Effect of Crack Length on Mechanical Field of Stress Corrosion Crack Tip of Cold Working 316L Stainless Steel

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Abstract. The effect of crack length at different cold working level on stress and strain state and fracture parameters of stress corrosion cracking tip of 316L stainless steel in high temperature water environment of the nuclear pressure vessel was studied by sub-model technology of elastic plastic finite element method. It combined with the mechanical properties of 316L stainless steel under different cold working level, and the effect of crack length on the Mises stress, equivalent plastic strain, tensile stress and tensile strain and J integral of 316L stainless steel under different cold working level was compared. The results indicate that crack length of stress corrosion cracking has certain effect on stress and strain state at crack tip. With the increase of crack length, Mises stress and equivalent plastic strain, tensile stress and tensile strain increase at crack tip, at the same time, J integral increases with increase of crack length.

Cold working level has changed the mechanical properties of 316L stainless steel. When the stress intensity factor K is constant, with the increase of cold working level, Mises stress increases and equivalent plastic strain decreases at crack tip, while tensile stress increases and tensile strain decreases at crack tip. The rate of change of stress strain curve from 0° to 90° is different because of cold working level. The higher the level of cold working, the faster the Mises stress and the tensile stress increase at 90° in front of the crack tip, and equivalent plastic strain and tensile strain decrease most slowly at 90° in front of the crack tip. As the degree of cold working increases, the J integral of crack tip also increases. The increase of crack length and the level of cold working aggravate the stress corrosion cracking of 316L stainless steel under high temperature and high pressure in a certain range.

1. Introduction

Tensile stress, sensitivity of material and corrosion environment are three conditions for the occurrence of stress corrosion cracking[1,2]. Cold working in the process of pressure vessel manufacturing often leads to large residual plastic deformation, resulting in a larger residual tensile stress, which tends to make the material reach yield strength[3-5], such as cold rolling, cold bending, straightening, welding, assembly and so on. In the process of crack propagation, the length of the crack changes continuously, and the stress and strain of the crack tip varies with the length of the crack. Therefore, the effective prediction and control of residual stress in the manufacturing process of pressure vessels and the study of the influence of crack tip stress on material sensitivity of different length cracks help to further understand the mechanism of stress corrosion cracking (SCC), so as to effectively predict and control nuclear structural materials damage the purpose of failure. Andresen et al. studied the stress corrosion
cracking behavior of stainless steel and nickel-base alloy after cold working. The results show that the cold working deformation introduced during the processing of the structural material is the main factor to promote and accelerate the stress corrosion cracking of the material. The crack growth rate of the cold rolled nickel base alloy and stainless steel is more than 100 times higher than that of the cast alloy[6-8]. France EDF’s pressurized water reactor (PWR) nuclear power operation experience shows that there is no stress corrosion cracking phenomenon in the part without obvious cold processing. Cold working is the main factor to produce SCC[9]. The residual tensile stress on the austenitic stainless steel surface caused by cold working is now considered to be one of the major causes of cracking[10-13]. Ilevbare[14] et al. reported that 53% of PWR assembly failures were related to cold working in material processing. Different cold working methods and degrees will affect the mechanical properties of the material, and the crack tip stress-strain state and propagation law of different crack lengths under different mechanical properties also become more complex.

Therefore, the effect of crack length on SCC with different degrees of cold work has become a hot issue. It is an important practical significance to analyze the effect of crack length on the mechanical state of crack tip of SCC under different degrees of cold working. In order to understand the effect of crack length on mechanical state of cold working 316L stainless steel at crack tip, the stress-strain field at crack tip of the stress corrosion crack was analyzed by using the ABAQUS simulation software in the hope of obtaining the influence of cold working on the stress and strain field at crack tip of 316L stainless steel in stress corrosion cracking.

2. Finite element modeling

2.1. Geometric model

The use of finite element analysis of crack tip stress and strain state selection of compact tensile specimen 1T-CT sample, the sample geometry shown in Fig.1.

