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Study on torsional fretting behavior of UHMWPE

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ABSTRACT

Torsional fretting tests of UHMWPE against titanium alloy ball (TC4) had been carried out. A frictional torque–angular displacement (T–θ) curve was used to analyze the kinetics behaviors of torsional fretting mode. The wear morphology and damage mechanisms of UHMWPE were studied based on examinations by scanning electron microscopy (SEM). It is found that the contact stiffness and friction-dissipated energy initially rise and then gradually reach a steady state. The worn surface is characterized by adhesion in the centre zone, while in the outer annulus, ripples, ploughs and delamination appeared. In addition, a transfer film is found on the surface of titanium alloy ball.

1. Introduction

The use of artificial joints for the treatment of degenerative diseases of the hip and knee is becoming widespread. Nowadays, there are several bio-implant materials available in total joint replacements (TJR). The best combinations are ultra high molecular weight polyethylene (UHMWPE) for the cup and alumina, titanium alloys, stainless steel or CoCrMo alloy for the head [1]. UHMWPE's high abrasion resistance, low coefficient of surface friction, high impact strength, high toughness, low elastic modulus, biocompatibility, corrosion resistance, and ease of fabrication make it suitable for several decades. However, wear of UHMWPE components remains to be a leading cause of failure in TJR so far. The main modes of movement in most kinds of joints include slipping, rolling, and fretting [2]. Considering complexity of the human body, some movements are required as the rotation of the head in the acetabular cup [3], where torsional fretting occurs between two contact surfaces. Torsional fretting is relative torsion motion between contact pairs with oscillatory microangular displacement amplitude under imposed normal load. As one kind of motion modes of fretting, torsional fretting has hardly been studied and only a few papers have been published [4,5]. Wear of UHMWPE has been widely studied over the last three decades, however, the study of torsional fretting wear of UHMWPE has not yet been done up to now. In this paper, torsional fretting tests of UHMWPE were conducted. Furthermore, there is a focus on the influence of variation characteristics of friction torque with the increase of number of cycles and the wear damage mechanisms of UHMWPE.

2. Experimental details

The torsional fretting experiments of the UHMWPE against titanium alloy (TC4) were carried out on a new torsional fretting rig [6]. The wear behavior was investigated under a ball-on-flat configuration, as shown schematically in Fig. 1. Flat UHMWPE specimens (20 mm × 10 mm × 10 mm) were polished with R_a = 0.03–0.04 μm. The counterpart was TC4 ball with hardness of 390 $HV_{0.05}$ and diameter of 10 mm. The tests were carried out under normal force of 30 N and 90 N, at an angular velocity of 1 rpm. The torsional angular displacement varied between 0.95° and 85°, over 1000 cycles. Wear scars were examined and analyzed by scanning electron microscopy (FEI Quanta 200).

3. Results and discussion

3.1. T–θ curve

F_t–D curve is used in tangential fretting and radial fretting to analyze kinetics behaviors [7], T–θ curve is applied in torsional fretting mode correspondingly. Fig. 2 shows evolution of T–θ curves under a normal load of 90 N and angular displacement of 0.95° (Fig. 2a–c) and 85° (Fig. 2d–f). In both situations, the curves generally display quasi-parallelogram shape. When the angular displacement is 0.95°, the curves are much slimmer at the first 50 cycles. After 100 cycles, no considerable changes of the shape of curves are observed. And the friction torque is slightly increased

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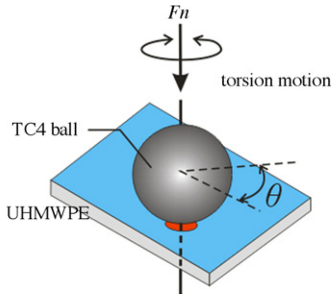

Fig. 1. Schematic diagram of torsional fretting test under sphere/flat contact condition.

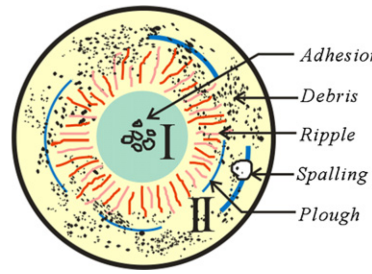

Fig. 4. Schematic diagram of wear scar.

with the number of cycles. When the angular displacement is 85°, the friction torques are much higher than those of 0.95°.

In general, the slope of friction–displacement represents stiffness which is affected by system stiffness and contact stiffness [7]. The system stiffness can be considered as a constant during the whole testing process. So, the change of slope reflected the change of contact stiffness. The area enclosed by the T–θ curves represented friction energy that has been dissipated during the cycle. The evolution of contact stiffness and dissipated energy per cycle are illustrated in Fig. 3. It can be seen that the value of contact stiffness rise rapidly at the first 200 cycles, and then it gradually reached a steady state. It is observed that the graphical representation of the energy dissipated per cycle as a function of time is similar to that of the contact stiffness. It may be explained that work hardening happened during torsional fretting wear.

