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Dual-rotary fretting wear of 7075 alloy in media of oil and water

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ABSTRACT

Dual-rotary fretting (DRF) is a complex fretting wear mode combining torsional mode with rotational mode. With the contact configuration of ball-on-flat (7075 aluminum alloy flats against AISI 52100 steel balls), the DRF wear tests in oil and water were carried out respectively under varied rotary angular displacement amplitudes and tilt angles. By combining the dynamic behavior analyses with damage morphology examinations, the wear mechanisms of DRF in dry condition, oil and water were analyzed in detail. Compared with the dry friction condition, both oil and water acted as lubricants and played an important role during the running and damage processes of DRF, which significantly changed the fretting running regimes and third-body behaviors. It is found that the oil media can effectively mitigate DRF damage, especially when the tilt angle and the angular displacement amplitude are large, because the oil can penetrate into the contact interface and form a lubricant film. Relatively, the water can easily penetrate into the micro-cracks on the surface and promote the propagation of cracks because the viscosity of water is low. Therefore, the delamination is more obvious in the water.

1. Introduction

Fretting is a small-amplitude oscillatory movement between two contacting surfaces [1]. It can cause two kinds of damage: fretting wear (material removal and debris formation) and fretting fatigue (crack initiation and propagation, even fracture failure). There are only four basic fretting wear modes for a ball-on-flat contact *i.e.*, tangential, radial, rotational and torsional fretting [2]. The dual-rotary fretting (DRF) is combined with the torsional and the rotational fretting modes [3]. The probability of encountering the DRF in many modern industrial and biomedical fields is extremely high, such as the ball joints in automobile suspension, ball valves in fluid transfer systems and even artificial joints of orthopedic implants. The failures induced by the DRF damage have incurred enormous economic loss or a lot of troubles.

Based on the understanding of fretting damage mechanisms, a lot of researchers have proposed different mitigation measures which are summarized into three basic methods by Fu et al. [4], *i.e.*, change in design, application of surface engineering (surface modification, coating, *etc.*) and use of lubricants (liquid, grease and solid lubricant). Compared with the two former ways, the use of lubricants is a simple but effective method for improving the fretting wear resistance [5]. Besides, lubrication is one of the important methods for preventing the fretting damage caused by a remarkable reduction in the coefficients of friction [6]. Generally, in many cases, fretting damage could reduce under the lubricated condition. However, under certain working conditions, the fretting damage could be even more serious because the lubricants infiltrate into the micro-cracks and promote the propagation of the cracks, while it significantly depends upon the fretting amplitude [6–8]. Recently, the fretting wear behavior in different lubricating media has been extensively investigated or even compared with that under dry friction conditions [7–9], and the transitions in wear behavior as a function of testing parameters (*e.g.* displacement amplitude, material, load and sliding speed) were discussed in detail. Additionally, some important experimental results have been obtained to better understand the fretting wear behavior in different lubricating media. For the special application background in orthopedic implants, Zdravecká et al. [10] investigated the fretting wear behavior of the Ta–C coatings against corundum ball (α-Al_2O_3) under unlubrication and lubrication (bovine serum) conditions, and the results showed that the Ta–C coatings had very low friction coefficients and low volume losses in bovine serum, despite their high hardness. It revealed that the humidity could dominate the fretting running behavior. The role of humidity on torsional fretting wear behavior of 7075 aluminum alloy was investigated in various relative humidity environments [11]. It indicated that the humidity played a very important role in the running behaviors and damage mechanisms.

However, it should be noted that most research related to the fretting has focused on the tangential fretting mode (*i.e.*, linear reciprocating mode). Up to now, a few literatures have discussed other fretting modes, especially in the lubricating media. It should be recognized that the fretting behavior depends upon many

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influential factors, for example, fretting modes and contact configuration. On the other hand, it is generally recognized that because of the very low sliding speed and high contact pressure even at high-frequency occurrence in fretting, it is very difficult to establish the dynamic fluid lubrication, thus lubricants are not very effective under the tangential fretting conditions, especially in the partial slip state [4,7]. As far as the present understanding, no DRF test performed in some lubricating media has been reported in the literature so far, namely, the effect of lubricant on tribological behavior of the DRF is still unclear.

Actually, the unlubricated (dry friction condition) DRF test of 7075 aluminum alloy has been reported in detail elsewhere [17]. This paper systematically analyzes the effect of two different lubricants (oil and water) on the DRF damage behaviors; it also mainly assesses the effect of the two lubricants on the fretting damage resistance of DRF.