Using finite element analysis of crack tip stress and strain state, the of compact tensile specimen 1T-CT sample is selected, and the sample geometry is shown in Fig.1. The geometric size and experimental process of the sample according to American Society for Testing and Materials Standard. Initial prefabricated crack length \( c = 2 \text{mm} \), It changes the crack length \( a \), the initial crack length \( a = 0.5W = 25 \text{mm} \), and takes \( \Delta a = 1 \text{mm}, 2 \text{mm}, 3 \text{mm} \) respectively.

![Figure 1. 1T-CT sample geometry dimensions (W=50mm, a=0.5W, c=2mm) (a) and crack tip (b) (a)](image-url)

2.2. Material model

The mechanical constitutive relations of 316L austenitic stainless steel for nuclear power materials are obtained by the tensile test and belong to the power hardening material. The relationship between stress and strain beyond yield at crack tip of 316L stainless steel is described by Ramberg-Osgood equation in this numerical simulation[15,16].

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

(1)

Where \( \varepsilon \) is strain; \( \sigma \) is stress; \( E \) is Young’s modulus of the material; \( \sigma_0 \) is the yield strength of the material; \( \alpha \) is the yield offset and \( n \) is the hardening exponent for the plastic.
The mechanical properties of 316L austenitic stainless steel for nuclear power in high temperature and high pressure water environment are shown in Table 1.

| Cold work level | 5%  | 10% | 20% |
|-----------------|-----|-----|-----|
| Yield strength, MPa | 388 | 478 | 643 |
| Young’s modulus, GPa | 197 | 193 | 191 |
| Hardening exponent | 3.19 | 3.54 | 4.95 |
| Yield offset   | 8.06 | 7.87 | 4.47 |
| Poisson's ratio | 0.3  | 0.3  | 0.3  |

2.3. Finite element model
Using ABAQUS to calculate stress and strain distribution in crack tip, it is a commonly software used to precision calculation. Using the plane deformation model and adopting 8-node biquadratic plane strain quadrilateral reduced integration[18].

3. Results and Discussion

3.1. Effect of crack length on Mises stress of 316L stainless steel with different cold working level
The cold working level was 5%, 10%, 20% respectively. According to Fig.1, the initial crack length is $a=0.5W=25\text{mm}$. Change the crack length $a$, and respectively take $\Delta a = 1\text{mm}, 2\text{mm}, 3\text{mm}$. Effect of crack length on the Mises stress of 316L stainless steel with different cold working is shown in Fig.2. The cold working degree of the graph (a) is 5%, (b) is 10%, and (c) is 20%.

Figure 2. Mises stress distribution at crack tip

From Fig. 2 (a), (b) and (c), it can be seen that the Mises stress at the crack tip increases with the increase of the crack length. From 0° to 90°, the Mises stress first increases slightly and then decreases, and the minimum Mises stress occurs at 90° just in front of the crack tip. The level of cold working is different, and the Mises stress at the crack tip is also different. The Mises stress increases with the increase of cold working level. However, with the increase of cold working level, the Mises stress curve gradually flattened and the minimum Mises stress at the crack tip approaches to the maximum value. That is, the increasing rate of Mises stress is maximum at 90°, and the cold working level could change the Mises stress distribution. This is due to the mechanical properties of the materials changed by cold working. The 316L stainless steel produced cold working plastic deformation. The yield strength $\sigma_{0.2}$ of 316L stainless steel is increased by plastic deformation, and the hardening exponent $n$ is increased to a certain degree. Under the condition of certain stress intensity factor $K$, it is known from the formula (3) that the Mises stress at crack tip will also increase, therefore, it will aggravate the stress corrosion cracking to a certain extent.

