Effect of the Surface Scratch Angle on the Mechanical Characteristics of Nickel-Based Alloy

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Abstract. Stress corrosion cracking (SCC) produced by surface scratches has great effect on the safety and reliability of nuclear power plant. To understand the effects of the angle of surface scratches on SCC behavior of nickel-based alloy, the stress and strain field nearby the surface scratches of nickel based alloy is simulated using ABAQUS. Results show that the high stress and strain region increases as the angle increases, which lead to an increase in SCC growth rate. The high stress and strain region offset toward the scratch angle, which indicates that the crack is more likely to crack and extend along the direction of scratch angle.

1. Introduction
Generally, SCC is a failure mechanism that is caused by environment, susceptible material and tensile strain of nuclear power structural materials under high temperature and high pressure aqueous environments [1]. Owing to the oxide film formed on its surface, the nickel base alloy is a strong anti-corrosion material, and is commonly used to fabricate transfer tubes of pressurized water. However, research shows that surface scratch tends to appear during manufacture, transport and installation of steam generator [2]. And many research result also shows that surface scratch is one of important origins of SCC in steam generators, which also seriously threaten the safety and reliability of nuclear power plant [3-4]. Micro-cracks induced by surface scratch will also greatly influence the SCC when the corrosion-enhanced dislocation emission and motion reach a certain condition [5-6]. Mechanical state around the surface scratch is one of the main mechanical factors determining SCC crack growth rate for nuclear pressure vessels and steam generators [7].

However, the effects of the variation of the angle of surface scratch on mechanical field of nickel-based alloy has not been investigated and understood. Based on a finite element method (FEM), the effects of scratch angle on the SCC stress field was also analyzed, which is of great significance for the study of SCC crack initiation and propagation behavior.

2. Finite element modeling

2.1. Specimen geometric model
Figure 1 shows the cross-section morphology of Alloy 690TT under SCC using scratch technique in high temperature oxygenated water at 325 °C after constant load experiment [2]. Mechanical cracks is
produced at the bottom of scratch groove during slow strain rate tensile stage. The oxides were also formed on scratch groove.

Figure 1. Scratch section of stress corrosion cracking

A finite wide plate, tensile specimen with a single edge crack is selected to simulate this process. The plate width $W$ is 80 mm and length $2L$ is 160 mm, as shown in Fig.2(a). The $\alpha$ is the surface scratch angle and its values equals to $0^\circ$, $15^\circ$ and $30^\circ$ respectively in this study, which is shown in Fig.2(b).

Figure 2. Geometry size of finite wide plate specimen

The finite element mesh of the finite wide plate global model and the local region around the surface scratch are shown in Figure 3(a) and Figure 3(b), CPE8R is used in simulation and total number is 3819. To obtain a more accurate crack tip stress-strain, the mesh is refined around the surface scratch and its number is 1375.
2.2. Material model
The Ni-based Alloy 600 is a power-hardened material whose constitutive relationship is usually characterized by the Ramberg-Osgood relationship [8], and its form is as follows:

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

(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.

Material mechanical parameters of nickel-based alloy 600 are: Young’s modulus \( E \) is 190GPa, Poisson’s ratio \( \nu \) is 0.3, yield stress \( \sigma_{0.2} \) is 436MPa, strain hardening exponent \( n \) is 5.29 and the offset coefficient \( \alpha \) is 1 [9]. The main component of oxide film is \( \text{Cr}_2\text{O}_3 \), which is generally simplified as a linear elastic material, and its Young’s modulus \( E \) is 19GPa, Poisson’s ratio \( \nu \) is 0.3 [10].

2.3. Loading and boundary conditions
In surface scratch period, external load including working load and residual stress has little mechanical effect on the SCC, so the load in this period is mainly the film induced stress. Because of Aiming at the different coefficients of thermal expansion of the base metal and the oxide film, the growth process of oxide was simulated by expansion. The thermal expansion coefficient \( \beta \) and the temperature difference \( \Delta T \) was assumed to be 0.001 and 6 °C, respectively [5-6].

3. Results and Discussion
3.1. Effect of surface scratch angle on Mises stress of nickel-based alloy
With different surface scratch angle under the same film induced stress, the Mises stress distribution in front of the crack front is shown in Figure 4. Figure 4 shows that the region of high Mises stress at the crack front is smallest when the angle \( \alpha=0^\circ \) and the high stress region increases as the angle increases. Meanwhile, the Mises stress becomes small and small when the distance ahead of the crack front is larger. It also shows that the high stress region offset toward the direction of the scratch angle, which indicates that the crack is more likely to crack and extend along the direction of surface scratch.
3.2. Effect of surface scratch angle on PEEQ of nickel-based alloy

With different surface scratch angle under the same film induced stress, the PEEQ distribution in front of the crack front is shown in Figure 5. Figure 5 shows that the PEEQ at the crack front also increases as the angle increases. The larger the distance ahead of the crack front, the smaller the PEEQ is. It also shows that the high strain region offset along the scratch angle, which indicates that the crack is more likely to crack and extend along the direction of scratch angle.

4. Conclusions

(1) The high Mises stress region of nickel-based alloy increases as the surface scratch angle increases, and the larger the distance ahead of the crack front, the smaller the Mises stress is. The plastic strain has the same rules.

(2) The high stress and strain region offset toward the surface scratch angle, which indicates that the crack is more likely to crack and extend along the direction of scratch angle.

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