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Friction and wear properties of UHMWPE composites reinforced with carbon fiber

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Abstract

The artificial joint acetabular material ultrahigh molecular weight polyethylene (UHMWPE) was reinforced with carbon fibers (CF) in different contents. The effects of CF content on hardness and tribological properties of the materials were studied. The morphologies of wear surfaces were examined with a Scanning Electron Microscope (SEM). The results show that the hardness and wear resistance of CF-reinforced UHMWPE composites increased with CF content; the friction coefficients under distilled water lubrication were decreased greatly by the addition of CF; that adherence, plowing, plastic deformation and fatigue wear are dominant for the UHMWPE under dry sliding, and that abrasive wear and drawing out of CF from the wear surface of the composites are dominant for the CF-UHMWPE composites under both dry and distilled water lubrication conditions.

Keywords: Ultrahigh molecular weight polyethylene; Carbon fiber; Artificial joint; Wear

1. Introduction

Ultrahigh molecular weight polyethylene (UHMWPE) possesses many excellent properties, such as bio-compatibility, chemical stability, impact strength, high wear resistance and low friction, thus it has been the choice as a major bearing surface material of total joint replacement prostheses for many years. However, UHMWPE has some disadvantages: its hardness and Young's modulus are low, and it easily creeps under load. This restricts its load-bearing capacity. On the other hand, wear does occur in UHMWPE and this has been recognized as one of major factors for the long-term failure of total joint replacement in recent years [1]. Therefore, much effort has been made to enhance the life span of total joint replacements. These include (i) modifying UHMWPE by gamma radiation [2], ion implantation [3–5] and self-fiber reinforcement [6]; (ii) optimizing surface roughness [7] and size of the femoral head [8], selecting or engineering counterfaces [9–11]; (iii) searching for alternate bearing materials other than UHMWPE, such as metal on metal or ceramic on ceramic bearing couples [12]. Jacobs et al. [13] studied the wear and creep resistance of a new composite material consisting of high density polyethylene reinforced by UHMWPE fibers, and found that the composites creep much slower than UHMWPE, but the wear rates of the composites are all higher than that of UHMWPE. Wang et al. [14] prepared carbon fiber reinforced PEEK composites, and found that the carbon fiber reinforced PEEK composites offer a far superior wear resistance over UHMWPE in a conforming ball-in-socket contact situation such as in the hip joint, however, all composite specimens exhibited significantly higher wear rates than the UHMWPE in a high-stress nonconforming contact situation such as in the knee joint, therefore, the composite material should not be used as a tibial component for a total knee joint replacement. Deng et al. [15] found that the strength, modulus, and creep resistance were significantly increased after incorporating UHMWPE fibers into a UHMWPE matrix, but the wear resistance of the self-reinforced UHMWPE composites could not be improved. In this paper, carbon fiber (CF) reinforced UHMWPE compo-

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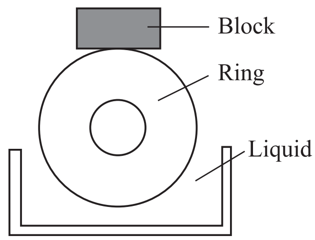


Fig. 1. Contact mode of friction pair for wear tests.

sites were prepared, and the effect of the CF content of the composites on the hardness and tribological properties under both dry and distilled water lubrication conditions were investigated. This work was designed to screen CF content in the composites, so the conventional unidirectional test apparatus was used to perform a comparative test.

2. Experiment

2.1. Sample preparation

PAN-based carbon fibers with an average diameter of 7 μm were cut to length less than 1 mm, and then fully mixed with the UHMWPE powder of 3,000,000 molecular weight in different weight percentages. The mixtures were put into a hot press, and the press was heated up to a temperature of 200 °C. At this temperature, a pressure of 120 MPa was applied for a period of 80–90 min. After cooling to room temperature, the composites were machined to the dimensions of 10×6×12 mm.

