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ORIGINAL PAPER

Pre-Polishing the Metal Counterface of Metal–UHMWPE Wear Pair with Filler-Filled UHMWPE Composites to Generate Counterface Changes for an Effective Reduction in Pure UHMWPE Wear

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Abstract Ultra-high molecular weight polyethylene (UHMWPE) is well known for high-wear-resistance applications. Its long-chained easy sliding molecules and semi-crystalline structures enable the polymer's great wear resistance. UHMWPE composites made for higher wear resistance study have been analyzed in this paper. Pure UHMWPE, 1 wt% CNT UHMWPE, 1 wt% PEEK UHMWPE, 1 wt% alumina (nano)–UHMWPE composites were made to be tested against metal disk on pin-on-disk tribometer. The metal disk surface conditions were found to have significant influence on the UHMWPE–polymer wear than the composite itself. This result indicates a simple and industrial applicable method that involves transfer film on the counterface to reduce polymer wear for metal–polymer wear pair applications.

Keywords UHMWPE · UHMWPE composite · Polymer polishing process · Pre-polished metal surface

1 Introduction

Ultra-high molecular weight polyethylene (UHMWPE) is well known for its high wear resistance due to its extremely long and easy sliding carbon back-boned chains and its semicrystalline structure. Its high wear resistance enables it to be used in many industrial and clinical applications such as joint prosthesis implants. Researchers are developing ways to further reduce UHMWPE wear debris generation during its usage by modifying the polymer itself or through UHMWPE composites. Crosslinking is the most common way to improve UHMWPE wear resistance for clinical applications. Crosslinked UHMWPE shows at least one order lower wear rate than conventional UHMWPE as shown in many publications [1–4]. However, crosslinked UHMWPE also shows more brittleness than conventional UHMWPE does, especially if the polymer has been oxidized due to free radicals generated during crosslinking process [3–9]. Clinical fracture of UHMWPE has been reported for crosslinked UHMWPE due to increased loading at certain parts of the acetabular liners during usage [10]. Therefore, some researchers proposed to add vitamin E into UHMWPE to prevent oxidation and increase the crosslinked UHMWPE's toughness [11, 12]. There are also many interesting facts about the UHMWPE molecular movements during the wear processes, regardless of crosslinked or conventional UHMWPE. Firstly, the wear sliding forces would arrange the crystalline lamellae of UHMWPE on the wear surface into one aligned direction [3, 13, 14]. This effect has also been seen for UHMWPE under mechanical forces that crystalline lamellae will be aligned along applied force direction [8]. Only the top layer of UHWMPE wear surface would see crystalline alignment after wear test, and the thickness of this layer depends on how much frictional energy needs to be used to mobilize UHMWPE molecules. Crosslinked UHMWPE costs more energy to mobilize molecules due to crosslinking points hindering molecular movements, while conventional UHMWPE takes less energy compared to crosslinked ones. And it has been observed that crosslinked UHMWPE has

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thinner aligned crystal lamellae layer than conventional UHMWPE after wear tests [3]. In addition, the wear process could damage the top-layer crystalline lamellae [13, 15]. These facts indicate that frictional energy degrading crystalline lamellae and disentangling UHMWPE molecules is the major wear mechanism for UHMWPE–polymer wear.

UHMWPE composites for wear improvement applications have been studied by many researchers. The filler used are widely ranged from metal oxides to carbon nanotubes, and some nanoparticles as well. The experimental improvements are reported to have around 40 to 80 % wear rate reduction for UHMWPE composites compared to original UHMWPE in bovine serum solution or simulated body fluid lubrication conditions or dry sliding conditions [16–24]. The major proposed wear improvement mechanisms have been linked to improved mechanical strength and the hard filler to take the localized loading during wear process, thus protecting the surrounding polymer matrix [16–24]. However, few have reported the impact of the hard fillers in the UHMWPE composite on the wear counterfaces. Plumlee and Schwartz's paper has reported that the counterface material has shown reduced roughness after wear tests for both UHMWPE and UHMWPE–zirconium composites [23]. The transfer film generated on the metal counterface during wear testing of polymer–metal wear pair was originated from the adhesive forces between polymer and metal, and it has been reported in many research works of wear study [25, 26]. Research has found out that different counterfaces would have different adhesive forces with polymer, and polyethylene adheres more strongly to CoCrMo than other TiN coating or zirconium oxide coating [27]. Marcus et al. [28] found that different sliding directions of UHMWPE against metal machining marks on the stainless steel would generate different effects on transfer films and thus on wear performance of the polymer. In this paper, a few common fillers, size ranging from nano to micro ranges, have been added into UHMWPE to form UHMWPE composites. Wear tests have been conducted, and the effects of counterface changes on wear performance have been carefully evaluated. Interesting results obtained in this paper indicate the significance of counterface change effects on the wear performance of the polymer.