3.2. Worn surfaces

The damage of torsional fretting wear of UHMWPE is very different from the metal materials [6]. The typical damage morphology of UHMWPE can be schematically drawn in Fig. 4. Due to low relative slip displacement, slight damage occurs at the

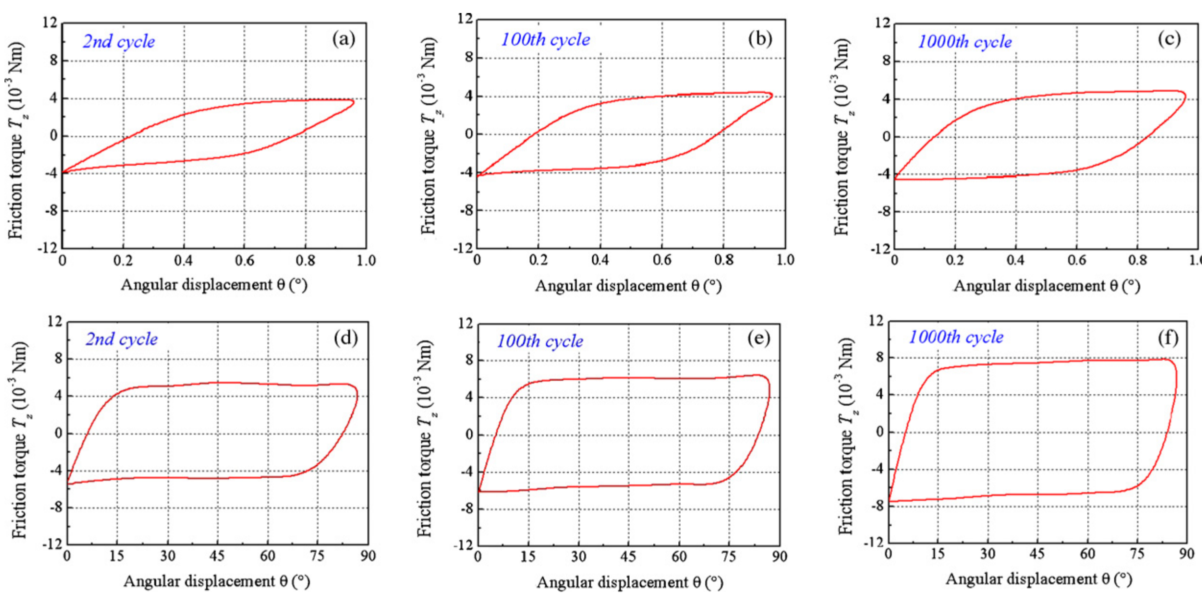

Fig. 2. Relation between frictional torque and angular displacement F_n = 90 N, (a–c) θ = 0.95°, and (d–f) θ = 85°.

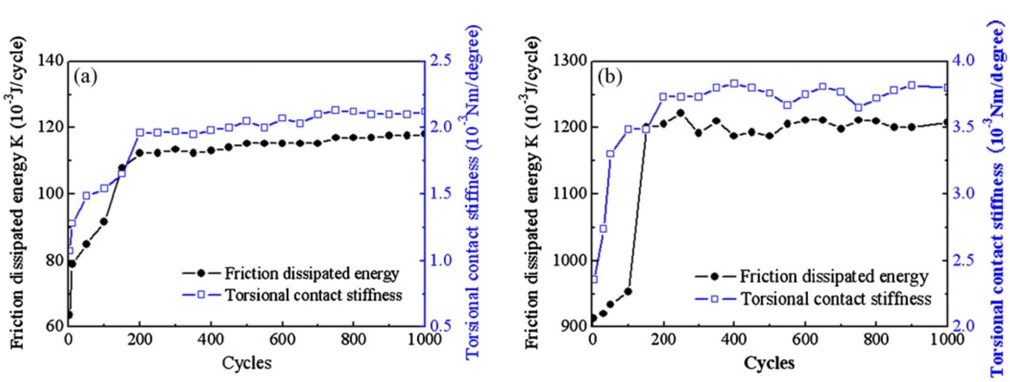

Fig. 3. Evolution of contact stiffness and dissipated energy per cycle F_n = 90 N, (a) θ = 0.95°, and (b) θ = 85°.