3.2. Effect of crack length on equivalent plastic strain of 316L stainless steel with different cold working level
The effect of crack length on the equivalent plastic strain of 316L stainless steel at different cold working level is shown in Fig.3.
It can be seen from Fig.3 (a), (b) and (c), the equivalent plastic strain at crack tip increases with the increase of the crack length. From 0° to 90°, the equivalent plastic strain at crack tip first increases and then decreases, and the minimum value of equivalent plastic strain appears at 90° in front of the crack tip. The cold working level is different, the equivalent plastic strain at the crack tip is also different, and the equivalent plastic strain decreases with the increase of cold working level. However, with the increase of cold working level, the equivalent plastic strain curve gradually flattens and the minimum value at the crack tip approaches the maximum value. The decreasing rate of equivalent plastic strain is maximum at 90°. Cold hardening occurs after cold working of 316L stainless steel. Hardening exponent $n$ is improved, and yield strength $\sigma_{0.2}$ is also increased. Therefore, when the stress intensity factor $K$ is constant, the equivalent plastic strain at the crack tip decreases with the increase of the cold working degree.

3.3 Effect of crack length on tensile stress of 316L stainless steel with different cold working level

Effect of crack length on tensile stress of 316L stainless steel with different cold working level is shown in Fig.4. It can be seen from Fig.4 (a), (b) and (c), the tensile stress at the crack tip increases with the increase of the crack length. From 0° to 90°, the increase rate of tensile stress increases, and the maximum tensile stress occurs at 90° in front of the crack tip. The tensile stress at the crack tip is different because of cold working, and the tensile stress increases with the increase of cold working level. Tensile stress plays an important role in stress corrosion cracking, so the increase of tensile stress will aggravate the stress corrosion cracking to a certain extent.

3.4 Effect of crack length on tensile strain of 316L stainless steel with different cold working level

Effect of crack length on tensile strain of 316L stainless steel with different cold working level is shown in Fig.5.

It can be seen from Fig.5 (a), (b) and (c), the tensile strain of the crack tip increases with the increase of the crack length. From 0° to 90°, the tensile strain at crack tip first increases and then decreases, and the minimum value of tensile strain appears at 90° in front of the crack tip. The tensile strain at the crack tip decreases with the increase of cold working level. The decreasing rate of tensile strain is minimum at 90°.
3.5. Analysis of J integral at crack tip

In fracture mechanics, $J$ is a parameter that can quantitatively characterize the stress and strain field strength at the crack tip, and can also be used as a parameter to characterize elastic-plastic fracture. Crack length also affect the fracture parameter. Ignoring the influence of the elastic part on $J$, only taking the $J$ integral of the plastic part into considered, and the calculation formula of $J$ can be simplified to the formula (8).

$$J = \frac{K^2 (1 - \nu^2)}{E}$$

The change of $J$ integral with crack length under different cold working is shown in Fig.6. It can be seen from Fig.6 that the $J$ integral at crack tip increases with the increase of crack length. Cold working level also has an impact on the distribution of $J$ integral. At the same time, $J$ integral also increases with the increase of cold working level.

4. Conclusion

(1) The crack length of (SCC) has a certain influence on the stress and strain at the crack tip. Mises stress, equivalent plastic strain, tensile stress and tensile strain of stress corrosion crack tip increase with the increase of crack length.

(2) The $J$ integral at crack tip increases with the increase of crack length. The cold working level also affect the distribution of the $J$ integral at crack tip. $J$ integral increase with the increase of cold working level. The increase of crack length and the level of cold working aggravate the stress corrosion cracking of 316L stainless steel under high temperature and high pressure in a certain range.

(3) Cold working level changes the mechanical properties of 316L stainless steel, and also affects the stress corrosion cracking stress-strain state. When the stress intensity factor $K$ is constant, with the increase of cold working level, Mises stress increases and equivalent plastic strain decreases at crack tip, while tensile stress increases and tensile strain decreases at crack tip.