2 Experimental Procedures

2.1 Sample Preparation

Pure UHMWPE, 1 wt% CNT UHMWPE, 1 wt% PEEK UHMWPE, and 1 wt% Al_2O_3 UHMWPE samples were prepared by powder compression molding. The UHMWPE powder was of grade GURX2105 obtained from Ticona Representative Office, Singapore. The CNT powder was single-walled CNT obtained from Hanwha NANOTECH Corp. The PEEK powder was obtained from Victrex company. The Al_2O_3 powder used was nanoalumina powder of average size 50 nm. The Al_2O_3 powder was mixed with 0.02 wt% stearic acid in advance to prevent agglomeration during the composite forming process. It was done by adding stearic acid and Al_2O_3 powder into ethanol and mixed with a magnetic stirrer for an hour. Then, the solvent was evaporated at 60 °C until the powder was dry. All the types of composite powders were mixed in a rotational roller blender for at least 4 hours to ensure uniform mixtures prior to compression molding. The composites and pure UHMWPE samples were made by powder compression molding into cylinder-shaped pins with a diameter of 10 mm and height ranged from 8 to 12 mm. The sample powders were first compressed at 1 metric ton (pressure = 125 MPa) for 1 min prior to heating. The heating temperature was 175 °C for a duration of 4 h. Immediately after heating, the sample was removed from oven and first compressed while it was still hot at 0.1 metric ton (pressure = 12.5 MPa) for 5 min and was pressed at a raised pressure of 0.75 metric ton (pressure = 93.6 MPa) for another 10 min before taken out from the compression die.

2.2 Disk Polishing Procedure and Pin-on-Disk Wear Tests

The metal disks used for pin-on-disk wear tests were made of high-Cr tool steel (1.55 % C, 11.8 % Cr, 0.4 % Mn, 0.8 %V, and 0.3 % Si) of hardness approximately 60 HV (Vickers hardness), and the surface was polished by an outsourced supplier to give a uniform surface roughness Ra = 0.3 μm on average. All the disks were cleaned with soap water and acetone and blown dried before any test. The disk polishing processes and wear tests were all conducted on a lab-designed pin-on-disk tribometer. The polishing process was to polish the disk with a polymer pin on the tribometer. The wear test was to run pure UHMWPE polymer pin on the disk surface on the tribometer. The pre-polishing and actual testing run were the same in the form of machine setup but mainly differed on the duration of the test. In other words, the disk polishing process was to pre-polish the metal disk with an UHMWPE polymer pin or an UHMWPE–polymer composite pin. Then, the pre-polished metal disk was used for pure UHMWPE wear test to see the wear performance of pure UHMWPE. The disk polishing process took 75 h, but the wear test conducted took only 15 h. The tribometer disk rotation speed was computer controlled at 100 rpm (sliding speed = 0.314 m/s), and the applied force on the polymer pin surface was

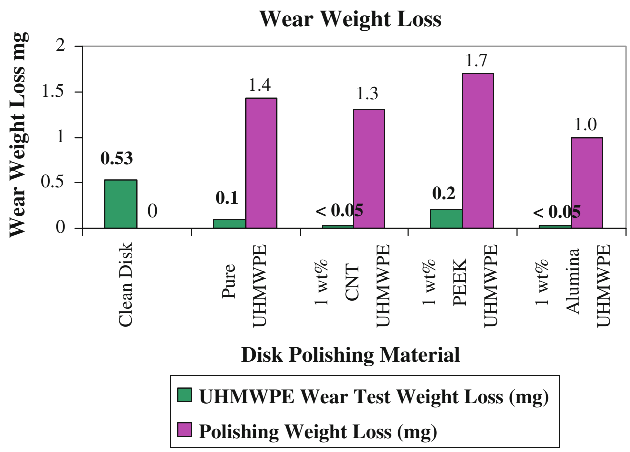

Fig. 1 Wear test and polishing wear weight losses for different disk polishing conditions