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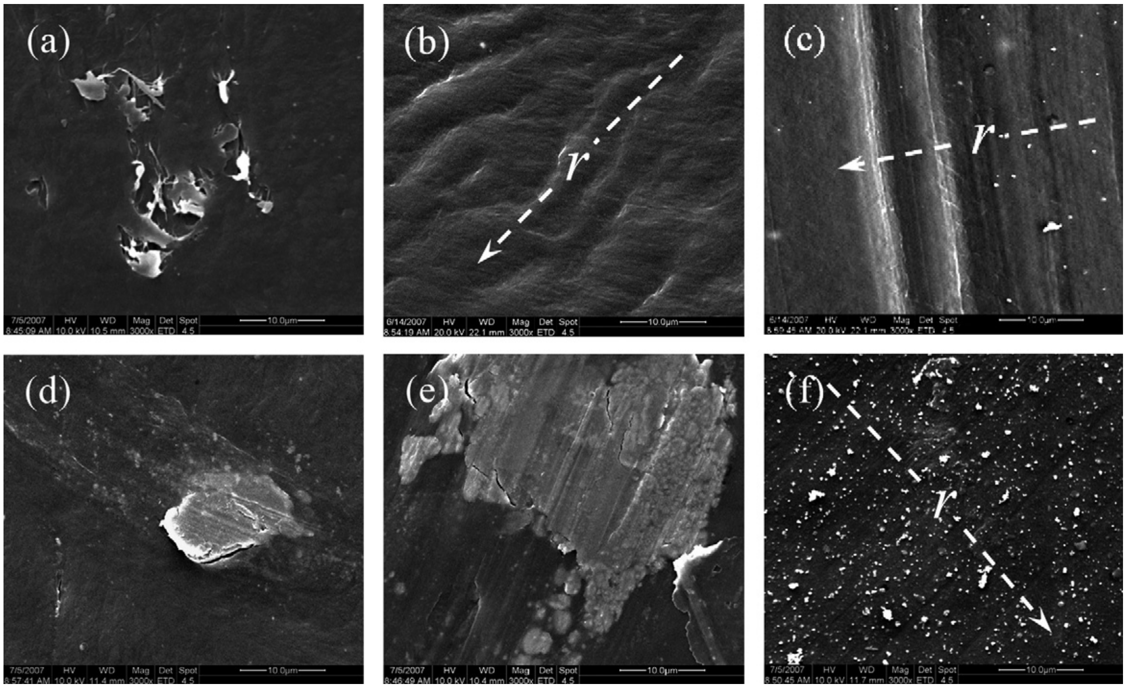

Fig. 5. SEM photographs of wear surfaces. (a–c) F_n = 30 N, (d–f) F_n = 90 N.

centre zone (zone I), and only some adhesion is observed (Fig. 5a). With the increase of the radius of contact area (zone II), corresponding with the increase of the angular displacement, the extent of fretting damage increase gradually. There are a lot of radial ripples observed on the worn scars of UHMWPE in zone II, which lead to form bulgy ridges (Fig. 5b). The ripples which are perpendicular to the sliding direction on the worn surfaces have been discussed in many papers under the testing condition of sliding. However, no clear mechanism has been investigated so far. Silva and Sinatora believed its mechanism with abrasive origin [8]. Schwartz and Bahadur attributed them to slower-wearing regions of the wear surface that exhibit recovery once the loading was removed [9]. In this study, radial ripples are also appeared. According to the SEM images of this study, the formation of ripples may be caused by plastic flow. Alone the relative slip direction, as seen in Fig. 5c, wide and deep grooves with signs of plastic deformation are also observed, which may be caused by the asperities of ball specimen. As plastic deformation cumulate, the micro-cracks initiate, propagate and coalesce, and then some flakes are detached from the base material by delamination (Fig. 5d and e). In Fig. 5e, it is visible that cracks appeared at the edge of the plate-like detached pit. After flake debris break-off, it is ground and crushed into fine particles. As shown in Fig. 5f, lots of loose debris is spread out and scattered in zone II.

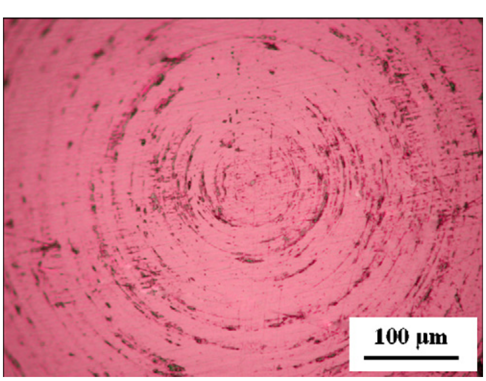

Fig. 6. OM photographs of TC4 ball after torsional fretting test.

The surface morphology of the TC4 ball is observed by optical microscope, as seen in Fig. 6. It can be clearly seen that UHMWPE has been transferred to the counterpart exhibiting morphology of concentric circles. Therefore, it can be concluded that a transfer film of UHMWPE is formed on the surface of the ball specimen. However, no titanium is found on the surface of UHMWPE.

4. Conclusions

In this work, the torsional fretting tests of UHMWPE against titanium alloy ball (TC4) were carried out. It has been shown that the T–θ curves present a quasi-parallelogram shape. The contact stiffness and friction-dissipated energy first rise and then gradually reach a steady state. The wear scar of UHMWPE is characterized by adhesion in the centre zone, and ripples, curved ploughs and delamination appeared in outer annulus of the contact area. At the same time, a transfer film of UHMWPE is formed on the surface of the ball specimen.

Acknowledgements

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