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Fretting corrosion fatigue of Alloy 690 in high-temperature pure water

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ABSTRACT

Fretting fatigue behavior of Alloy 690 in room-temperature (RT) air and high-temperature pure water was investigated under the condition of a normal load of 100 N. Fretting fatigue life in high-temperature water reduced by about 30% compared to that in RT air due to combined effects of high-temperature water and highly localized tangential stress. The main fatigue cracks were inclined to initiate in the crevice region along the contact edges in high-temperature water, but none was observed in RT air. Related mechanisms of fretting corrosion fatigue failure of Alloy 690 in high-temperature water are discussed.

1. Introduction

Nickel-based Alloy 690 with high corrosion resistance, good creep rupture property and high-temperature strength has been extensively used as an important structural material for steam generator (SG) tubes in pressurized water reactors (PWRs) [1–4]. To ensure its safe service in PWRs, numerous researches have been focused on the environmental degradations, such as pitting, stress corrosion cracking (SCC) and corrosion fatigue (CF) [5–15]. Thus far, the CF behavior of Alloy 690 in high-temperature pressurized water has been investigated in detail, including the effects of temperature, dissolved oxygen, strain rate, strain amplitude, inclusions and so on [14–18].

Fretting fatigue, a typical type of fatigue, results from infinitesimal relative surface motion between two contact materials while cyclic fatigue load is applied. In PWRs, fretting fatigue is a popular CF degradation phenomenon between the SG tubes and anti-vibration bars/tube supports [19,20]. During operation, inevitably subtle amount of vibration may occur due to the flow-induced vibration and thermal stratification. With increasing service time, the fretting fatigue failure of Alloy 690 SG tubes tends to occur [9]. To ensure the safe operation of PWRs, it is necessary to investigate the fretting corrosion fatigue of Alloy 690 in high-temperature pressurized water and to clarify the related degradation mechanisms. However, due to the limitation of simulating equipment and technology, previous work on the fretting fatigue of Alloy 690 was mainly conducted in RT and high-temperature air [21,22], little work has been done in high-temperature water environments.

In the present work, the fretting fatigue behavior of Alloy 690 in RT air and high-temperature pure water (285 °C and 7.8 MPa) was investigated. The differences in fatigue lives and morphologies of the fretting fatigue scars were identified. The effects of high-temperature water environment on fretting fatigue behavior and cracking characteristics were also discussed.

2. Experimental

2.1. Materials and specimens

Nickel-based Alloy 690 and type 405 stainless steel (SS) were used in the present work. Table 1 shows their compositions. The Alloy 690 was used as the fretting fatigue specimen, and its microstructure is shown in Fig. 1, consisting of a typical austenite structure. The type 405 SS was used as the contact pad.

The shapes and dimensions of the fretting fatigue specimen and the contact pad used in the present work are shown in Fig. 2. A kind of plate fatigue specimen was designed according to ASTM E606-04 [23]. The contact mode between the fatigue specimen and the contact pad is flat-on-flat contact mode as shown in Fig. 3, and the theoretical contact area is 3 mm × 3 mm. Before the tests, all the surfaces of the fatigue specimens were ground to #1000 emery papers and the contact pads were cut directly from the as-received anti-vibration bars. Both of the fatigue specimens and the contact pads were cleaned with acetone in an ultrasonic cleaner.

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Table 1
Compositions of Alloy 690 and type 405 SS (wt.%).

Material	C	N	Mn	P	Si	S	Al	Ti	Cr	Fe	Ni
Alloy 690	0.03	0.013	0.29	0.007	0.29	0.001	0.20	0.20	29.73	10.5	57.7
405 SS	0.06	–	0.50	0.014	0.46	0.002	0.14	–	12.90	85.6	0.14

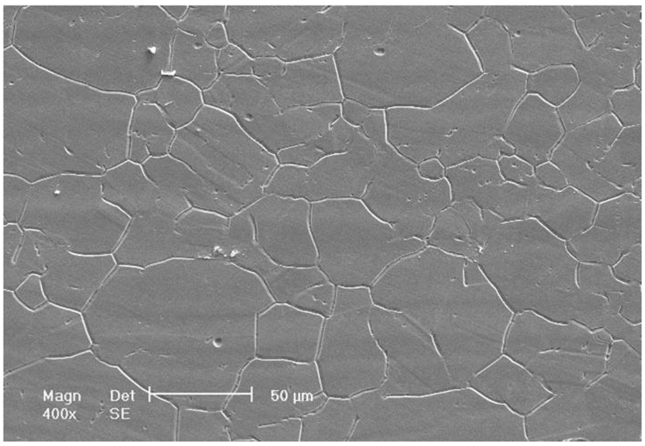

Fig. 1. SEM morphology of microstructure of nickel-based Alloy 690.

