Available online at www.sciencedirect.com
SCIENCE DIRECT®
Materials Chemistry and Physics xxx (2004) xxx–xxx
MATERIALS CHEMISTRY AND PHYSICS
www.elsevier.com/locate/matchemphys

Wear behavior of UHMWPE sliding on artificial hip arthroplasty materials

H.J. Cho[a], W.J. Wei[a,*], H.C. Kao[b], C.K. Cheng[c]

[a] Institute of Materials Science and Engineering, National Taiwan University, 1 Roosevelt Road, Section 4, Taipei 106, Taiwan, ROC
[b] Medical Research Department, Mackay Memorial Hospital, Taipei 251, Taiwan, ROC
[c] Institute of Biomedical Engineering, National Yang Ming University, Taipei 251, Taiwan, ROC

Received 25 July 2003; received in revised form 15 September 2003; accepted 13 October 2003

Abstract

A study on the wear behavior of an ultra high molecular weight polyethylene (UHMWPE) sliding on the discs made of two types of ceramics was conducted by a ring-on-disc reciprocal wear test. The properties including friction coefficient, wear factor, debris, and transfer film of UHMWPE were evaluated and correspondent to the variables in the wear tests. Those variables included type of disc materials (zirconia and alumina), lubricants, types of contact face of UHMWPE rings, and surface roughness of discs. The results indicated that the friction coefficient and wear factor were closely controlled by the roughness of the disc. The wear mechanisms of UHMWPE sliding on zirconia could be categorized by two types of surfaces differentiated by a critical roughness (R_a) of 0.10 μm. The effects of debris and transfer film (i.e. third body effect) were investigated. By reducing the initial roughness of UHMWPE, pre-coating a transfer film onto the disc, and using saline as a lubricant can slightly reduce the friction coefficient, and improve the wear factor of the UHMWPE on ZrO_2 disc.

Keywords: UHMWPE; Zirconia; Ring-on-disc; Wear; Third body

1. Introduction

The artificial hip arthroplasty substituted the damaged articular cartilage by artificial materials. The life of the artificial hip arthroplasty is decided by the wear conditions between the femoral ball and cup. A ceramic ball and an UHMWPE cup pair has the last friction and reported to be an idea combination [1–3]. Alumina and zirconia are the only choices for ceramic femoral ball. Among those ceramics, yttria doped-tetragonal zirconia polycrystals (Y-TZP) shows higher strength and toughness than alumina. These excellent mechanical properties and bio-compatibility make the zirconia a great potential in bio-medical application.

The hardness of UHMWPE is far inferior to zirconia. When used in long-term clinical situation, it would be worn and generate wear debris. The worn-out UHMWPE debris likely induce osteolysis, then lead to bone loosening. Finally, patient needs a revision operation [4,5]. How to reduce the degree of UHMWPE wear in human body is the most important issue in increasing the survive life of the artificial arthroplasty. Laboratory wear test apparatus of artificial hip arthroplastic materials include four types [3,6–11]: pin-on-plate, pin-on-disc, hip simulator, and ring-on-disc. Since the survive life of the arthroplasty depended on the wear rate. The factors influenced the wear are tremendous complex. No apparatus has been claimed that can simulate all wearing conditions. But, it is assured that the higher the wear rate, the more the debris would form and cause osteolysis. In addition, the friction coefficient value has a relationship with the wear behavior and the comfort of human. Therefore, the evaluating factors should include: wear mechanism, friction coefficient, wear factor, UHMWPE debris and transfer film. A review of literature shows the wear factors are between 10^{-7} to 10^{-8} $mm^3\,N^{-1}\,m^{-1}$ [3,6–8,12–15]. The material

* Corresponding author. Tel.: +886-2-2263-0231x2701; fax: +886-2-2263-4562.
E-mail address: wjwei@ccms.ntu.edu.tw (W.J. Wei).

0254-0584/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.matchemphys.2003.10.021

adopted in these literatures include ZrO_2, Al_2O_3, Co–Cr–Mo alloy, or stainless steel. The apparatus used in previous papers was either pin-on-disc or pin-on-plate.

The main objectives of this study are to investigate the wear behavior of an UHMWPE against zirconia (yttria doped-tetragonal zirconia polycrystals (Y-TZP)) using ring-on-disc configuration under various lubricated conditions. Besides, the examination of the wear mechanism, UHWMPE debris and transfer film, and the measurements of wear factor and friction coefficient will help to interpret the effects of surface condition (R_a) of ceramics, third-body wear and lubricating fluid. From the result, we could understand the behavior, wear mechanism and the limitation of the UHMWPE in an artificial arthroplasty application.