2. Experimental details

2.1. Materials

In general, the damage of steel-to-aluminum contact induced by fretting can be manifested distinctly [12–14]. Thus, in order to clearly reveal the damage mechanisms of the DRF under the lubrication conditions, a fretting counter-pair involving the contact of 7075 aluminum alloy flat against an AISI 52100 steel ball was used in all tests. The flat specimens with dimensions of 10 mm × 10 mm × 20 mm were polished until an average surface roughness (R_a) of 0.04 μm was reached. An AISI 52100 steel ball as the counter-body with a diameter of 40 mm and surface roughness (R_a) of 0.04 μm was used. The chemical composition and mechanical properties of the experimental materials are shown in Tables 1 and 2, respectively.

2.2. Fretting tests

The DRF wear tests with a ball-on-flat configuration were performed on a computer-controlled DRF test rig developed from a low-speed reciprocating rotary motor system, as shown in Fig. 1. The details of the experimental set-up can be found elsewhere [14]. In addition, subsidiary transparent organic glass (PMMA) container (13) was mounted to the lower holder (4), and filled with the lubricants (14), so that the top of the steel ball was fully immersed in the liquid lubricant. Two lubricants were used in this test: laboratory distilled water and commercial oil (shell Tellus T46), and the physical characteristics of lubricant oil are listed in Table 3. Before the tests, all specimens were cleaned by using acetone in ultrasonic bath and dried with cold air, and then the specimen was dipped into the corresponding lubricant bath for 10 min prior to the DRF tests.

During the fretting tests, the friction force (F_t) was measured with a 6-D sensor attached to the upper holder which supported the flat specimen, and the rotary angular displacement was monitored by a sensor; the obtained signal as control signal was fed back to the control unit of the tester. This test would be stopped after the set number of cycles (*e.g.* $N=10^3$ cycles) were reached.

In order to make a comparison, the parallel tests were carried out at ambient temperature (20 ± 2 °C) and humidity (60 ± 2% RH). All the DRF test parameters under varied media were the same as follows: a constant rotary speed of 0.1°/s, a settled normal load (F_n) of 50 N, different contact conditions with changing tilt angle ($\alpha=10°$, 20°, 40°, and 60°) and varied rotary angular displacement amplitudes ($\theta=0.25-10°$).

2.3. Micro-examinations

After the DRF tests, the worn surfaces were ultrasonically cleaned to remove any residual oil or dirt, and then dried with cold air. The wear scars were detected by optical microscopy (OM), scanning electron microscopy (SEM, Quanta 200), and energy dispersive spectroscopy (EDX, EDAX–7760/68 ME). And, the wear volume and the 2D-profile were measured by a dual mode (contact/non-contact) 3D surface profile-meter (Aep, NanoMap-D) after 20 min of ethanol ultrasonic surface cleaning.

3. Results and discussion

3.1. F_t–θ curves

The F_t–θ curves also can be used to characterize the DRF running behavior [3,14]. The F_t–θ curve (*i.e.*, fretting loop) shows the evolution of the tangential force as a function of the displacement amplitude during each cycle. Many researches [11,14,15] showed that in not only the pure torsional fretting or rotational fretting but also the DRF, the fretting loops presented three simple types, *i.e.* linear, elliptic and parallelogram loop. The F_t–θ curves of the DRF under lubrication condition showed the same characteristics.

As shown in Fig. 2, in the case of tilt angle $\alpha=40°$, under a low angular displacement amplitude of $\theta=0.25°$ (Fig. 2(a)), all F_t–θ curves under three different environmental conditions show approximate elliptic shapes in the different cycles, it is indicated that the relative motion of contact interface was mainly accommodated by elastic–plastic deformation. Therefore, it can be concluded that the fretting was running in the partial slip regime (PSR), and the contact center was always in sticking state.

When the angular displacement amplitude increased to $\theta=0.5°$ (Fig. 2(b)), the F_t–θ curves transformed from parallelogram to elliptic after about dozens of cycles under dry condition, which implied that the fretting changed from the gross slip state to the partial slip state. Thus, the fretting was running in mixed fretting regime (MFR) [14]. Compared with the dry condition, the transformation of the F_t–θ curves in oil occurred after 250 cycles, so the fretting was also running in the MFR. However, the transformation of the F_t–θ curves in water occurred after only

Table 2
Main mechanical properties of the tested materials.

Material	σ_s (MPa)	σ_b (MPa)	E (GPa)	Hv
AA 7075	502	524	72	60
AISI 52100	1700	2000	210	870–890

Table 1
Chemical composition of the tested materials (mass %).

Material	Si	C	Fe	Cu	Mn	Ni	Mg	Cr	Zn
AA 7075	0.04	–	0.5	1.8	0.3	–	2.2	0.26	6.7
AISI 52100	0.25	1.00	–	< 0.2	0.30	0.20	–	1.50	–