63.85 N deadweight giving an apparent pressure of 0.81 MPa. The wear test was 15 h, and the running distance was equivalent to 17 km. The wear test friction force was measured by a metal ring force transducer with full bridge strain gauge configuration which was in contact with the pin holder. The digital data logger recorded the strain readings which were then converted into friction force according to a calibration curve for the force transducer. The digital weight balance to measure the polymer pin weight difference before and after wear tests was of accuracy of 0.1 mg.

2.3 Disk Surface Analysis

The metal disk surface was observed under microscope to see the surface changes before and after disk polishing process. Atomic force microscope (AFM) was also used to obtain the disk surface roughness before and after disk polishing process.

3 Results and Discussion

Figure 1 shows the disk polishing material weight losses and the UHMWPE wear test weight losses on the pin-on-disk tribometer for different-material-polished disks. It is a surprising result because it shows that polymer-pre-polished metal disk can reduce UHMWPE wear rate from more than 60 % to even 90 %. This result also directly provides a simple solution for industrial wear problem of metal–polymer wear pair. Pre-polishing the metal part with a polymer before putting it into application can reduce the polymer wear loss for more than 60 % in the case of UHMWPE. Figure 1 also shows the polishing material weight losses for different-material-polished disks. 1 wt% CNT UHMWPE and 1 wt% alumina UHMWPE have

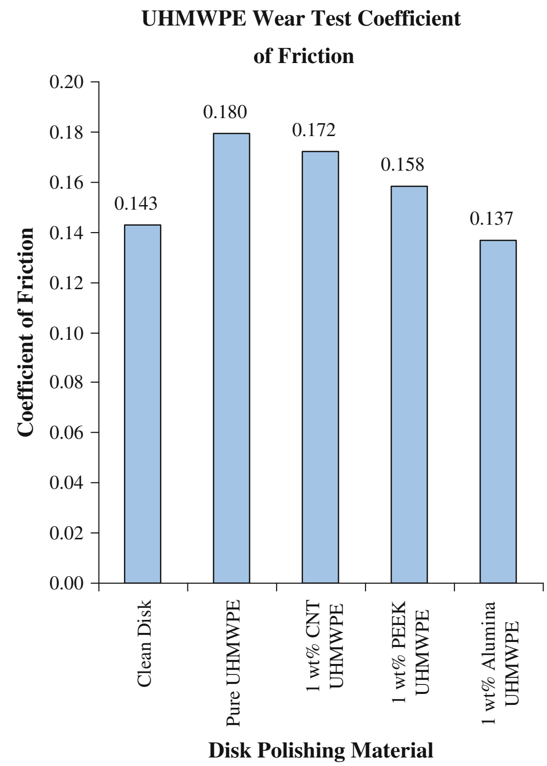

Fig. 2 UHMWPE wear test coefficient of friction on different condition polished disks

slightly less polishing weight losses than pure UHMWPE, and therefore, these two UHMWPE composites have an apparent higher wear resistance compared to pure UHMWPE from the polishing weight loss results. However, both 1 wt% CNT UHMWPE and 1 wt% alumina–UHMWPE-polished disks have UHMWPE wear weight loss of less than 0.05 mg; in other words, the weight balance cannot detect a weight difference before and after the wear tests for the UHMWPE test pin. This is much less than the UHMWPE wear weight loss on a new disk surface of 0.53 mg. Therefore, the changes on the metal disk from the polymer polishing process have far more significant influence on the polymer wear effect than the reasons from the composite making of polymer that hard fillers seem unable to improve UHMWPE wear resistance, but the transfer film and scratch marks can significantly reduce UHMWPE wear.

