Effect of crack length on tip field of 304 stainless steel SCC

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Abstract: Stress corrosion cracking (SCC) is one of the key issues affecting the long-term safe operation of high temperature pressure vessels and pipeline. In this paper, the effect of crack length on the SCC crack tip field of austenitic 304 stainless steel is studied by using a compact tensile specimen. Firstly, the finite element model of SCC crack tip creep is established by using ABAQUS, and the crack tip creep and creep to crack tip mechanics are analyzed. The influence of different crack lengths on crack tip creep and creep rate was studied. It can be obtained by numerical simulation analysis software. The high creep variable area is mainly concentrated in the near crack tip region. The crack length has a great influence on the SCC crack tip creep field. With the continuous expansion of the austenitic 304 stainless steel crack, crack tip creep variables and creep rates are also increasing. It provides a theoretical reference for the safety evaluation and analysis of high temperature pressure vessels and pipelines.

1. Introduction

Stress corrosion cracking (SCC) is a behavior of structural materials that generate cracks and then fail under the combined action of stress and corrosive environment. It is one of the main failure modes of austenitic stainless steel [1][2], and its existence will be a serious threat to safe operation and service life of pressure vessel piping equipment. Studies have shown that austenitic 304 stainless steel is used in high temperature and high pressure water for a long time. When SCC crack is generated and expanded under high stress conditions, the crack tip will creep [3][4][5], and then the crack propagation have an important impact. Kassner M E et al. conducted a critical assessment of low temperature creep and irradiation creep in nuclear reactors. It is concluded that even under relatively low temperature and stress conditions, with or without radiation, metallic materials are subject to measurable creep deformation [6]. Wang guo zhen et al. studied the crack tipping effect of high temperature creep cracks and established a creep crack propagation life evaluation method for high temperature parts incorporating crack tip restraint effect [7]. Garud YS et al. applied low temperature creep and irradiation to nuclear reactors. The significance and evaluation of creep is discussed [8]. Kumar Y et al. evaluated the rate of creep crack propagation (CCG) and its micromechanical properties in welds [9].

The expansion process of stress corrosion cracking is similar to the expansion of fatigue cracks [10], including the two stages of initiation and expansion. The incubation period of the crack initiation phase lasts for a long time, and the expansion rate is slow, when the crack grows to the small crack stage. Under the action of the service load, the expansion rate will gradually increase.

In this paper, using the concept of “field” in the numerical simulation software ABAQUS, the creep strain field of crack-containing materials is established by the finite element model to obtain the micro-mechanical parameters of the crack tip, and the influence of the crack length a on the crack tip creep is analyzed. The effect of different crack propagation stages on the crack tip creep field of SCC...
was quantitatively studied.

2. Establishment of finite element model

2.1 Materials and geometric models

Most of the experiments on stress corrosion at laboratory and abroad use standard compact tensile (0.5T-CT) specimens for structural material selection and safety assessment [11] [12]. The model still uses compact tensile specimens. Figure 1 is a schematic view of the dimensions of a sample of a compact tensile specimen in accordance with ASTM-E399.

![Fig.1 CT sample geometric model and size(mm)](image)

The Ramberg-Osgood model is a stress-strain relationship model established by Ramberg and Osgood in 1943 without a significant yielding platform. The theoretical model is used to describe the stress-strain relationship of a material near its yield point, and is mostly used in solid mechanics [13]. [14], at the same time the model is also suitable for nonlinear metal materials, 304 austenitic stainless steel is a power hardening material, its mechanical properties meet the RO model, the expression is as in formula 1 [15]:

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

Where \(\sigma\), \(\varepsilon\) are the actual stress and the actual strain, respectively, \(\sigma_0\) is the yield limit of the material, \(\varepsilon_0\) is the corresponding strain value when the stress reaches the yield limit, \(\alpha\) is the hardening coefficient, and \(n\) is the hardening index. By fitting the true stress-strain curve of 304 stainless steel, it can be known that the 304 austenitic stainless steel material parameters commonly used in the primary circuit of nuclear power are shown in Table 1.

| Material | Elastic modulus/MPa | Poisson's ratio | Yield/MPa | Offset coefficient \(\alpha\) | Hardening index \(n\) |
|----------|---------------------|----------------|-----------|-----------------------------|----------------------|
| 304SS    | 204.55              | 0.33           | 366       | 15.01                       | 2.38                 |

2.2 Load selection and calculation

The stress intensity factor is usually used to characterize the stress field of the crack tip in the fracture mechanics sample [16]. Whether the crack propagation factor is measured by the stress toughness of the material exceeds the fracture toughness of the material, so this part simulates the external load on the specimen. Characterized by the crack tip stress intensity factor. The literature shows that the crack tip K is generally selected from 10~50MPam\(^{1/2}\) [17] in the stress corrosion cracking test of stainless steel structural materials. The crack tip K applied in the finite element simulation calculation is set to 20MPam\(^{1/2}\). The relationship between the crack stress intensity factor K and the applied load and crack length of the compact tensile specimen is shown in Table 2 [18], and the calculated load in the numerical
simulation is applied to the reference point coupled to the upper and lower force surface of the specimen.