Table 1
The physical properties of ZrO_2, Al_2O_3,and UHMWPE used for wear test

	Disc		Ring
	ZrO2[a]	Al_2O_3[a]	UHMWPE[b]
Molecular weight	–	–	>3 million
Process	Slip casting	Slip casting	–
Density	99.8% T.D.	99.4% T.D.	0.936 g/cm^3
Average grain size (μm)	0.42	2.7	–
Flexural strength (MPa)	723	442	46.6
Tensile strength at yield (MPa)	–	–	22.9
Elongation at breaking point (%)	–	–	350
Maximum grain size (μm)	0.76	9.4	–

[a] Tested by ceramic processing laboratory in NTU.
[b] Supplied by United Orthopedic Corporation, Taiwan, ROC.

2. Methods and materials

2.1. Apparatus

Reciprocal sliding tests were carried out by using a ring-on-disc test apparatus. Fig. 1 shows the ring-on-disc test apparatus. All testing conditions followed the Standard ISO 6474 [16]. Each test in this study was run for 100 h with a reciprocal turning frequency of 1 ± 0.1 Hz and a rotation angle ±25°. The vertical load on ring was 1500 N (equal to 9.4 MPa contact stress). All tests were carried out at room temperature (25 ± 2 °C) in circulating distilled water or saline solution. The ring and disc samples were pre-loaded and soaking in the lubricating solution for 30 min before test.

2.2. Materials

Medical grade UHMWPE samples (Westlake Plastics Company, PA, USA) were cut into a ring shape with 14 mm inner diameter, 20 mm outer diameter, and 12 mm height. The mass of an UHMWPE sample was controlled within 2.290 ± 0.010 g. The disc materials included zirconia and alumina. The zirconia and alumina samples were prepared by slip casting and adopted the best condition in prior studies [15,17]. The properties of ring and disc materials are shown in Table 1. All the discs had a size of 36 ± 0.5 mm diameter and 8 ± 0.5 mm thickness. The disc contact face of the disc was polished to different roughness. Surfacord SE-2300 (Kosaka Laboratory Ltd., Japan) was used to measure the average surface roughness (R_a) across a distance of 2 mm. The average of 10 measurements was taken. The procedure to clean the rings and discs samples before test followed the ASTM F732-82 [18].

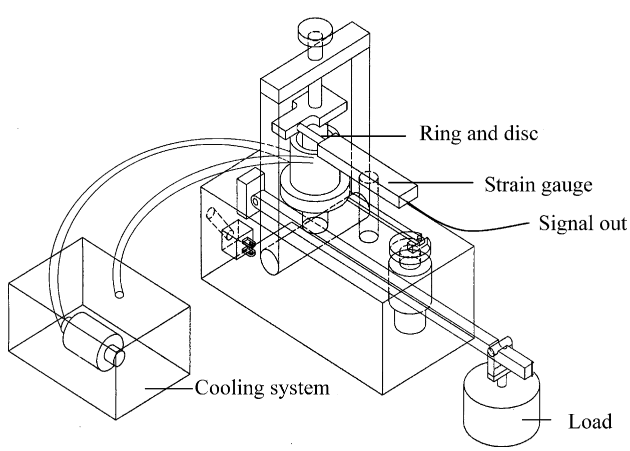

Fig. 1. Schematic diagram of ring-on-disc wear test apparatus.

2.3. Friction coefficient measurement

In the testing process, the moment generated by friction will balance with the moment generated by the rotation of the disc holder. Therefore, a strain gauge was used to measure the friction coefficient.The output signal from strain gauge was calibrated to tangential force. We take the average of one-third of the highest amplitude to calculate the friction force (F) and friction coefficient (μ) as below.

$$F = \frac{F_t \times d_1}{d} \quad (1)$$

$$\mu = \frac{F}{F_N} \quad (2)$$

where d_1 is the distance from strain gauge to the center of the ring sample (5.0 cm), d the radial of ring sample (0.85 cm), F_N is the load (1500 N).

2.4. Wear factor measurement

The wear test results are shown by mean wear factor which is defined as [2]:

$$K = \frac{\text{volume loss}}{\text{load} \times \text{sliding distance}} \ (\text{mm}^3\,\text{N}^{-1}\,\text{m}^{-1}) \quad (3)$$

Three UHMWPE samples were put in each test condition: load and lubricate for 100 h to measure the average mass change (M_{ab}), which gain weight by moisture absorption in distilled water. Three UHMWPE specimens were used to measure the M_{ab}. The mass changes of UHMWPE samples were measured by Sartorious research microbalance to an accuracy of 0.01 mg. The worn mass of UHMWPE samples was calibrated by deduction of M_{ab} (average M_{ab} is 0.16 mg per piece). The UHMWPE volume loss can be calculated from dividing the mass loss by the density (0.936 g cm^{-3}). The sliding distance is equal to 5026.6 m. In order to understand the relationship between surface roughness of disc and wear factor of UHMWPE in long-term, the data presents in this paper is the wear result of the wear testing through 100 h.

