Wear 400–401 (2018) 119–126

Contents lists available at ScienceDirect

Wear

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

# Fretting wear of alloy 690 tube mated with different materials in high temperature water

Xianglong Guo[a,*], Ping Lai[a], Lichen Tang[b], Junqiang Lu[b], Jiamei Wang[a], Lefu Zhang[a]

[a] School of Nuclear Science and Engineering, Shanghai Jiao Tong University, No. 800 Dongchuan Road, Shanghai 200240, China
[b] Shanghai Nuclear Engineering Research & Design Institute Ltd. Co., No. 29 Hongcao Road, Shanghai 200233, China

ARTICLE INFO

*Keywords:*
Alloy 690
Fretting wear
High temperature water
Corrosion
Anti-vibration bar materials

ABSTRACT

Fretting wear of alloy 690 steam generator heat exchange tube against different anti-vibration bar materials is studied in simulated secondary water conditions of pressurized water reactors (PWR). The results indicate that the wear mode of alloy 690 is largely dependent on the mating materials, and the material transfer during wear influences the corrosion resistance of alloy 690. The depth and volume of the wear scar on alloy 690 is the lowest when the mating material is as-received and heat-treated 405 stainless steel, respectively. When the mating material contains higher chromium content, the wear resistance of alloy 690 tube is increased due to the chromium transferred from the mating material to alloy 690 in the fretting process.

## 1. Introduction

According to the survey carried out by Dow [1], about 60 pressurized nuclear power reactors were reported fretting related leaking of steam generator (SG) heat exchange tube in the years from 1992 to 1993, mainly due to the flow induced vibration between the SG tube and the anti-vibration bars (AVB) [2,3]. In 2012, San Onofre Nuclear Generating Station (SONGS) Unit 3 was unplanned shutdown due to the fretting damage of SG tube [4]. So fretting wear between SG tube and AVB is still a threat to the safety of the nuclear power plant. Lots of experimental and numerical work [5–9] has been carried out to reveal the effects of testing parameters, such as temperature, displacement, normal load and water chemistry, on the fretting wear behavior of the SG tube. With the temperature increasing from room temperature to over 300 °C, the wear resistance of alloy 690 firstly decreases then increases, no matter tested in air or water [10,11]. The synergy effects of displacement and normal force on fretting wear of materials exist. When the displacement is high and the normal force is low, the fretting wear is prone to be in the gross slip regime, however, at low displacement and high normal load, the fretting wear is prone to be in the stick regime [12]. Those research results provide the designers and operators with useful information to improve the safety of the nuclear power plant (NPP).

Nowadays most of SG tubes are made of alloy 690, except some are made of alloy 800. The fretting wear analysis indicates that the wear mode of SG tubes is either abrasive or delamination wear [13,14], depending on the testing parameters. In high temperature and pressure water environment, the mechanical properties of the frictional pair materials, such as hardness and elastic modulus [15,16], are key parameters that determine the wear rate and mechanism. It has been reported [17] that when sliding distance is constant, the wear rate of alloy 690 against 409 stainless steel (SS) is much lower than against 405 SS. Therefore, revealing the effects of different mating materials on the fretting wear behavior of SG tube is of great importance for the selection of the best materials for manufacturing anti-vibration bar.

The present research aims to evaluate the effects of different anti-vibration bar materials on the fretting wear behavior of alloy 690 tube exposed to high temperature water. 405 SS in as-received and heated treated state, alloy 600 and chromium plated alloy 600 were used for manufacture of anti-vibration bar specimens. The fretting wear mechanism of different frictional pairs has also been discussed.

## 2. Experimental procedure

Commercial nuclear grade alloy 690 tube (690) was used for the fretting wear tests. 405 SS in as-received state (405) and heat-treated state (405HT), alloy 600 (600) and chromium plated alloy 600 (600Cr) were used for producing anti-vibration bar specimens. The microstructures of the materials are shown in Fig. 1. The hardness of the testing materials was examined and the results are shown in Fig. 2. It is observed that the hardness of all anti-vibration bar materials is higher than that of alloy 690. The hardness of 405, 405HT and alloy 600 is similar, whereas that of chromium plated alloy 600 is much higher and about 2.7 times as high as alloy 690.

* Corresponding author.
*E-mail addresses:* guoxianglong@sjtu.edu.cn (X. Guo), lfzhang@sjtu.edu.cn (L. Zhang).

https://doi.org/10.1016/j.wear.2018.01.001
Received 7 September 2017; Received in revised form 2 January 2018; Accepted 2 January 2018
Available online 04 January 2018