Figure 2 shows the UHMWPE wear test frictional coefficients on clean disk and pre-polished disks by different UHMWPE composites. Pre-polished metal disks give higher UHMWPE coefficient of friction except for 1 wt% alumina–UHMWPE-polished disk. Figure 3 shows the microscope images for pre-polished metal disks and clean disk. The major changes on pre-polished disks are the transfer films and some scratch marks. The transfer films are formed by polymer deposition during the wear process,

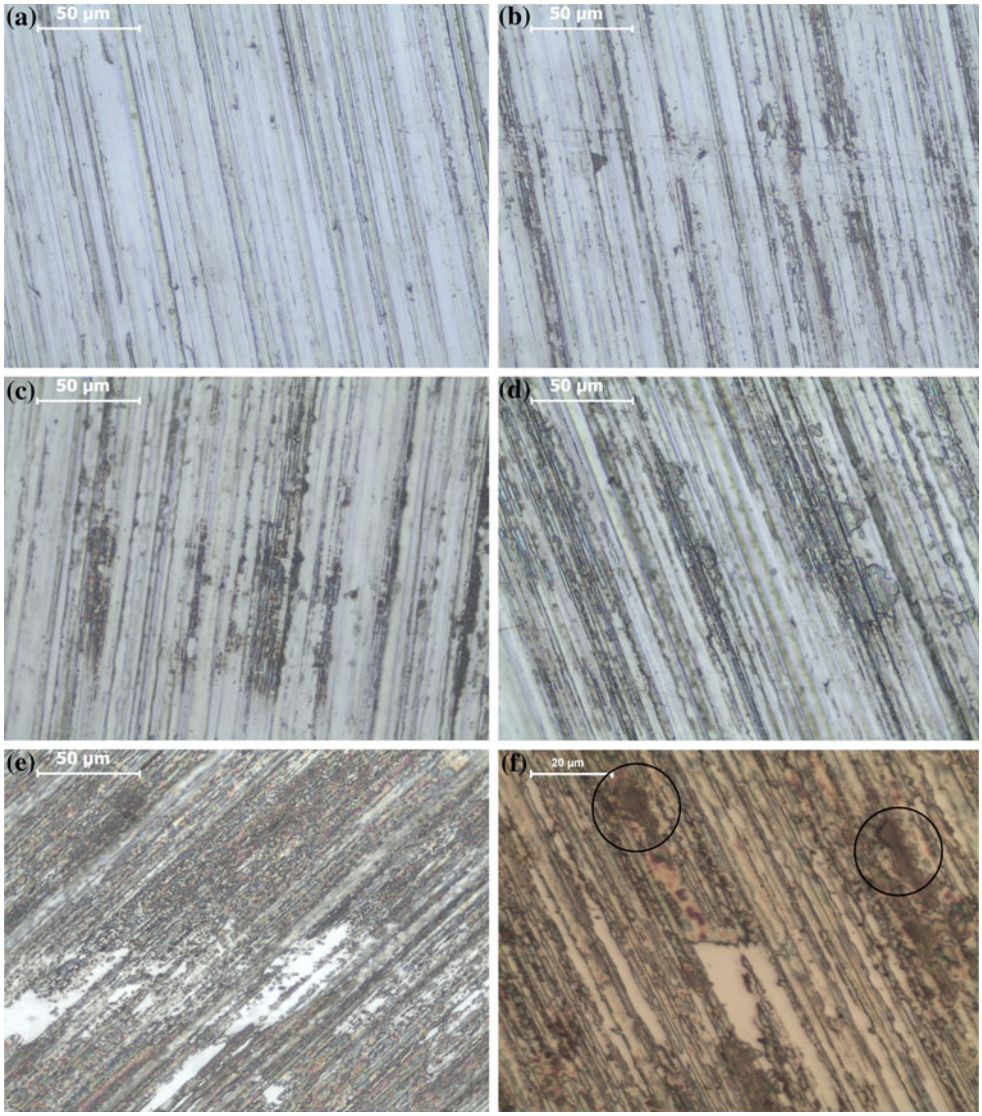

Fig. 3 Microscopy images of different disk conditions with/without polishing effects: **a** clean disk **b** pure UHMWPE-polished disk **c** 1 wt% CNT–UHMWPE-polished disk **d** 1 wt% PEEK–UHMWPE-polished disk **e** 1 wt% alumina–UHMWPE-polished disk **f** 1 wt% alumina–UHMWPE-polished disk of higher magnification, *circled parts* show rusty spots