2.5. Observation of debris and transfer film

Wear debris was retrieved from the circulating water through a 0.1 μm mesh polymer filter. All debris and disc contact faces were sputtered with a Au coating before examined by scanning electron microscopy (SEM XL30-EDX Philips Instrument Co., The Netherlands).

3. Results and discussion

3.1. Friction behavior

The 100 h frictional behaviors of UHMWPE and four ZrO_2 samples with various surface roughness are similar (Fig. 2). The friction coefficient reduces from 0.15 to lower than 0.05 as the testing time extend, until the surface arrived a steady state. This indicates that the contact surface between ring and disc gets into a stable condition. This trend is consistent with the reported wear results of UHMWPE sliding on zirconia (PSZ) [6].

The average friction coefficient after 1000 min testing shows the friction coefficient of steady state and is named as stable friction coefficient. When the surface roughness of discs is less than 0.10 μm (R_a), the friction coefficients are not significant different among these surface (Fig. 2). The initial and stable friction coefficients were approximated 0.100 and 0.056 (±0.020), respectively. For a rougher surface (the roughness of disc is more than 0.10 μm), the initial and stable friction coefficients increased as the surface roughness increase. The coefficients are 0.150 and 0.092, respectively for the discs with the surface roughness 0.16 μm (R_a).

The frictional behaviors of UHMWPE on Al_2O_3 alloy were similar to that on TZP, but the friction coefficients are different. Fig. 3 shows the friction coefficient (which refers to the stable friction coefficient hereafter in this paper) of the above materials with various surface roughness and some relative references [7,8,13,14,19]. It appears that when the ring reciprocally slide on smoother contact surface (R_a < 0.04 μm), the friction coefficient of Al_2O_3 was lowest (μ = 0.033 ± 0.003).

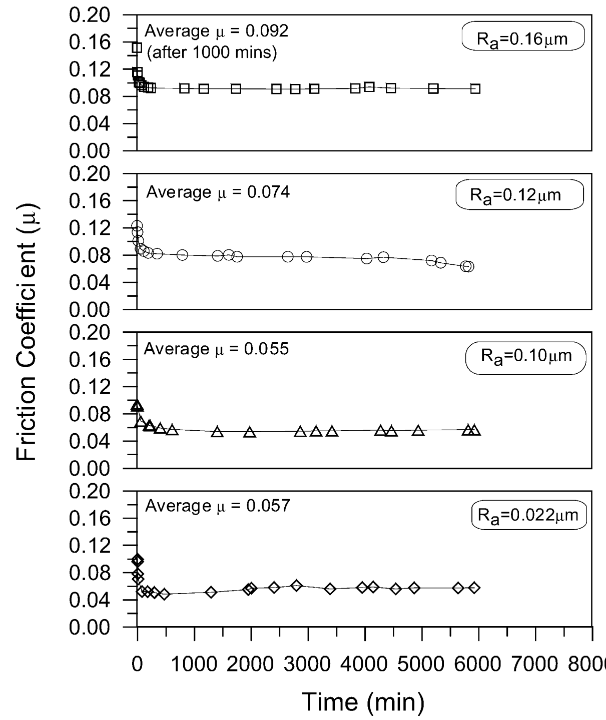

Fig. 2. Frictional behavior of UHMWPE on TZP disc with specified surface roughness tested in distilled water.

3.2. Wear factor

In general, the wear factor is high in the initial stage of the wear testing. Then, it gradually reduces to a stable value [6,20]. The wear factors of UHMWPE sliding on TZP discs with various different roughness are shown in Fig. 4. The wear factor has no significant different when the roughness is less than 0.10 μm. The wear factors are from 1.56×10^{-8} to 2.97×10^{-8} mm^3 N^{-1} m^{-1}. An upswing of the wear factor

