Nuclear Engineering and Design 327 (2018) 51–60

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Effect of temperature on fretting wear behavior and mechanism of alloy 690 in water

Ping Lai[a], Xiaochuan Gao[b], Lichen Tang[c], Xianglong Guo[a,*], Lefu Zhang[a]

[a] School of Nuclear Science and Engineering, Shanghai Jiao Tong University, No. 800 Dongchuan Road, Shanghai 200240, China
[b] The First Middle School of Linyi, No. 57 Yinqueshan Road, Linyi, China
[c] Shanghai Nuclear Engineering Research & Design Institute, No. 29 Hongcao Road, Shanghai 200233, China

ARTICLE INFO

Keywords:
Fretting wear
Alloy 690
Temperature
Glaze layer

ABSTRACT

The tangential fretting wear of alloy 690 tube mated with 405 stainless steel (SS) plate exposed to different temperature water was investigated. The worn surfaces were examined with optical microscope (OM), scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and 3D microscopy. The cross-section of wear scar was examined with transmission electron microscope (TEM). The results indicate that temperature has a significant effect on fretting wear of alloy 690 in water. The principle wear mechanism is delamination and abrasive wear at room temperature and 90 °C, however, the principle wear mechanism changes to be abrasive wear at 285 °C and 350 °C. The wear depth of alloy 690 tube tested in 90 °C water is the highest among all the tests. Wear affected zone (WAZ) is defined on the surface of alloy 690 tube tested in high temperature water, and there is protective oxide glaze layer formed on specimen exposed in 285 °C and 350 °C water. WAZ and oxide glaze layer formed in high temperature water can enhance wear resistance.

1. Introduction

Steam generator is one of the most important components in pressurized water reactor. Alloy 690 is widely used as tubing material for steam generator in nuclear power plants (Xin et al., 2016a; Zinkle and Was, 2013). Due to flow-induced vibration, the tubes of steam generator are expected to vibrate with small amplitude oscillatory motion against their supporters, which results in the occurrence of fretting wear at the contacting surface between steam generator tube and anti-vibration structure (Wang, et al., 2016; Yong et al., 2014). Fretting wear is likely to cause catastrophic failure (like the fretting-related leaking) (Kwon et al., 2011; Lee et al., 2001) that brings economic loss and environmental disaster.

Extensive researches have been carried out to study the effects of testing parameters, such as displacement (Chung and Lee, 2011; Li and Lu, 2013; Yong et al., 2014), normal force (Xin, et al., 2016a; Lim et al., 2003), temperature (Jeong et al., 2005; Mi et al., 2016), frequency (Yong et al., 2014) and water chemistry (Jeong et al., 2005; Zhang et al., 2014) and pH (Wang et al., 2016)), on the fretting wear of steam generator tube materials. Those researches indicated that the wear mechanism of alloy 690 tube was mainly delamination in air (Jeong et al., 2005). Besides, the steady value of coefficient of friction (COF) firstly increased then decreased with the increase of air temperature. The results also indicated that the wear volume of alloy 690 in 285 °C air was smaller than that in room temperature (RT) air, due to the formation of glaze layer (the smooth area on the tube surface) at high temperature (Mi et al., 2016). For alloy 690, the width of the wear scar and the wear volume increased with water temperature increasing from RT to 90 °C (Jeong et al., 2005; Mi et al., 2016). In the fretting wear process, particles, which usually act as solid lubrication, can be formed on the worn surface. However, most of them were carried out in high temperature air, room temperature air or room temperature water, and experiments carried out in high temperature water are of great necessity to study the fretting wear behavior of alloy 690 tube in service condition.

Oxide film, which is easily formed in high temperature water (Kuang, et al., 2017), can enhance wear resistance (Mi et al., 2016; Yun et al., 2016). However, Argibay and Sawyer (2012) has reported that oxidation is not always good for the increase of wear resistance. In the water environment, water can not only act as lubrication, but also promote the removal of wear particles (Xin et al., 2016a). The oxidizability of water will be enhanced with the increase of temperature, which can promote the formation of oxide scale. At the same time, the viscosity relating to the lubrication ability of water decreases with temperature. Thus, the fretting wear behavior and mechanism in water is partly different from that in air and needs further research.

Fretting wear experiments were mostly carried out by using ball-on-

* Corresponding author.
E-mail address: guoxianglong@sjtu.edu.cn (X. Guo).

https://doi.org/10.1016/j.nucengdes.2017.12.007
Received 7 April 2017; Received in revised form 1 December 2017; Accepted 3 December 2017

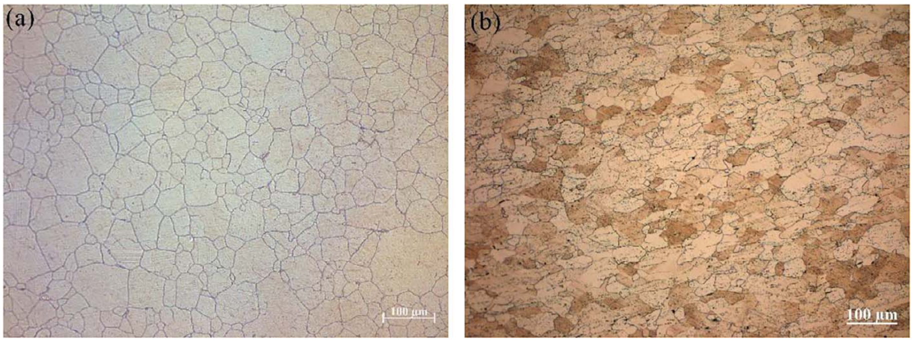

Fig. 1. Microstructure of (a) alloy 690 and (b) 405 SS.