| a/w  | f(a/w) | a/w  | f(a/w) | a/w  | f(a/w) |
|------|-------|------|-------|------|-------|
| 0.450| 8.34  | 0.485| 9.23  | 0.520| 10.29 |
| 0.455| 8.46  | 0.490| 9.37  | 0.525| 10.45 |
| 0.460| 8.58  | 0.495| 9.51  | 0.530| 10.63 |
| 0.465| 8.70  | 0.500| 9.66  | 0.535| 10.80 |
| 0.470| 8.83  | 0.505| 9.81  | 0.540| 10.98 |
| 0.475| 8.96  | 0.510| 9.96  | 0.545| 11.17 |
| 0.480| 9.09  | 0.515| 10.12 | 0.550| 11.36 |

\[ K_I = \frac{P}{B \sqrt{W}} f\left(\frac{a}{W}\right) \]  \tag{2} 

\[ f\left(\frac{a}{W}\right) = \frac{(2 + \frac{a}{W})[0.886 + 4.64 \frac{a}{W} - 13.32 \left(\frac{a}{W}\right)^2 + 14.72 \left(\frac{a}{W}\right)^3 - 5.6 \left(\frac{a}{W}\right)^4]}{(1 - \frac{a}{W})^{3/2}} \]  \tag{3} 

Where \( K_I \) is the stress intensity factor, \( P \) is the load, \( B \) is the specimen thickness, \( W \) is the sample size, \( a \) is the crack length, and the initial \( a/W=0.5 \) is obtained by looking up Table 2, which can be calculated by formula (2). At this time, the value of the load \( P \) is 470N.

2.3 Finite element mesh model
The finite element global mesh model and the refined mesh model at the crack tip are shown in Fig. 2(a), where the global model has a mesh number of 13516 and the unit type is CPE4R. In order to obtain a more detailed and accurate creep variable at the crack tip, the sub-model technique is used to analyze the mechanical state of the crack tip, and the mesh at the crack tip of the sub-model is refined, while maintaining the sub-model mesh type and the main model. Consistent, the number of grids is 15027, as shown in Figure 2(b).

In order to characterize the stress and strain of the crack tip and the change of creep in more detail, observation paths 1 and 2 are respectively arranged along the circumferential direction of the crack tip and the crack propagation direction, as shown in Fig. 2(c).

2.4 Setting of boundary conditions
In order to prevent the rigid body from rotating and moving in the X direction during the stretching process, the center point of the loading hole is created as a reference point, and the reference point is coupled with the upper and lower force receiving holes, and then the movement of the reference point in the X direction is restricted. And the rotation in the Z direction is only realized by releasing the movement in the Y direction.
2.5 Creep numerical simulation process

The finite element analysis process of SCC creep is realized by two analysis steps: the first stage through Static Analysis, that is, the sample forms a stable crack tip stress strain field under the action of the crack tip stress intensity factor $K$; the second stage passes Creep analysis is used to obtain the influence of creep on the crack tip stress field under the time cumulative effect. It is achieved by setting the creep analysis step, and the creep equivalent loading time is $t=500h$. In the calculation process, the initial crack tip stress intensity factor $K_0=20\text{MPa}\cdot\text{m}^{1/2}$ and the initial crack length $a_0=2\text{mm}$ are guaranteed.

3. Calculation results and analysis

The crack length is set to 0.8, 0.9, 1.0, 1.1, and 1.2 times of the initial crack length $a_0$, respectively. Considering the actual working conditions, the crack length $a/W = 0.5$ and the crack tip stress intensity factor is $20 \text{MPa}\cdot\text{m}^{0.5}$. As the applied load, the influence of different crack lengths on the crack tip creep field is compared, and the relationship between crack length change and crack tip creep and creep rate is obtained.

3.1 Analysis of creep variables in crack tip regions

The distribution of the equivalent creep of the crack tip region is shown in Figure 3. The creep time is consistent and set to 500h. It can be seen from the figure that the high creep region is mainly concentrated in the near crack. In the tip region, at the same creep time, the area of the crack tip high creep variable increases with the crack propagation length, and the crack is in the relatively small creep region with the creep variable less than 0.03. The effect of the extended length on the creep variable is relatively small.
3.2 Effect of crack propagation length on crack tip creep and creep rate

The creep curve after creeping along the crack tip path 2 and the path 1 under different crack propagation lengths $a$ is shown in Figs. 4 and 5. It can be seen from Fig. 4 that the crack propagation length has little effect on the creep distribution on the horizontal path 2 of the crack tip, and is still bounded by the crack tip distance $r=1\mu m$. When the feature distance is smaller than the feature distance, the crack tip creep variable $\theta$ drops sharply. After the characteristic distance, the creep variable value has little effect and the data remains stable. It can be seen from Fig. 5 that there is a positive correlation between the creep variable and the crack propagation length, and the crack length increases the same proportion. Within the range, the increase of the creep variable gradually becomes larger, that is, the increase of the creep variable is slightly larger than the increase of the crack propagation length.

Figure 6 shows the creep distribution curve of the crack tip under different crack propagation lengths. In the first stage of creep, the creep variable of the crack tip has little change under different crack propagation lengths.
propagation lengths. As the creep progresses, the crack can be seen. The tip creep rate increases with the increase of the crack propagation length. It can be more clearly seen from Fig. 7 that the creep rate of the crack tip increases with the increase of the crack propagation length in the second stage of creep, but the increase is larger small.

![Graph showing creep time and equivalent creep strain](image1)

**Fig.6 Analysis of Influence of Crack Length on Crack Tip Creep**

**Fig.7 Analysis of the Influence of Crack Length on Crack Tip Creep Rate**

### 4. Conclusion

1. At the initial stage of creep, the crack length is positively correlated with the crack tip creep. In the steady creep stage, the creep rate of the crack tip under different plastic parameters is reduced.

2. The crack length of the material is positively correlated with the creep rate of the crack tip, and the increase of the crack length leads to the increase of the creep rate of the crack tip. As the creep progresses, the creep rate tends to the same level, and as the time continues to increase, the creep rate does not change much.

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