2.2. Wear tests

The friction and wear behavior of the composites were evaluated on a MM-200 tester. The CF-filled UHMWPE block samples were loaded against 316 L stainless steel rings as shown in Fig. 1. The diameter and width of the rings was 40 and 10 mm, respectively, with a rotating velocity of 200 r/min, i.e. the sliding velocity was 0.42 m/s. The test was carried out under dry and distilled water lubrication conditions with 196 N normal load for 2 h. The

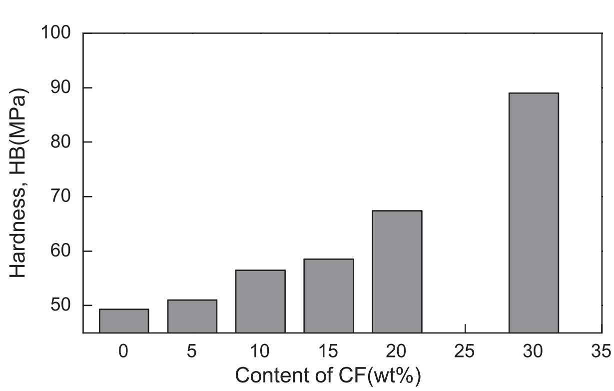


Fig. 2. Effect of CF content on hardness of UHMWPE.

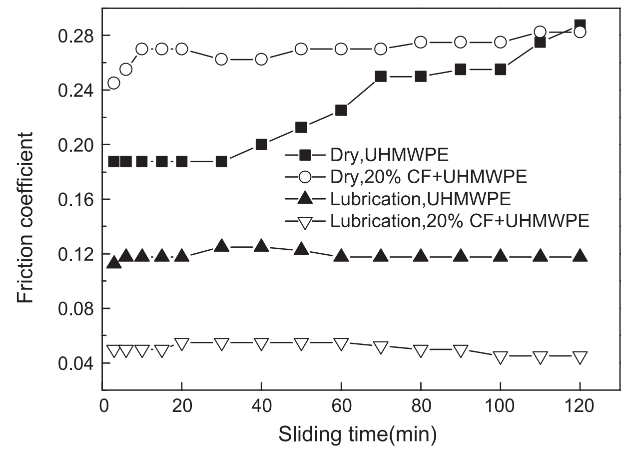


Fig. 3. Variation of friction coefficient with sliding distance.

wear mass loss of the samples was determined by an electronic analytical balance with an accuracy of 0.01 mg. Prior to the test, both sample block and 316 L stainless steel ring were ground using $500^{\#}$ sandpaper, washed with ethanol, and dried. The wear traces of samples were examined by scanning electron microscopy (SEM).

3. Result and discussion

3.1. Effect of CF content on hardness of UHMWPE

The effect of CF content on hardness of the samples is shown in Fig. 2. The hardness increased with the CF content slowly from 0% to 15% CF content, and more rapidly above 15%.

3.2. Effect of CF content on friction and wear

Fig. 3 shows the variation of friction coefficient with sliding distance. It can be seen that the friction coefficient of the CF reinforced UHMWPE composite was higher but

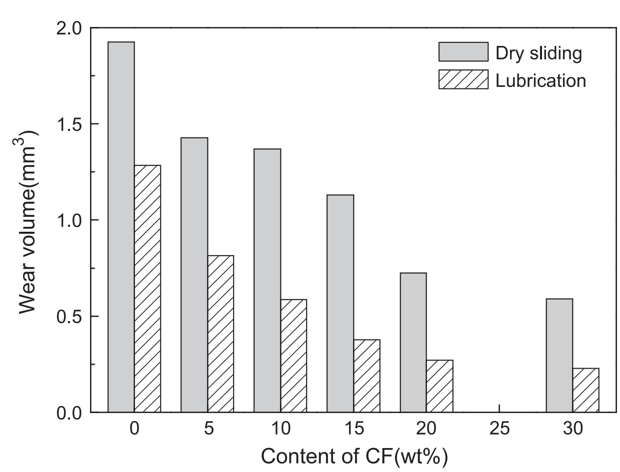


Fig. 4. Effect of CF content on wear volume loss of the samples under dry and distilled water lubrication conditions.