(4) The rate of change of stress strain curve from 0° to 90° is different because of cold working level. The higher the level of cold working, the faster the Mises stress and the tensile stress increase at 90° in front of the crack tip, and equivalent plastic strain and tensile strain decrease most slowly at 90° in front of the crack tip.
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References
[1] Yang Hongliang, Xue He, Yang Fuqiang, Zhao Lingyan. Effect of Film-Induced Stress on Mechanical Properties at Stress Corrosion Cracking Tip. Rare Metal Materials and Engineering, 46(2017): 3595-3600.
[2] I.I. Ahmed, B. Grant, A.H. Sherry et al. Deformation path effects on the internal stress development in cold worked austenitic steel deformed in tension. Materials Science & Engineering A 614 (2014) 326–337.
[3] HOU Juan, PENG Qunjia, SHOJI Testuo et al. Study of microstructure and stress corrosion cracking behavior in welding transition zone of Ni-based alloys[J]. ACTA METALLURGICA SINICA, 2010, 46(10): 1258-1266.
[4] Donghai Du, Kai Chen, Hui Lu et al. Effects of chloride and oxygen on stress corrosion cracking of cold worked 316/316L austenitic stainless steel in high temperature water, Corrosion Science 110 (2016) 134–142.
[5] J. Hou, T. Shoji, Z. P. Lu et al. Residual Strain Measurement and Grain Boundary Characterization in the Heat Affected Zone of a Weld Joint between Alloy 690TT and Alloy 52[J]. Journal of Nuclear Materials, 397(2010)109-115.
[6] P. L. Andresen, M. M. Morra. IGSCC of non-sensitized stainless steels in high temperature water. Journal of Nuclear Materials 2008, 383:97-111.
[7] S. Yamazaki, Z. P. Lu, Y. Ito, Y. Takeda, T. Shoji. The effect of prior deformation on stress corrosion cracking growth rates of Alloy 600 materials in a simulated pressurized water reactor primary water[J]. Corrosion Science, 2008, 50: 835.
[8] Q.J. Peng, J. Hou, T. Yonezawa, T. Shoji, Z.M. Zhang, F. Huang, E.-H. Han, W. Ke, Environmentally assisted crack growth in one-dimensionally cold worked Alloy 690TT in primary water[J]. Corros. Sci. 57 (2012) 81-88.
[9] T. Couvant, L. Legras, C. Pokor, F. Vaillant, Y. Brechet, J-M. Boursier, P. Moulart. Investigations on the mechanisms of PWSCC of strain hardened austenitic stainless steels. Proc. of the 13th International Conference on Environmental Degradation of Materials in Nuclear Power Systems Whistler, British Columbia, 2007. p.1.
[10] A. Sáez-Maderuelo, D. Gómez-Briceño. Stress corrosion cracking behavior of annealed and cold worked 316L stainless steel in supercritical water, Nuclear Engineering and Design 307 (2016) 30-38.
[11] Johsei Nagakawa , K. Ueno, Y. Murase , N. Yamamoto. Effect of cold-work on the radiation-induced deformation of austenitic stainless steels. Journal of Nuclear Materials 367-370 (2007) 910-914.
[12] Litaow Zhang, Jianqu Wanga. Effect of dissolved oxygen content on stress corrosion cracking of a cold worked 316L stainless steel in simulated pressurized water reactor primary water environment. Journal of Nuclear Materials 446 (2014) 15-26.
[13] T. Terachi, T. Yamada , T. Miyamoto , K. Arioka. SCC growth behaviors of austenitic stainless steels in simulated PWR primary water. Journal of Nuclear Materials 426 (2012) 59-70.
[14] G.O. Ilevbare, F. Cattant, N.K. Peat, SCC of Stainless Steels under PWR Service Conditions. 42, INIS, 2011, RN:42088756.
[15] Xue He, Li Yongqiang. Micro-mechanical State at Tip of Environmentally Assisted Cracking in Nickel-based Alloy[J]. Rare Metal Materials and Engineering, 2016, 45(3): 0537-0541.
[16] YANG Hongliang, XUE He, CUI Yinghao. Effect of material mechanical properties on stress distribution at crack tip of Ni-based alloys in high temperature water environment [J]. Hot Working Technology, 2016, 45(24): 83-85.
[17] Masayuki Kamaya. Elastic-plastic failure assessment of cold worked stainless steel pipes[J]. International Journal of Pressure Vessels and Piping, 131 (2015) 45-51.
[18] YANG Hongliang, XUE He, ZHAO Lingyan et al. Effect of Oxide Film Shape on Stress-Strain at Stress Corrosion Cracking Tip of Ni-Based Alloy[J]. Hot Working Technology, 2016, 45(20): 58-60.