The synergy of corrosion and fretting wear process on Inconel 690 in the high temperature high pressure water environment

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HIGHLIGHTS

- The fretting damage in high temperature high pressure water environment was simulated.
- The synergy of fretting and corrosion behavior was investigated by a self-designed tester.
- Fretting damage was enhanced by corrosion process with the increment of temperature.
- The mechanism of fretting behavior in high temperature high pressure water was discussed.

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ABSTRACT

The synergistic effect of corrosion and fretting process of the steam generator (SG) tube was investigated by using a self-designed high temperature test rig in this paper. The experiments were performed at 100°C, 200°C and 288°C, respectively. The fretting corrosion damage was studied by optical microscopy (OM), scanning electron microscope (SEM), energy dispersive spectrometer (EDS), Raman spectroscopy and auger electron spectroscopy (AES). The results demonstrated that the corrosion process in high temperature high pressure (HTHP) water environment had a distinct interaction with the fretting process of Inconel 690. With the increment of temperature, the damage mechanism changed from a simple mechanical process to a mechanochemical process.

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1. Introduction

For the advantages of the high power generating efficacy and low greenhouse gas emission properties, nuclear power plant (NPP) have been widely built up all over the world. However, with the increment of the running time, lots of environmental degradations occurred on the NPP components. The most vulnerable structural component is the SG tube in the pressurized water reactor (PWR) [1–3]. In the past few decades, researchers mainly focused on the stress corrosion crack (SCC) of PWR-SG for its apparent damage phenomenon, few attentions were paid on the fretting issues. Recently, the fretting damage gradually appears and grows into one of the major problems of the SG tube with the increment of service time. In this case, to study the fretting damage of SG-tube is very important and urgent for people to understand the safety issues of the NPP.

Fretting damage is a high frequency tribological issue, which occurs at the joint point between the SG tube (Inconel 690 alloy) and its supportor (304 SS) at the secondary side in PWR-SG at 288°C. At the same time, high temperature corrosion also occurs at this joint point. In this case, fretting damage of the SG-tube is a complex process of fretting and corrosion. Up to now, many fretting related works have been done at room temperature, high temperature dry condition, pure water, corrosive medium and so on [4–9]. However, the synergistic effect of fretting and corrosion, which occurs in the real PWR-SG working condition, has not been widely studied yet. A fretting test rig in HTHP water has been introduced to
fretting test by other researchers [10]. However, it could only conduct the fretting fatigue test. Meanwhile, it cannot maintain a stable amplitude and normal force on the fretting pairs, which are critical parameters for the fretting damage [11,12]. Moreover, these works did not reveal how exactly the fretting damage interacts with the corrosion process in HTHP environment due to the limitation of the equipment. Our previous works have performed the fretting test under corrosive environment [13]. However, the attention was mainly paid to the evolution of material degradation process, the synergic effect of fretting and corrosion was not discussed in detail yet.

In this paper, a self-designed test rig, which guarantees a stable fretting amplitude and normal force, was used to conduct the fretting corrosion test in the autoclave with a high frequency tensile testing machine. A water chemistry controlling system was also introduced into this test. It can control the dissolved oxygen (DO) and dissolved hydrogen (DH) to simulate the PWR secondary water chemistry. The synergy of the fretting and corrosion process of the SG tube in HTHP environment was investigated in detail.

2. Experimental

Tables 1 and 2 show the chemical compositions of Inconel 690 and 304 SS (wt.%). Fig. 1 shows the schematic of the fretting test system. The test rig was set in an autoclave at 288 °C with a water pressure of 8.5 MPa [14]. A ball-on-plate (304 SS ball and Inconel 690 plate) fretting system was used to simulate the SG tube and its supportor. While the machine was running, the 304 ball could load a steady normal force on the Inconel 690 plate. Meanwhile, a relative movement occurred at the contact point between the ball and the plate. The experiments were carried out at a normal force of 150 N, a frequency of 20 Hz and a displacement amplitude of 500 μm. The time duration for one test was 2 h. These parameters are selected according to the structure of our self-designed fretting test rig. The detailed elaboration could be found in our previous work [14]. The test temperatures are 100 °C, 200 °C and 288 °C. The pressure and the DH were kept at 8.5 MPa and 10 ppb (μg/kg), respectively. However, the DO was kept at 200 ppb (μg/kg), which is higher than the actual DO in PWR secondary water (usually less than 5 ppb). This is because the actual corrosion rate of the SG tube in secondary water is very slow. In case to investigate the synergistic effect of the corrosion and fretting process, an acceleration test was taken into consideration. At the same time, the pH value of the secondary water usually is kept at 9.8 to provide enough corrosion resistance of Ni based alloy which used as the tube material in the real working condition. However, considering the temperature also plays a critical role on corrosion in this experiment, a pure water was used to reduce the variables of the corrosion process. The Inconel 690 plate was cut into 10 mm × 10 mm × 1 mm and solution treated at 1110 °C for 5 min and tempered at 715 °C for 5 min. Then the surface was polished by diamond paste to 0.02 μm and ultrasonically cleaned in ethanol.

After the test, the morphologies were observed by optical microscope (OM) and scanning electron microscope (SEM). The chemical composition was analyzed by energy dispersive spectrometer (EDS) and Raman spectroscopy. The elemental depth profile was detected by auger electron spectroscopy (AES) by continuous sputtering.

3. Results

Fig. 2 shows the morphologies of the oxide particles on the surface of Inconel 690 at 288 °C. Fig. 2a shows the worn scar and its surrounding area. Fig. 2b–f shows the magnified morphologies of positions 1, 2, 3, 4 and 5 in Fig. 2a. As shown in Fig. 2a, an ellipse-shape oxide ring is found at the surrounding area of the worn scar. From the magnified images (Fig. 2b–f), it can be clearly observed that this oxide ring can be divided into five different regions according to their different morphologies. As shown in Fig. 2b, no oxide could be observed and the surface is clean. Only some slight scratches could be found on the surface, which should be introduced by the polishing process during the sample preparation. As shown in Fig. 2c, a thin and dispersed sheet-like oxides lie on the surface. Through the oxides, the bare surface could still be seen. Several pyramid oxide particles are lying on the top of the sheet-like oxides. In Fig. 2d, more pyramid oxide could be found, which looks like a typical double layer oxide structure: an outer pyramid oxide layer covers an inner sheet-like oxide layer. In this experiment, the oxide layer is very thin which might due to the short testing time. As shown in Fig. 2e, both sheet-like and pyramid oxides disappeared, only a needle-like oxide layer can be observed. These needle-like oxides are even thinner than previous observed oxides. In Fig. 2f, the oxides become very small on the outer most region. Except position 1 (without visible oxide) and position 5 (with very limited oxide), obvious oxide particles can be observed in a considerable amount in other 3 regions. Fig. 2 reveals that the different oxide types generate on different locations and no oxide can be found on other place of the specimen. This is unique by comparing with the oxides found in general corrosion tests on Ni based alloy [15–17]. This demonstrates that the oxides formed near the worn scar might be influenced by the fretting process.

Fig. 3 shows the Raman spectroscopy of positions 1, 2, 3 and 4 in Fig. 2. According to the SEM results, position 1 is basically bare metal. Therefore, no obvious shift shows at position 1, which

| Table 1
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<th>Chemical compositions of Inconel 690 (wt.%).</th>
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<td>C</td>
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| Table 2
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<th>Chemical compositions of 304 SS (wt.%).</th>
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<td>C</td>
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<td>0.018</td>
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Fig. 1. Schematic diagram of fretting corrosion test rig in 288 °C water with a pressure of 8.5 MPa [14].
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