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Characterization of friction-induced local convex topography under dual-rotary fretting

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ABSTRACT

Dual-rotary fretting (DRF) is a complex fretting wear mode combining torsional fretting with rotational fretting. Two different typical friction-induced convex topographies (Type I and Type II) in contact area were showed, which are under the control of torsional and rotational fretting components, respectively. To investigate their evolution characteristics and formation mechanism, the convex topographies were analyzed by SEM, XPS, a nano-hardness tester and surface profilometry, etc. The results show that the convex topographies significantly depended on the test parameters and environmental conditions. The initiation and propagation of fretting fatigue cracks were found related with the convex topography under the fretting wear.

1. Introduction

Fretting is a small amplitude oscillatory movement which occurs between two contacting surfaces, and it is different from sliding and rolling. The fretting damage is a complex degradation process due to mechanical and chemical attack under complex stress state, for instance, damage morphology, third body behavior, initiation and propagation of fatigue cracks behavior, etc. Generally, the local Λ-type character (namely, the height of worn morphology is higher than that of surrounding region or even the original surface) has been labeled by most scholars, as ripple [1–2], convex [3], bulge [4–6], or hillock [7] and so on. Many researchers have found the convex phenomenon by fretting induced. Li et al. [6] pointed out that the large flaking and convexity with metallic luster were the typical characteristics of fretting damage, when they performed fracture analysis on cage rivets of a cylindrical roller bearing. A lot of researches have proved that the nucleation and propagation process of the fatigue microcracks or the formation of the gaps was closely related to the convex topography, which ultimately induces premature structural failure [8–11]. On the other hand, the fretting-induced convex topography might be successfully applied in the field of remanufacturing engineering [12–13]. Hence, further research on the evolution characteristics and formation mechanism has important significance to reveal the fretting damage mechanism and engineering applications. However, it is hardly to see the research on the formation mechanism of convex topography under the dual-rotary fretting. Even under the common tangential fretting mode, the mechanism still exists some dispute at present. [1,7,14–15].

Dual-rotary fretting (DRF) is a complex fretting wear mode combining torsional fretting with rotational fretting. It would occur inevitably in some engineering applications, such as the artificial joints in prosthetic devices, ball joints in automobile suspension, and ball valves in the fluid transfer system [10]. The friction and wear behavior of PMMA polymer against steel have been investigated by Briscoe and his colleagues, under varying motions from pure torsional to pure rotational [1–2]. The result showed that the damage induced by torsional component was severer than that dominated by rotational component when the integrated micro-displacement was same within the contact area. Meanwhile, obvious convex topography could be formed on contact center under rotational fretting. They believed that the convexity was mainly generated by the accumulation and compaction of debris particles [1–2,16]. Qian et al. [7] reported their studies on nano-fretting wear behavior of monocrystalline silicon (100), and the hillocks were observed on Si (100) surface even though the displacement amplitude of nano-fretting was less than 25 nm. They indicated that the oxidation had only led to a very small height increment of the detected hillocks, but mechanical interaction had played a dominant role in facilitating the formation of the hillocks. In our earlier research work [10], it is also founded that two different kinds of local convexity (Type I—the annular convex topography around the contact area and Type II—local convex topography in the contact center) were formed

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under the fretting mode of DRF which were controlled by the torsional fretting component and rotational fretting component, respectively.

Usually, severe damage occurs under the contact of steel-to-aluminum (e.g. aluminum wire with plating steel or aluminum conductor steel reinforced (ACSR)). Therefore, in order to significantly expose the local convexity behaviors, a contact of an aluminum alloy flat against a steel ball was used in this study, and the dual-rotary fretting tests of 7075 aluminum alloy against 52100 steel were conducted, two different kinds of local convexity controlled by torsional fretting component and rotational fretting component were reproduced successfully. The evolution characteristics and formation mechanism of the two kinds of local convex topographies were analyzed in detail.

2. Experimental details

2.1. Materials

In all tests, the contact of aluminum alloy flat against steel ball was used as a fretting couple. 7075 aluminum alloy flats with dimensions of 10 mm × 10 mm × 20 mm and surface roughness (R_a) of 0.04 μm were chosen as the flat specimens. An AISI 52100 standard bearing steel ball with a diameter of 40 mm and surface roughness (R_a) of 0.04 μm was used as the counter-body. The chemical composition and mechanical properties of 7075 aluminum alloy and AISI 52100 steel are shown in Tables 1 and 2, respectively.

Table 1
Chemical composition of materials (mass %).