and the reasons of the scratch marks on the metal surface is unknown. 1 wt% alumina–UHMWPE-polished disk shows much more transfer films and even rusty spots on the metal surface. It is suspected that the friction heating corrodes away some metal during the polymer polishing process for the case of 1 wt% alumina–UHMWPE-polished disk. Therefore, 1 wt% alumina–UHMWPE composite is not recommended for disk polishing processes for long-term usage applications, for accumulation of rusty spots may in future result in more wear of the polymer. However, for other commonly used implant alloys such as CoCr alloys, this is yet to be checked of the rust problem. Table 1 gives the AFM-measured disk roughness Ra for new disk and different-UHMWPE-composites-polished disks. New disk has the highest roughness value of around 0.3 μm. UHMWPE–polymer-composite-polished disks all show less roughness values, but the reduction is not much. All the roughness values maintain at 0.15 to around 0.3 μm. The polymer polishing process alters the disk roughness, but the reduction in surface roughness is limited. Yet pre-polished disks show much less UHMWPE wear rate compared to new disk. The exact reason of why polymer polishing process can reduce UHMWPE wear rate greatly is not clear. The transfer films and scratch marks on the pre-polished disks may help to sooth the polymer during the wear process.

This research has found out a simple and great application to polymer–metal wear pair (for UHMWPE polymer) to reduce UHMWPE wear rate in industrial applications. That to pre-rub the metal surface with

Table 1 AFM-measured disk roughness (Ra, nm) for different-material-polished disks

Disk conditions	Clean disk	Pure UHMWPE-polished disk	1 wt% CNT–UHMWPE-polished disk	1 wt% PEEK–UHMWPE-polished disk	1 wt% alumina–UHMWPE-polished disk
Roughness value (Ra, nm)	308.70	250.14	244.95	154.39	285.10

UHMWPE polymer or UHMWPE–polymer composites for long enough time would result in much lower UHMWPE wear rate in its application time. This phenomena itself is not first to be found through history. Mckellop et al. [26] have conducted wear test analysis for UHMWPE in one paper in 1978 and have found that UHMWPE long-term wear rate is much lower than the UHMWPE beginning wear rate. The rough metal counterface can have much higher wear rate of UHMWPE compared to mirror-like smooth metal counterface, but both would have similar long-term steady-state wear rate. In Mckellop et al. paper, the counterface transfer film was defined as a layer of polymer that is not stable and could be rubbed off, unlike in this research, the transfer film generated is thin, transparent, and stable. In Mckellop et al. [26] paper, the long-term lower wear rate has not been connected with the metal counterface changes. In some other research papers, long-term wear of UHMWPE and its polymer composite show much lower wear rates than the beginning polymer wear rates [4], and some research papers show large scatters in wear rate results due to the difference in the beginning wear rates and long-term wear rates [1, 19], but none of them mention the relation between metal counterface changes with the lower long-term wear rate of UHMWPE, and one even suggest the much lower value of UHMWPE long-term wear rate is due to the ultra-high transient creep period [4]. This phenomena although is not new but has never been thoroughly studied and has not been utilized in industry. However, the great reduction in wear of UHMWPE arisen from the polymer polishing process cannot be fully explained in this paper. This still needs more research to be conducted to pursue the exact mechanism of wear rate reduction in UHMWPE.

4 Conclusion

Polymer polishing process on metal disk has a significant influence on UHMWPE wear. The pre-polished metal disks polished by UHMWPE polymer or UHMWPE composites show more than 60 % to even 90 % wear rate reduction for UHMWPE tested on such disks. The changes on the metal disks are mainly transfer films and scratch marks. 1 wt% alumina–UHMWPE-polished disk has rusty spots, which is not desirable for long-term applications, but the selection of testing counterface was high-chromium tool steel, so for other types of implant alloys, this rust problem remains to be tested and verified. The polymer polishing process provides a very simple but effective improvement for industrial metal–polymer wear pair applications to reduce the wear rate of the polymer. That is to pre-polish the metal part before placing it into applications.

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