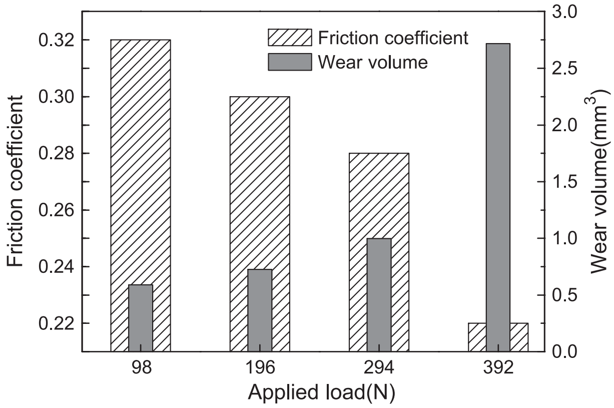


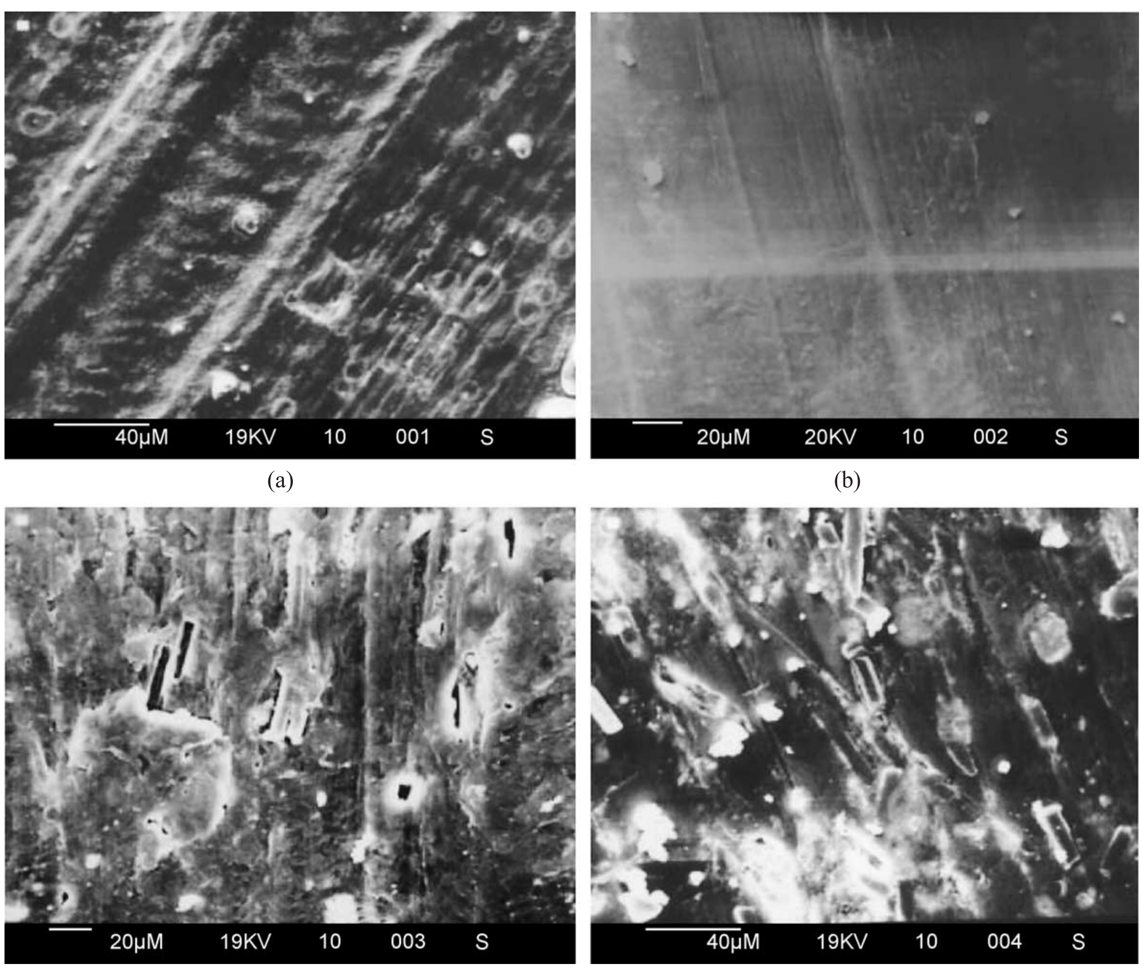
Fig. 5. Effect of load on friction and wear of 20% CF-UHMWPE under dry sliding.

more stable than that of the pure UHMWPE under dry sliding. Under distilled water lubrication, the friction coefficient of the CF reinforced UHMWPE composite was lower than that of the pure UHMWPE.