Table 1
Chemical composition of alloy 690 and 405 SS in wt%.

Chemical composition	Ni	Cr	Fe	Al	C	Si	Mn	S	P
Alloy 690	Bal.	30.3	9.6	0.25	0.023	0.30	0.23	0.002	0.008
405 SS	0.50	12.5	Bal.	0.15	0.056	0.60	0.58	0.013	0.025

plate contact (Li et al., 2015), crossing tube contact (Chung and Lee, 2011), or tube surface machined into a rectangular shape against plate contact (Lim et al., 2003; Yun et al., 2016). Only a few investigations were carried out with tube-on-plate contact between steam generator tube and anti-vibration bar materials in high temperature water. In addition, tube-on-plate contact is similar to the practical operating condition of nuclear power plant.

In this work, fretting wear tests were carried out on alloy 690 in low and high temperature water. The effects of temperature on the fretting wear behavior alloy 690 were studied. The microstructure and composition of the wear scar was analyzed to reveal the failure mechanism of the materials.

2. Material and experimental procedure

2.1. Test specimens

The materials used in this study are alloy 690 (steam generator tubes, R_a = 0.254 μm) and 405 SS (anti-vibration bars, R_a = 0.376 μm), which have been widely used in nuclear industry. The microstructure and chemical composition of the materials are shown in Fig. 1 and Table 1, respectively. The alloy 690 tube specimen has the following specification: external diameter = 17.5 mm, inner diameter = 15.5 mm, length = 16 mm. The 405 SS plate specimen is 7.6 × 12.2 × 3 mm^3. Before and after testing, all specimens were ultrasonically cleaned in ethyl alcohol and dried with hot compressed air.

Table 2
Experimental parameters for fretting wear test.

Parameter	Value (unit)
Temperature (pressure)	RT (2 MPa), 90 °C (2 MPa), 285 °C (10 MPa), 350 °C (18 MPa)
pH	9.75
DO	< 5 ppb
Frequency	5 Hz
Cycles	5,00,000
Displacement	100 μm
Normal force	40 N

2.2. Fretting wear test and analysis

The experiments were carried out on a fretting wear testing equipment with a tube-on-plate contact configuration (Guo et al., 2017), as shown in Fig. 2. The axial direction of alloy 690 tube was parallel to the

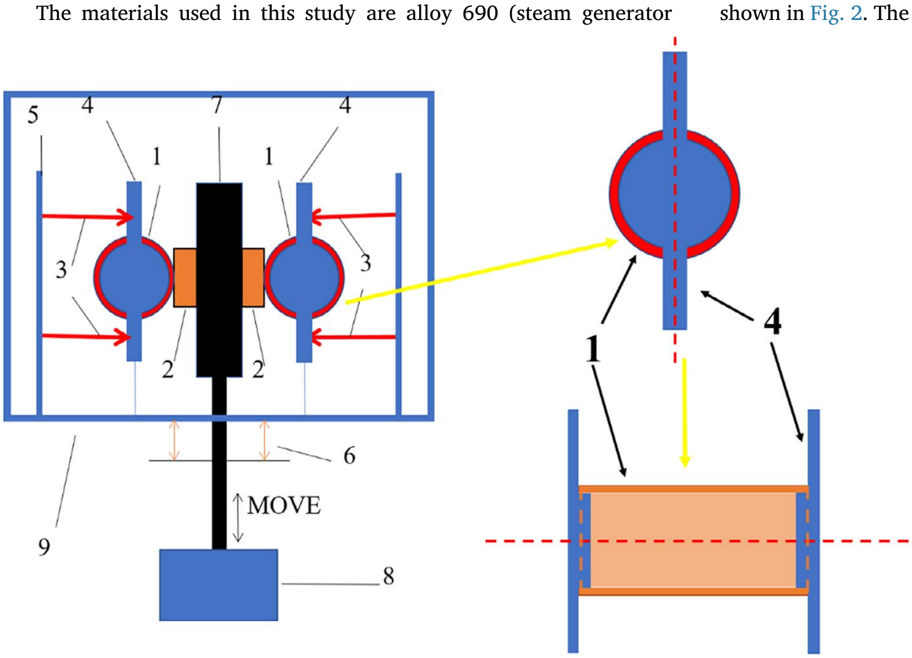

Fig. 2. Schematic diagram of fretting wear tester: 1-tube specimen; 2-plate specimen; 3-springs; 4-holder of the Alloy 690 tube specimen; 5-spring plate; 6-displacement sensor; 7-holder of plate specimen; 8-servo motor; 9-autoclave.