Wear 414–415 (2018) 194–201

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Time-dependent wear behavior of alloy 690 tubes fretted against 405 stainless steel in high-temperature argon and water

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ARTICLE INFO

Keywords:
Alloy 690
Fretting wear
Corrosion
Microstructure

ABSTRACT

Fretting wear caused by flow-induced structural vibrations is a concern in the nuclear industry. The wear behavior of alloy 690 steam generator (SG) tube fretting against AISI 405 stainless steel, and exposed to 285 °C water and argon, was investigated using a fabricated apparatus. Compared with argon, high temperature water contributes to the removal of wear particles and the formation of oxide scale on the wear scar. Fretting promotes tribo-corrosion of alloy 690 in high temperature water and that results in the formation of a stable oxide scale. That oxide scale on the wear scar reduces the wear coefficient of the material and progressively changes the wear mode from one of delamination to one dominated by abrasion.

1. Introduction

In nuclear power plants (NPPs), fretting related failure of cladding tubes [1,2] and steam generator (SG) tubes [3,4] has always been a problem for the safe operation of NPPs. Alloy 690 has been used for producing SG tubes and their fretting wear behavior has been studied a lot. Lu [5] reported that the subsurface damage mechanism of Inconel 690 alloy induced by fretting wear is mainly deformation, oxidation, fatigue and delamination cracks. Kim's work [6] indicated that the oxidation of Alloy 690 can enhance the wear resistance by preventing metal-to-metal contact and material transfer. Cai [7] reported that delamination and abrasive wear are the main failure mechanism for alloy 690 under fretting conditions. The above research gives very meaningful results about the fretting wear behavior of alloy 690. Until now, most of the research about fretting wear of alloy 690 tube has been carried out in room temperature water or high temperature air. Experiments conducted in high temperature water are necessary to study the fretting wear behavior of alloy 690 in service environment.

Passive film can be formed on the surface of Fe-Cr-Ni alloys exposed to high temperature water [8,9], which protects the matrix from being further oxidized by hindering the outward diffusion of metallic ion and inward diffusion of oxygen. In the fretting process, the passive film can be broken due to the relative sliding between frictional pairs [10,11], which improves the oxidation rate of the materials in high temperature water. However, few research has been carried out to directly evaluate the evolution of microstructure and wear mode of alloy 690 in high temperature water with the increase of testing cycles. In addition, the fretting wear mechanism of alloy 690 tube in high temperature water is complicated because mechanical wear and corrosion act on this process simultaneously. So, it is necessary to compare the fretting wear behavior of the materials in corrosive and inert environment to isolate the effects of high temperature water.

In the present research, fretting wear tests of alloy 690 tube have been carried out in high temperature water and argon for different time. The morphology and composition of the wear scars on alloy 690 tube were analyzed to reveal the fretting wear mechanism.

2. Experimental procedure

The material used in this research was thermally treated alloy 690 tube with chemical composition of 0.023% C, 0.002% S, 0.3% Si, 0.008% P, 0.23% Mn, 0.25% Al, 9.6% Fe, 30.3% Cr and Ni balance (wt %). 405 stainless steel (SS) with chemical composition of 0.50% Ni, 12.5% Cr, 0.15% Al, 0.056% C, 0.60% Si, 0.58% Mn, 0.013% S, 0.025% P and Fe balance was used as counter materials. The microstructure of alloy 690 tube and 405 SS is illustrated in Fig. 1. The average grain size in alloy 690 is 63 μm and for 405 SS, the average grain size is 52 μm.

The experiments were carried out on the fretting wear testing system, as shown in Fig. 2. The test machine and configuration of the specimens were the same as that used in reference [12,13]. The alloy 690 tube specimen has the following specification: external diameter = 17.5 mm, inner diameter = 15.5 mm, length = 16 mm. The

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https://doi.org/10.1016/j.wear.2018.08.009
Received 7 March 2018; Received in revised form 6 August 2018; Accepted 14 August 2018
Available online 15 August 2018

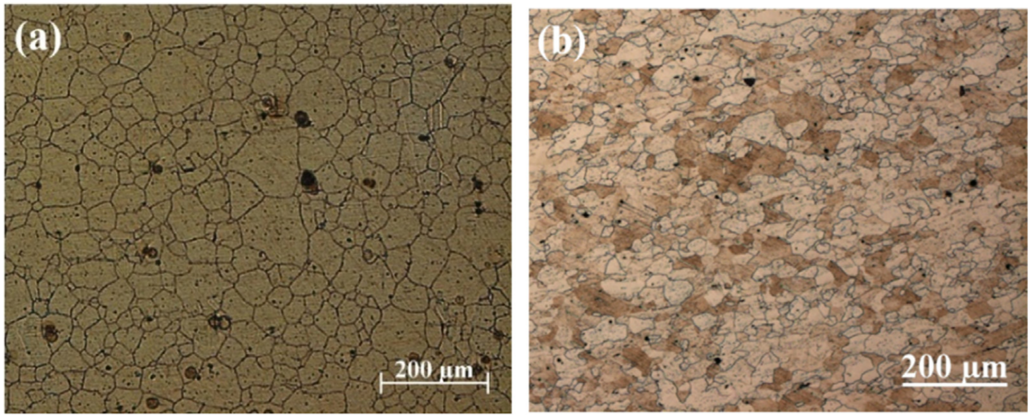

Fig. 1. Microstructure of (a) alloy 690 and (b) 405 SS.

