Quantitative prediction of EAC crack growth rate in high temperature water environment has been an important topic for Domestic and foreign scholars. It is hoped that an accurate SCC crack growth rate prediction model can be established [3-4]. Nuclear power safety end welding process of dissimilar metal welded joints can be divided into three steps: smelting, casting and heat treatment. Each step is very complicated, forming a difficult research topic, and residual stress is generated after welding, and residual stress It will cause stress corrosion cracking behavior of nuclear power materials [5]. After studying the X52 steel in depth, Contreras-Cuevas et al. used a number of different welding methods to study the behavior of SCC. The circumferential and longitudinal residual stresses were measured by the X-ray method. The measurement results show that 98% are circumferential residual stress and 74% are longitudinal residual stress. This study provides a reference for the effects of residual stress on SCC behavior [6]. Using A533, Alloy182 alloy and -
A533B low alloy, Zhao Lingyan established an inhomogeneous material model close to the actual welded joint in the finite element software, and studied the mechanical field of crack propagation crack tip under the interaction of complex working load and welding residual stress. A quantitative prediction model of crack growth rate. The results show that the residual stress has a certain influence on the mechanical field and expansion rate of cracks in metal welded joints [7]. Wang Haitao and other researchers at East China University of Science and Technology used experimental methods to perform fracture experiments on dissimilar metal materials. Their experimental results show that the crack propagation path has a certain relationship with the strength matching ratio of the welding consumables and the base metal of the welded joints. A new method for local damage assessment [8].

Through the knowledge of fracture mechanics theory, the length of the crack is a very important factor affecting the fracture toughness of the material, which will have a certain influence on the crack tip field. Many research scholars have done a lot of research on the relationship between the mechanical field and the crack length of the relevant static crack tip. And the SCC crack growth rate is calculated by the correlation formula.[9]. But there is a little research on the relationship between mechanical field and length of dynamic crack tip. Therefore, based on the elastoplastic material model, this paper approximates the nuclear welding joint to a “sandwich” material mechanics model, considering the residual stress, using the XFEM technology in commercial finite element software ABAQUS to study homogeneous materials and dissimilar metal materials. The mechanical field and expansion rate of crack propagation under different initial crack lengths are studied, and the crack propagation of dissimilar materials with different mismatch coefficients is discussed.

2. Numerical model

2.1. Geometric models and material models

EAC experiments in high-temperature water environments often use compact tensile specimens (CT) under constant load. The specimens are compact, so cracks can extend longer distances during loading. American Society for Testing and Materials Standards ASTM E399-90 [10]. In this paper, the crack tip mechanical field at the interface position of dissimilar materials will be studied. Therefore, a pre-cracked CT specimen is selected for analysis. The geometry is shown in Figure 1, a=W/2, W=50mm, B=W/2= 25mm. The simplified "sandwich" model of the welded joint is shown in Figure 2. The specimen with the crack at the material interface is selected (Figure 2-II), and the interface crack propagation characteristics are analyzed.

![Figure 1. Geometric size.](image1)

![Figure 2. Sample selection position.](image2)

Different locations of nuclear power dissimilar metal welded joints have different cracking and crack propagation behaviors. The traditional EAC crack propagation rate prediction method is based on linear elastic fracture mechanics (LFEM). However, a large number of experimental evidences indicate that the plasticity of the material The EAC crack growth rate has a very important effect. According to the elastoplastic theory, the plastic properties of isotropic materials are established. We know that the deformation process of elastoplastic metal materials consists of initial elastic segments...
and plastic deformation segments. In this paper, a plastic material with no obvious yielding platform is used. The material mechanics relationship is in accordance with the Ramberg-Osgood relationship.