The effect of CF content on the wear of samples is shown in Fig. 4. The wear volume loss of the pure UHMWPE was the highest under both dry and distilled water lubrication conditions. The volume loss under dry sliding was higher than that under distilled water lubrication for each sample. The volume loss decreased with the content of CF, and the rate of decrease of wear of samples at CF content from 0% to 20% was faster than that from 20% to 30% under both the dry and the distilled water lubrication conditions.

3.3. Effect of load on friction and wear

Fig. 5 shows the effect of load on friction and wear of the 20% CF-UHMWPE composite under dry sliding. The decrease in friction coefficient that is observed in CF-reinforced UHMWPE under increased loading is attributed to surface softening arising from frictional heating. The wear volume loss increased with load, especially above 300 N, the increase of the wear volume loss is also due to the surface softening from frictional heating under high load.



(a) (b) (c) (d)

Fig. 6. SEM photographs of worn surfaces of UHMWPE and 20% CF-UHMWPE composite under dry and distilled water lubrication conditions. (a) Worn UHMWPE surface after dry sliding. (b) Worn UHMWPE surface after sliding in distilled water. (c) Worn 20% CF-UHMWPE surface after dry sliding. (d) Worn 20% CF-UHMWPE surface after sliding in distilled water.

3.4. Analysis of worn surfaces and discussion

The worn surfaces of UHMWPE and 20% CF-UHMWPE composite under both dry and distilled water lubrication conditions are shown in Fig. 6. Except the furrow, there are many microscopic undulation on the pure UHMWPE worn surface [Fig. 6(a)] under dry sliding conditions, which is probably due to friction heat softening of the polymer matrix and adherence. Under distilled water lubrication conditions, the worn surface of pure UHMWPE [Fig. 6(b)] was smooth, and only exhibited fine scratches. The 20%CF-UHMWPE composite worn surfaces under both dry [Fig. 6(c)] and distilled water lubrication conditions [Fig. 6(d)] have not such microscopic undulation, and the scratches, but some carbon fibers on the worn surface were draw out and abrade.

Carbon fiber possesses high strength and a high clash modulus, and the load action on the composites is mainly borne by carbon fibers, thus, the friction behavior of the composites is mainly determined by carbon fibers. Under dry testing, the friction behavior of the composites with different CF content is similar: for example, the friction coefficients of the CF reinforced UHMWPE composites are relatively low at first, and increase slightly with sliding distance, and quickly goes to steady-state. However, the pure UHMWPE friction behavior is very unstable, and it started lower, then rose to a higher level after some sliding. This may be due to the contact area increasing with sliding distance and the friction heat making the surface of the pure UHMWPE become soft, thus, the friction adhesion component become strong. Under distilled water lubrication conditions, the water separated the direct contact between the pure UHMWPE block and stainless steel ring, and frictional heat is taken away by water, hence the friction coefficient is also more stable. Under distilled water lubrication conditions, the carbon fibers in the composites will fully absorb water, and the worn surface of carbon fiber containing various oxygenated group, it is therefore the passivation of carbon dangling covalent bonds by adsorption of water that allows carbon materials to maintain a low friction [16]. In addition, the wettability of the composites are greatly improved by exist many small interstice between carbon fibers and UHMWPE matrix. Because of these reasons, the friction coefficients of CF reinforced UHMWPE composites are all very much lower than that of pure UHMWPE under distilled water lubrication conditions.

4. Conclusions

(1) The hardness of the CF reinforced UHMWPE composites increases with CF content, and the wear volume loss of the composites decreases with CF content under both dry and distilled water lubricating conditions.

(2) The friction coefficients of the CF reinforced UHMWPE composites are all higher and more stable than that of the pure UHMWPE under dry sliding. And the friction coefficients of the composites are all very much lower than that of pure UHMWPE under distilled water lubrication conditions.

(3) The adhesion, ploughing, plastic deformation and fatigue are primary wear mechanisms for the pure UHMWPE under dry sliding. And the worn surface exhibits a lot of microscopic undulation. But the CF reinforced UHMWPE composite worn surface does not have such kind of microscopic undulation, and the abrasive wear and drawing out of CF in the wear surface of the composites are dominant in the wear mechanism of CF-UHMWPE composites.

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