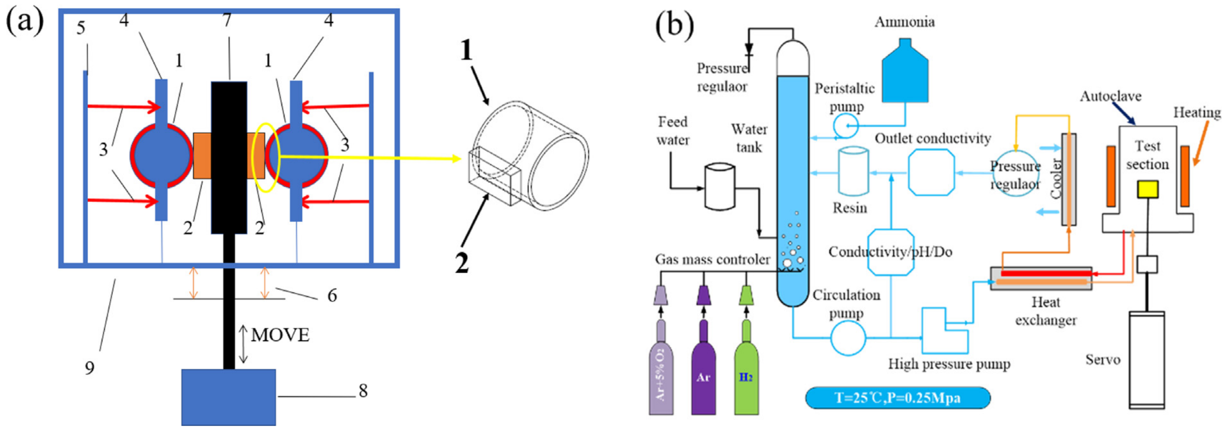

Fig. 2. Schematic diagram of (a) fretting wear tester: 1-tube specimen; 2-plate specimen; 3-springs; 4-holder of the Alloy 690 tube specimen; 5-spring plate; 6-displacement sensor; 7-holder of plate specimen; 8-servo motor; 9-autoclave; (b) fretting wear testing system.

405 SS plate specimen is $7.6 \times 12.2 \times 3\,mm^3$. The schematic diagram of fretting wear testing system is shown in Fig. 2a. The normal load was controlled by the springs. The displacement amplitude and frequency were controlled by the servo motor. And the displacement was measured by displacement sensor. Fretting wear tests with sliding amplitude of 100 µm, normal load of 40 N and frequency of 5 Hz were carried out in an autoclave that simulated the secondary water environment for 5×10^5 cycles, 2.5×10^6 cycles and 5×10^6 cycles. In pressurized water reactor (PWR), the temperature of the secondary water is in the range of 270–320 °C [6], so in this research, the testing temperature is chosen as 285 °C and the pressure is set as 8.6 MPa to make sure the liquid state of the water in the autoclave. The autoclave was connected to a water controlling loop system to control the water chemistry, as shown in Fig. 2b. Stable water chemistry (pH of 9.75 and dissolved oxygen content of lower than 5 ppb in mass) in the autoclave was maintained by a high-pressure metering pump at a refresh rate of two autoclave volumes per hour. Fretting wear tests were also carried out in 285 °C argon for 5×10^5 cycles and 5×10^6 cycles, and the other testing parameters were the same as that in high temperature water.

Morphology of the wear scars was examined by 3D optical microscope (Bruker Contour GT-I) and scanning electron microscopy (SEM). A TESCAN FE-SEM (GAIA3 GMU Model 2016) equipped with Dual-Beam focused ion beam (FIB) was used to prepare transmission electron microscopy (TEM) specimens of the cross section of the wear scar. FEI Talos F200X TEM was used to examine the microstructure and composition of the cross section of the wear scar.

3. Results and discussions

Fig. 3 shows the 3D-profile micrographs of the wear scars on alloy 690 tubes tested in high temperature water and argon for different cycles. For the specimens tested in water, the area of the wear scar increases with the increase of testing cycles. However, for the specimens tested in argon, no wear pit is observed, regardless of the testing time. Instead, the height of the wear scar is higher than the surrounding materials. In addition, the area of the wear scar on the specimens tested in argon does not change much with the increase of testing time.

The comparison between wear scars on alloy 690 tested in water and argon indicates that high temperature water has an obvious effect on the transportation of the wear debris in the fretting process: the wear debris is moved from the center of the wear scar to the edge and accumulates on it. So, the height of the materials around the wear scar is obviously higher, as shown in Figs. 3a, 3b and 3c. Argon has no ability to transport the wear debris, which is sticky on the wear scar and the height of the wear scar increases.

The wear volume of alloy 690 tube tested in water and the area of the wear scar on alloy 690 tube tested in argon are calculated (four specimens are used to obtain the average value) and shown in Fig. 4. With the increase of the testing cycles from 5×10^5 to 5×10^6, the wear volume of alloy 690 tube tested in water increases by 6.57 times, however, the area of wear scar on the specimen tested in argon only increases by 11.65%. The cross-sectional profile of the wear scar on alloy 690 tube tested in water (the point where the wear depth is the