This paper mainly analyzes the effects of two mismatched forms, high and low, on the crack propagation law. A typical high-profile welded joint, that is, the strength of the base metal is less than that of the weld metal, and vice versa. The specific material parameters are shown in Table 1, which are the parameters of the material under high temperature and high pressure.

| Materials                    | Elasticity modulus E(MPa) | Poisson's ratio ν | Yield strength σ₀(MPa) | Hardening exponent n | Deviation ratio α | M=σ₀W/σ₀B |
|------------------------------|---------------------------|------------------|------------------------|----------------------|------------------|-----------|
| Base metal                   | 206000                    | 0.28             | 254                    | 3.6                  | 1.0              | 1         |
| Welding material (high ratio)| 206000                    | 0.28             | 304.8                  | 4.04                 | 1.0              | 1.2       |
| Welding material (high ratio)| 206000                    | 0.28             | 355.6                  | 4.5                  | 1.0              | 1.4       |
| Welding material (low ratio)| 206000                    | 0.28             | 152.4                  | 2.78                 | 1.0              | 0.6       |
| Welding material (low ratio)| 206000                    | 0.28             | 203.2                  | 3.19                 | 1.0              | 0.8       |

2.2. Finite element model

The finite element mesh of this paper is 2658 linear plane strain elements (CPE4), the number of grids is 4926, and the crack extension area mesh is refined, and the number of grids is 1652, as shown in Figure 3.

In this paper, the XFEM technique is used to simulate the stress corrosion cracking crack propagation under the dead load condition. The amplitude curve is used to control the load application. According to the actual situation, the load is linearly increased to the maximum value through the 0.35s load within 1s of the analysis step time. All time calculations are kept constant.

Effect of Different Initial Crack Length on Crack Growth Rate

2.3. Variation of crack tip stress field of homogeneous and dissimilar materials

In this paper, the initial crack lengths are 1mm, 2mm, 3mm, and 4mm respectively. As shown in Figure 4(a→d), they are crack propagation stress field Mises with different initial crack lengths under residual stress and constant load interaction. It can be seen from the figure that the stress field on both sides of the crack tip of the extended crack is symmetrically distributed, and is the largest in the small range near the crack tip, this mean, the stress concentration zone appears in the crack tip during the
expansion process, and will increase with the initial length of the crack increase. And the crack tip is still symmetrically distributed, and the stress field is enhanced. Figure 5(a→d) shows the Mises stress cloud diagram of dissimilar metal crack propagation at a different initial crack length with a mismatch ratio of 0.6. In the figure, the stress field distribution on both sides of the crack tip is asymmetrical, but the difference of the stress cloud map is not obvious. With the increase of the initial crack length, the stress field of the dissimilar metal crack tip is enhanced.

Figure 4. Crack tip PEEQ in the process of crack propagation of dissimilar metals.

Figure 5. Crack tip PEEQ in the process of crack propagation of dissimilar metals.

2.4. Variation of strain field in homogeneous and dissimilar materials

Figure 6(a→d) shows the crack propagation field of Homogeneous materials and dissimilar metals under different initial crack lengths. It can be seen from the figure that in the elastic-plastic material, plastic strain occurs after the crack propagates, and the plastic strain continues to remain in the crack. With the increase of the initial crack length, the strain field of the crack tip increases, the stress concentration of the crack tip is obvious, and the symmetric distribution state remains. Figure 7 (a→d) is the dissimilar metal strain field. Under the external load, due to the material mismatch ratio (The difference in strength mismatch ratio of 0.6) is clearly asymmetrically distributed on both sides of the crack tip, and we can find that the plastic strain is larger on the side where the yield strength is smaller. And because it is an elastoplastic material, its plastic strain will remain in the expanded path.

Figure 6. Crack tip PEEQ in the process of crack propagation of dissimilar metals.
2.5. Crack growth rate change

Figure 8 is a graph showing the crack growth rate (CGR) of the homogeneous material and the dissimilar metal material as a function of the initial crack length. From the figure, we can find that when the initial length of the crack is different, the SCC crack growth rate will increase with time, and increase sharply in the later stage, which is the same as the stress-strain field cloud pattern. After cracking, the crack growth rate increases gradually; the crack growth rate of the homogeneous material is greater than the crack growth rate of the dissimilar metal, which indicates that the equivalence ratio is favorable for crack propagation of the welded joint, and as time goes by, we will find the rate of SCC crack propagation will increase faster and faster, almost exponentially increasing.

