Tribology International 117 (2018) 152–161

Contents lists available at ScienceDirect

Tribology International

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

The subsurface damage mechanism of Inconel 690 during fretting wear in pure water

J. Li [a], Y.H. Lu [a,*], L. Xin [a], T. Shoji [a,b]

[a] National Center for Materials Service Safety, University of Science and Technology Beijing, Beijing 100083, China
[b] Fracture and Reliability Research Institute, Tohoku University, 6-6-01, Aramaki Aoba, Aoba-ku, Sendai City 980-8579, Japan

ARTICLE INFO

Keywords:
Fretting wear
Nickel based alloy
Nano-grain
Oxidation

ABSTRACT

The subsurface damage mechanisms of Inconel 690 induced by fretting wear in pure water were investigated. The results showed that the major damage mechanism were oxidation, deformation, fatigue and delamination cracks in worn subsurface. Due to the low oxygen concentration in pure water, preferential oxidation of Cr occurred and plugged into tribologically transformed structure (TTS) at the interface of wear debris layer (WDL)/TTS, which produced complex structures of Cr-rich oxide zone surrounded by Ni-rich zone in TTS. Continued oxidation led to spread of Cr-rich oxide zone, accompanying with formation of WDL consisting of nano-sized oxides and Ni-based grains, however such a spread was limited by the TTS/general deformed layer (GDL) interface, and did not extend to GDL.

1. Introduction

Nowadays, with the coming energy crisis, the nuclear energy has considered as an effective way to overcome it. Therefore, much effort has always been dedicated to improve the safety and economics of nuclear power plant [1]. Fretting wear, which refers to small amplitude oscillatory movement between two surfaces in contact, occurs between steam generator (SG) tube and their support induced by flow vibrations and has become one of the most important safety problems in pressurized water reactor nuclear power plants [2–4]. The service life of SG tube could be dramatically reduced by thinned or worn out tube due to fretting wear. According to the tangential force-displacement hysteresis loop, three damage mode induced by fretting wear could be found: gross slipping regime (GSR), partial slipping regime (PSR) and mixed regime (MR). The hysteresis loop is wide and close to parallelogram in GSR, and is narrow and elliptic shape in PSR. While, the above two cases alternately appear in MR [5,6].

Up to now, many investigations have been carried out to improve the understanding of the fretting-wear process of SG tube [7–12]. However, the existing work are mainly focused on the macroscopic wear behavior such as wear volume, wear coefficient, which has ignored the microscopic wear behavior involving deformed structures, crack, oxidation process and subsequent behavior of oxide debris between contact surfaces [11]. For example, the material with low stacking fault energy exhibits better anti-fretting wear property than that with high stacking fault energy, which is closely related to the deformed structures in worn scar subsurface [12]. Especially, a well-known microstructure the so-called tribologically transformed structure (TTS) is the most important among these deformed structures as it is directly responsible for material loss [13–16]. Although various mechanisms have been proposed for the formation of TTS, such as dynamic recrystallization, mechanical alloying and phase transition, up to now, the formation and destruction of TTS is still highly controversial and far from been clearly understood as the conventional transmission electron microscopy (TEM) sample is prepared locally and randomly. In addition, the relationship between crack and structures has also not been revealed yet.

Due to the complex working environment of SG tube, the studies conducted in pure water are usually considered as a basis for study in the other solutions, such as hydrazine solution, acidic solution and alkaline solution, etc. With the aims of revealing the damage mechanism of Inconel 690 due to fretting wear in pure water in MR, comprehensive characterizations of structure in worn subsurface have been conducted and analyzed in present research. Furthermore, a schematic diagram for the evolution of microstructure in worn scar subsurface in pure water has been proposed.

* Corresponding author.
E-mail address: lu_yonghao@mater.ustb.edu.cn (Y.H. Lu).

http://dx.doi.org/10.1016/j.triboint.2017.08.024
Received 14 March 2017; Received in revised form 23 August 2017; Accepted 24 August 2017
Available online 1 September 2017

2. Experimental procedure

Nickel-based alloy Inconel 690 and 304 stainless steel (304 SS) were applied in this test, which were commonly used as steam generator tube and their supports. The chemical compositions and mechanical properties of the tribo-materials are given in Table 1.

All Inconel 690 specimens were ground and subsequently polished to get mirror finishing. The optical microstructure was revealed by electrolytic etchings in 10% oxalate solution at 5 V for 25 s, as shown Fig. 1(a). Fig. 1(b) presents the bright field transmission electron microscopy (BFTEM) image of the typical microstructure in the base material. It is apparent that many carbides with a grain size of 100 nm precipitate along grain boundaries.