Material	Si	C	Cu	Mn	Ni	Mg	Cr	Zn	Al	Fe
7075	0.04	--	1.8	0.3	--	2.2	0.26	6.7	Balance	0.5
52100	0.25	1.00	0.2	0.30	0.20	--	1.50	--	--	Balance

Table 2
Main mechanical properties of materials.

Material	σ_s (Mpa)	σ_b (Mpa)	*E* (Gpa)	*Hv*
7075	502	524	72	60
52100	1700	2000	210	870–890

2.2. Fretting tests

The DRF tests were performed on an advanced dual-rotary fretting rig developed from a low-speed reciprocating rotary motor system, as shown in Fig. 1. A detailed description of the fretting device has been stated in prior work [10]. The DRF tests were carried out in the air environment (20 ± 2 °C and 60 ± 2% RH), and the ratio of the torsional and the rotational fretting component was controlled by changing tilt angle (α=10° or 60°) and rotary angular displacement amplitudes (θ=0.25–2.0°). And it was performed under a constant rotary speed of 0.1°/s and a settled normal load (F_n) of 50 N. To investigate the evolution of convex phenomena, the fretting damages were shown in different cycles which varied from 1 to 10,000. The environment conditions for all tests were performed in air, if it was not being specified. Besides, to reveal the fretting environment on the formation of convexity, the fretting tests were repeated under the same testing parameters in oil and nitrogen. In order to create the nitrogen and oil-lubrication (a kind of paraffinic mineral base oil with the viscosity of grade ISO VG 46) environment, a tailor-made container was placed between the upper and lower holders, as shown in Fig. 2.

2.3. Characterization method of wear morphology

A dual-mode (contact/non-contact) 3D surface profilometer (Aep, NanoMap-D) of which the accuracy of height direction can reach 1 nm was used to measure the surface profiles of the scars. The wear morphologies were observed by an optical microscope (OM) and a scanning electron microscope (SEM, Quanta 200). The nano-indentation characterization of the surface and cross-section of fretting scars was observed by a NanoTest system (CSM, Swiss). The machine should be calibrated according to ISO standard methods before testing [17]. Indentation was loaded to a maximum depth of 400 nm by means of load control. The loading and unloading rates were 0.4 mN/s and the maximum load was held for 2 s. The chemical composition distributions in the contact zones were detected by an energy-dispersive X-ray analysis (EDX, EDAX-7760/68) and an X-ray photoelectron spectrometer (XPS, Kratos AXIS Ultra).

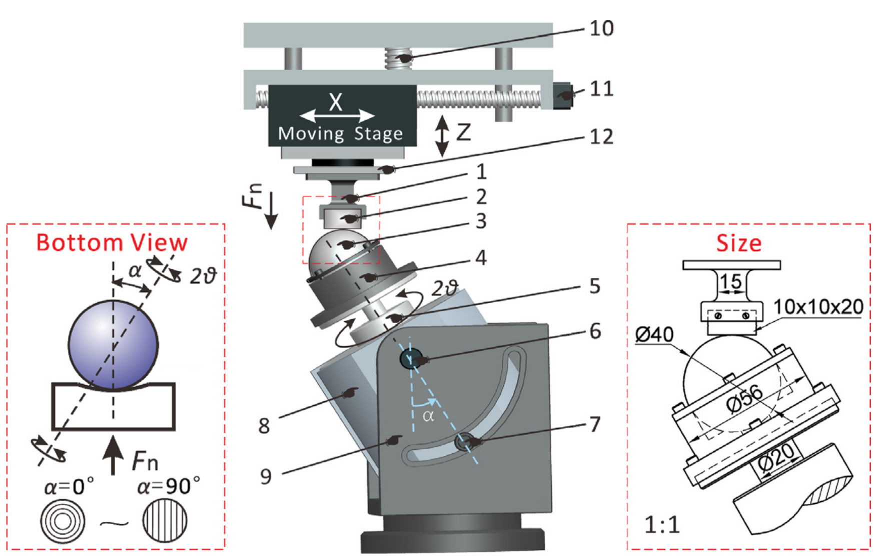

Fig. 1. Schematic diagram of dual-rotary fretting test rig. (1) Upper holder; (2) Flat specimen; (3) Ball specimen; (4) Lower holder; (5) Low-speed reciprocating rotary motor system; (6) Axis of rotation; (7) locating screw; (8) Sleeve of motor system; (9) Base platform; (10) Vertical positioning system; (11) Lateral positioning system; (12) 6-D sensor.