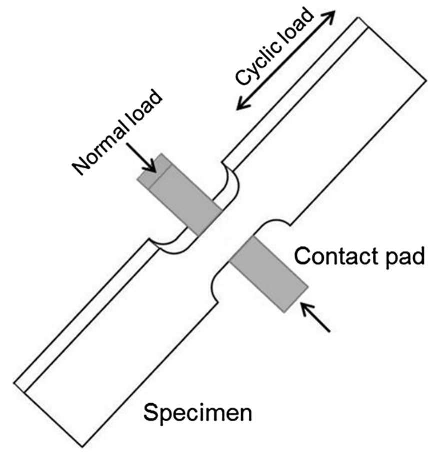

Fig. 3. Schematic illustration of flat-on-flat contact mode.

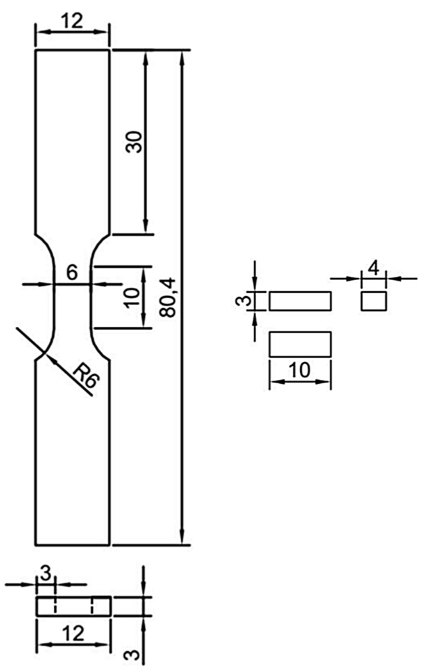

Fig. 2. Shapes and dimensions of fretting fatigue specimen and contact pad.

2.2. Methodology

The contact normal load was applied to the specimen surface through the contact pad by a kind of compression spring. The compression springs used in the tests were made of Hastelloy. It was a kind of Ni-based alloy with good corrosion resistance and thermostability. The value of the normal load was applied according to the Hooke's law. For a certain compression spring, the elastic coefficient is constant, once the applied normal load is determined, the corresponding compression spring length can be calculated. To reduce the error to the greatest extent, the lengths of the compression springs were measured before and after each test. The purpose was to make sure no plastic deformation happened and ensure a constant elastic coefficient during the test. In the present tests, the applied normal load was 100 N, and the error range of the normal load was well within ± 1%. The fretting fatigue tests in high-temperature pure water were performed in an autoclave with a water loop and a linear variable differential transformer (LVDT) system was employed to monitor the strain of the specimen gauge length in high-temperature water in situ [14,15]. The test parameters and conditions are summarized in Table 2. The fretting fatigue tests were performed in axial stroke control mode with triangular waveform. The displacement error of the fatigue testing machine was under 0.15% and the RT was 25 ± 1 °C. Under the high-temperature water condition, the autoclave was holding at 285 °C for 1 h before the cyclic load was applied. The fatigue life was defined as the number of cycles for the tensile stress drop 25% from its peak value.

After the fretting fatigue tests, the states of the contact surface and subsurface of Alloy 690 specimens were investigated. The surface macro morphologies were detected by an OLS4000 3D measuring laser microscope. The oxide characteristics on the surfaces were analyzed by a BWS905 custom Raman system. The micro morphologies of the contact surfaces and the longitudinal section state of the subsurface were analyzed by a scanning electron microscope (SEM) (FEI XL30). The subsurface deformation states on the longitudinal section of the specimens were inspected using a SEM (ZEISS MERLIN Compact) with an electron back scattered diffraction (EBSD) system.

Table 2
Fretting fatigue test conditions and parameters.

	Air	Water
Control mode	Stroke	
Waveform	Triangle	
Strain amplitude	0.15–0.45%	
Strain rate	$1\%\,s^{-1}$	
Strain ratio	−1	
Normal load	100 N	
Temperature	RT	285 °C
Pressure	1 atm	7.8 MPa
Dissolved oxygen	–	≤ 5 ppb