Fretting wear tests were carried out on an Optimol SRV IV tester with a ball (10 mm diameter, 304 SS) on flat (10 × 10 × 1 mm^3, Inconel 690) contact configuration in pure water at room temperature (25–30 °C). The test chamber with the oscillation block installed is shown in Fig. 2. The lower flat specimen was stationary and the upper ball specimen bearing a normal load was vibrating with small amplitude. The normal force and the tangential force were measured by force sensor during the fretting experiments. Then, the coefficient of friction (COF) was calculated according to the formula: f_{COF} = tangential force/normal force. Fretting

Table 1
Chemical compositions and mechanical properties of Inconel 690 and 304 SS

Specimen	Element (wt.%)										
	Ni	Fe	Cr	C	Ti	Mn	Si	N	S	P	Co	Mo
Inconel 690	Bal	11.6	29.9	0.025	0.30	0.25	0.33	0.020	0.025	0.01	0.015	–
304 SS	9.35	Bal	18.3	0.018	–	0.25	0.31	–	0.025	0.034	–	0.18
	Mechanical properties											
	Poisson's ratio			Young's modulus (GPa)			Yield strength (MPa)			Ultimate tensile strength (MPa)		
Inconel 690	0.29			211			352			703		
304 SS	0.25			194			205			520		

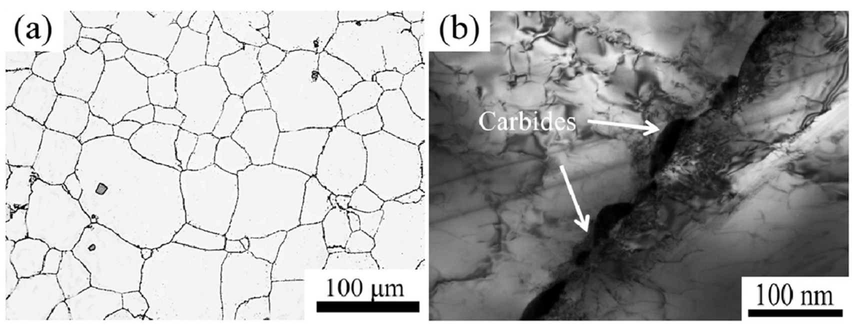

Fig. 1. Microstructure of Inconel 690: (a) optical image and (b) BFTEM image.

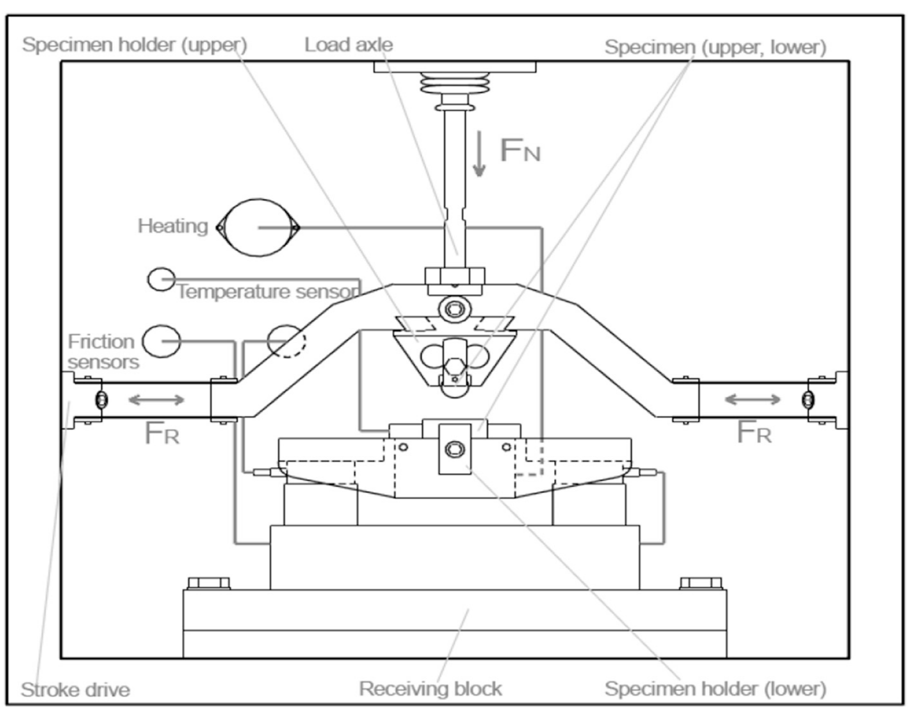

Fig. 2. The test chamber of the SRV IV with installed oscillation block.