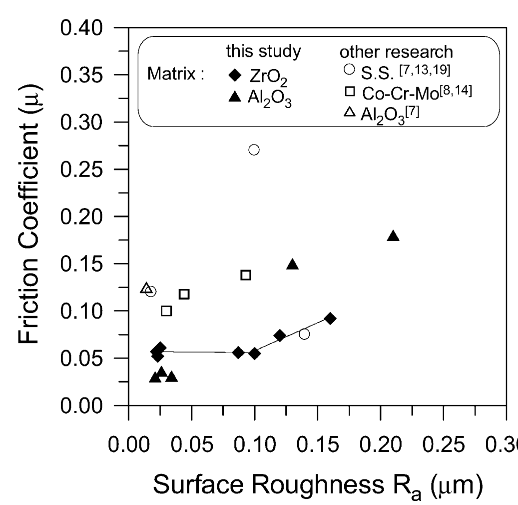

Fig. 3. Friction coefficient of different materials plotted against surface roughness of various discs.

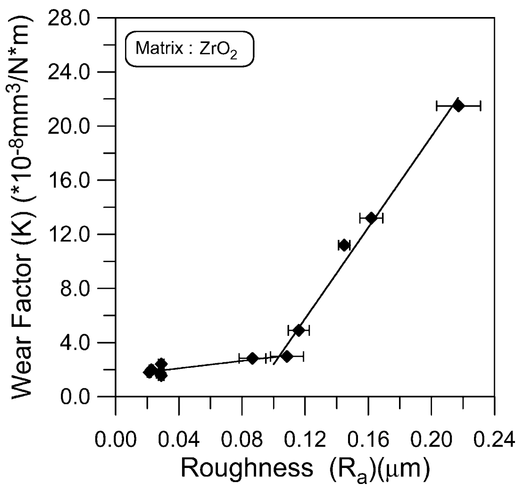

Fig. 4. The variation of wear factor with respect to roughness on ZrO_2 contact surface.

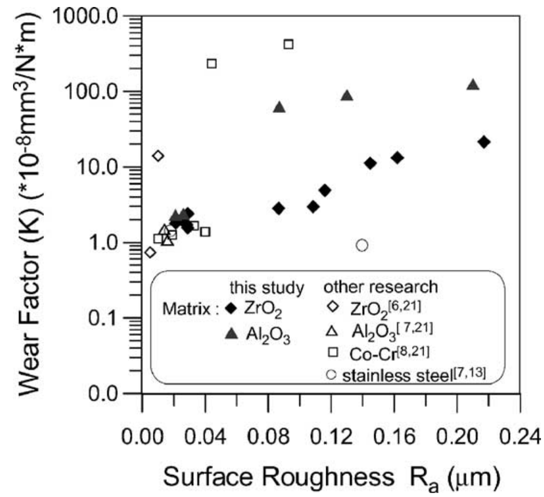

Fig. 5. The variation of wear factor of UHMWPE with the roughness on different contact surfaces.

is noted as the roughness is more than 0.10 μm. The wear factor was $21.5 \times 10^{-8}\,mm^3\,Nm^{-1}$ when the roughness of TZP disc was 0.22 μm. This trend was similar to previous results of the friction coefficient.

Cooper et al. [12] has presented two possible wear mechanisms of polymeric materials. On a smooth contact surface, the scale of the peaks and asperities of polymer was 10 to 100 times greater than the asperity on smooth matrix. When a load is applied, these peaks will deform and subsurface sustain concentrate stress and form a surface strain layer. The removal of material from these highly stressed polymer peaks was defined as "macroscopic polymer asperity wear". On a rough surface, the wear mechanism is an abrasive wear and the residual subsurface strains are not found. In these conditions, two materials contacted by mechanical interlocking or hard material impacted into soft material. When the relative motion generated between two materials, the soft material was ploughed by hard material then removed.

Fig. 5 shows the wear factors measured in this study and some other research results [6–8,13,21]. The wear factor on alumina is about $2.30 \times 10^{-8}\,mm^3\,N^{-1}\,m^{-1}$ when the roughness is less than 0.040 μm. On a rougher contact surface (R_a > 0.10 μm), the wear factor is significantly greater than that on TZP. For example, when the roughness is 0.21 μm, the wear factor on Al_2O_3 was six times higher than that on TZP (R_a > 0.22 μm). This may be due to grain pull-out on Al_2O_3 surface. From the literature, we can find that the wear factor is in the range of $0.74–1.65 \times 10^{-8}\,mm^3\,N^{-1}\,m^{-1}$, no matter what the material is ZrO_2, Al_2O_3, Co–Cr–Mo alloy, or stainless steel. The apparatus used in previous papers is either pin-on-disc or pin-on-plate. The results shown in these studies are in the same range as this study. Because of the contact condition of two materials and the debris accumulated between acetabular cup and femoral head, the ring-on-disc apparatus can simulate the arthroplasty condition better than pin-on-disc or pin-on-plate simulator. The advantages of this test include that is a standard adopted by ISO. The device can also retain debris particles at interface and perform reciprocally sliding motion. Therefore, using the ring-on-disc apparatus to simulate the hip arthroplasty is more representative.