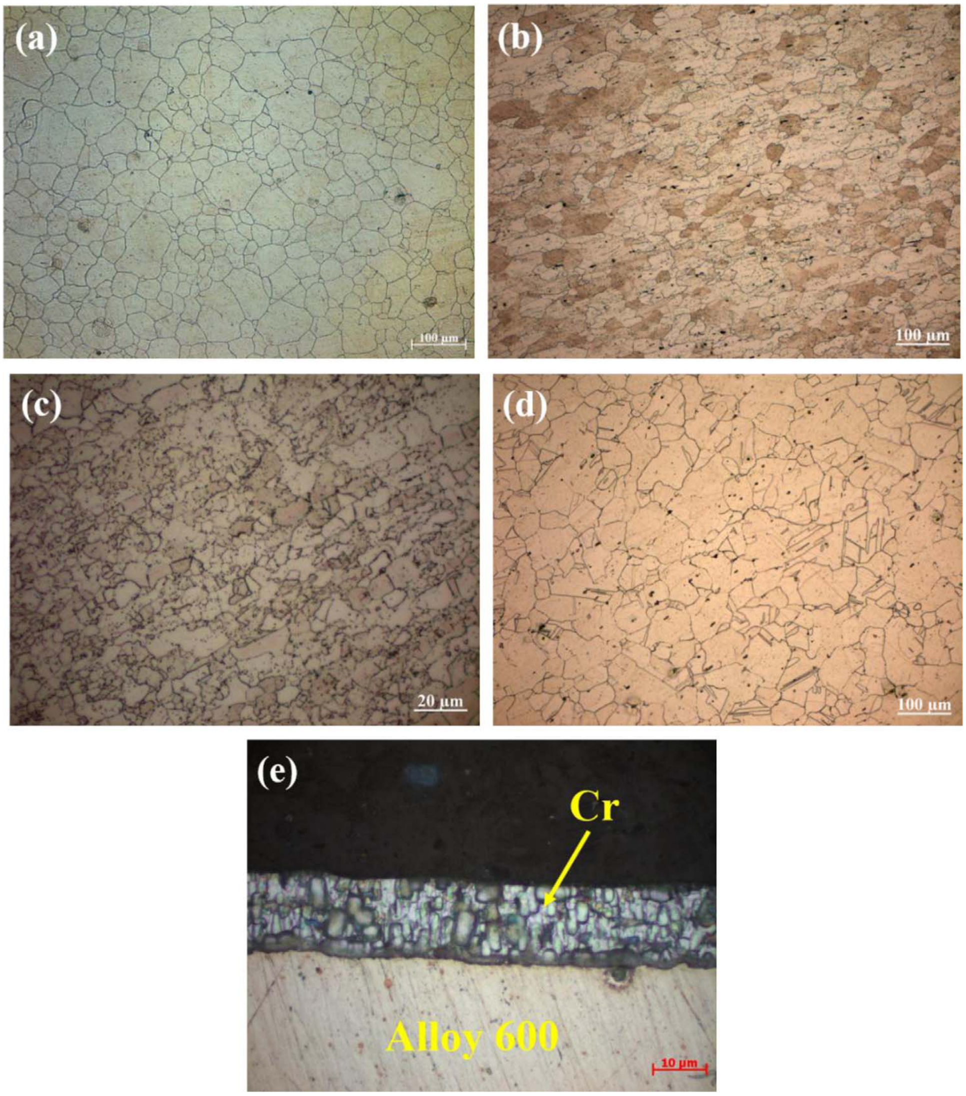


**Fig. 1.** The microstructures of (a) alloy 690; (b) 405; (c) 405HT; (d) 600; (e) 600Cr.

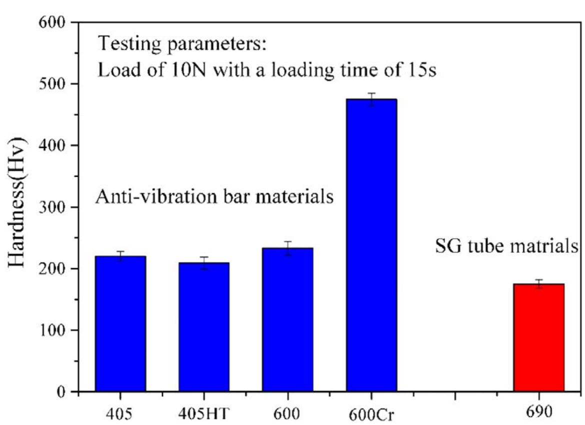


**Fig. 2.** Hardness of alloy 690 tube and mating materials.

The shape and size of the specimens used in the present research is schematically shown in Fig. 3a. Four specimens were tested for each kind of anti-vibration bar material. In the test, the SG tube specimen was kept static while the anti-vibration bar moved along vertical direction, as shown in Fig. 3a. The fretting wear tests were conducted in an autoclave system connected with an actuator to produce reciprocal movement of the fretting pair and a water chemistry control loop to maintain simulated secondary water chemistry in PWR. The detailed structure in autoclave is shown in [11], and the water chemistry control loop is schematically shown in Fig. 3b. The load acting on the SG tube was exerted with springs made of Hastelloy C 276, and a servo motor was used to control frequency and displacement. The testing environment was controlled by the water chemistry control loop. A high-pressure metering pump and a high precision back pressure regulator were used to maintain the high pressure and the flow rate of water. Online meters were used to monitor the conductivity, pH and dissolved oxygen (DO) of the water.

The testing condition in the present research is listed in Table 1. The solution was pure water with conductivity below 0.1 μS/cm, and the pH was adjusted to 9.75 with $NH_4OH$. The testing temperature of 285 °C was decided by the operating condition of SG secondary side of a prevailing PWR, and the pressure was maintained at 8.6 MPa, slightly higher than the saturated vapor pressure of water at 285 °C to ensure the liquid phase of water in the autoclave. High purity Argon was bubbled into the water of the storage tank to control DO. The normal load and displacement acting on the specimens were selected according to the SG practical operating conditions [5,18].

Before and after testing, all specimens were ultrasonically cleaned in ethyl alcohol and dried with hot compressed air. After fretting wear tests, the wear volume of the scars was examined with 3D optical microscopy. Scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) were used to examine the morphology and