3. Change of crack growth rate under different mismatch coefficients

Figure 9 shows the expansion rate of the extended crack at the interface of the dissimilar materials when the initial crack length is 2 mm under different mismatch ratios (0.6, 0.8, 1, 1.2, 1.4). Since the welded joints are made of different materials. There are inhomogeneities in the properties and geometry of the material, which results in different SCC crack growth rates. The crack growth rate at 0.35s, 0.41s, 0.5s, and 1s in the crack propagation history was selected. From the figure, we can see that when the intensity mismatch ratio is 1, the crack will first crack and its crack will occur. The expansion rate is the fastest, and the rate increases significantly in the late stage of crack propagation, indicating that the strength ratio is favorable for crack propagation. By comparing the crack growth rates of different intensity mismatch ratios, we found that when the mismatch ratio coefficient is high, the crack growth rate is the slowest, that is, the high composition ratio hinders the crack growth.

4. Conclusions

(1) In this paper, XFEM technology is used to study the crack growth rate of different initial crack lengths at the interface between uniform materials and dissimilar metal elastoplastic materials under constant load. It is found that the longer the initial crack length in dissimilar metal materials, the SCC crack propagation rate will be faster.
(2) By establishing different strength mismatch ratio material models, it is concluded that the different mismatch ratios of dissimilar metal materials affect the crack growth rate. When the ratio is low, the SCC crack growth rate is faster, and the high distribution time is lost. The larger the ratio, the smaller the crack growth rate and the better the crack growth rate when the mismatch ratio is 1.

Acknowledgments
This work was supported by the Structural Safety Evaluation Laboratory of School of Mechanical Engineering, Xi’an University of Science and Technology. And Gangbo Li also wishes to acknowledge the financial support the National Natural Science Foundation of China 51475362, Shaanxi Provincial Department of Education Research Project Funding Project 12JK0657

References
[1] Dai D P Numerical simulation of residual stress in austenitic stainless steel welded joints [D]
[2] Yang F Q 2014 Study on crack tip creep characteristics and environmental cracking quantitative prediction model of nuclear power structural materials. Xi’an University of Science and Technology
[3] Shoji T and Suzuki S 1995 Theoretical prediction of SCC growth behavior -- Threshold and plateau growth rate[J]. Nace International Houston Tx
[4] Shoji T and Lu Z 2010 Formulating stress corrosion cracking growth rates by combination of crack tip mechanics and crack tip oxidation kinetics Corrosion Science 52(3):0-779
[5] Ji J 2008 Austenitic stainless steel weldability analysis Coal mine machinery 29(7):85-86
[6] Contreras-Cuevas A and Alamilla-López 2014 The Role of Residual Stresses in Circumferential Welding Repairs of Pipelines in SCC Susceptibility[C]// Trans Tech Publications p 159-168.
[7] Zhao L Y 2014 Study on the mechanical characteristics of crack tip of nuclear power welded joints and the rate of environmental cracking crack growth Xi’an University of Science and Technology
[8] Huang J Y and Chiang M F 2013 Environmentally assisted cracking behavior of dissimilar metal weldments in simulated BWR coolant environments Journal of Nuclear Materials 432(1-3):189---197
[9] Wang H T and Wang G Z 2013 Local fracture behaviour of nuclear-electric 52M nickel-based alloy dissimilar metal welded joints nuclear technology 36(4):000139-144 [10] Shoji
[10] ASTM Standard E399-90. Standard test method for plane strain fracture toughness of metallic materials. Annual Book of ASTM Standards, 2002, (03.01)