3.3. Formation of transfer film and debris

The surface of the machined UHMWPE ring specimens always show grinding ridges. The average initial roughness (R_a) of UHMWPE is 0.71 μm. Fig. 6 shows the roughness of UHMWPE after wear test for 100 h against the discs with different roughness. The results appear that the roughness of worn UHMWPE is reduced and become smoother when testing with rougher discs. When the R_a of ZrO_2 disc is 0.16 μm, the R_a of UHMWPE decreases to 0.24 μm after 100 h wear testing. In order to slide easily, in the wear process, two

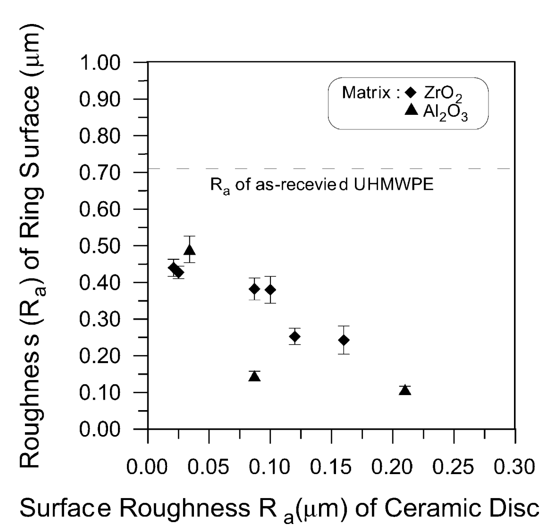

Fig. 6. The relationship of surface roughness of UHMWPE ring after worn (testing 100 h) against ceramic with specified surface roughness. All ring surfaces have a roughness R_a = 0.17 μm.

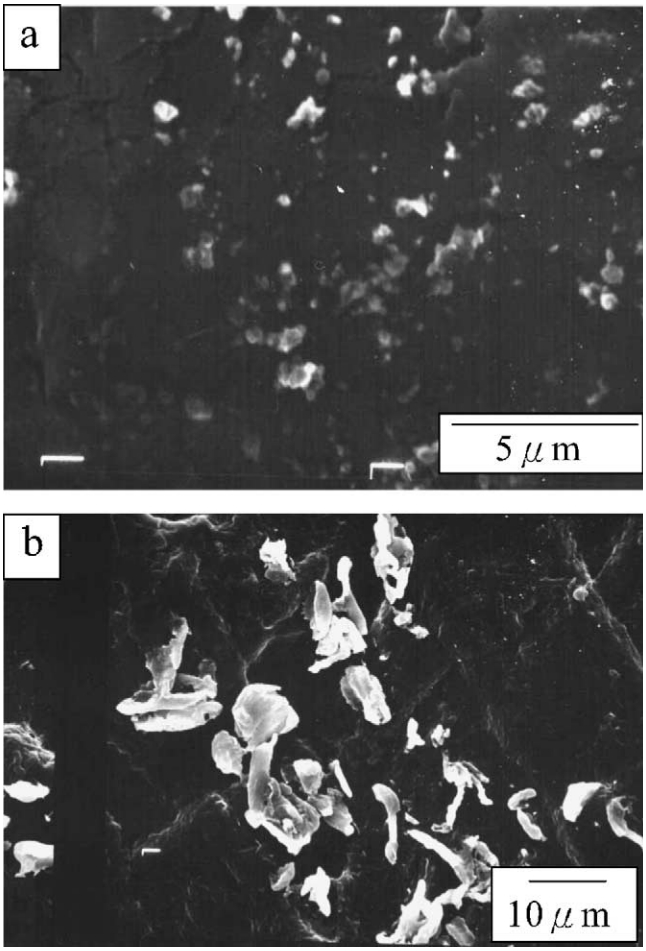

Fig. 7. SEM micrographs of UHMWPE worn debris (a) collected from the case of 0.03 μm TZP (b) from 0.22 μm TZP.

against materials will generate shear dislocation between the surface molecular and remove the material from the surface peaks to make the asperity smoother.

The mass loss of UHMWPE tested on rough disc was apparent, so the residual ridges disappeared and became to a smoother surface. Fig. 7 shows the image of debris recovered from the lubricant water by polymer filter with 0.10 μm mesh size. The debris size is below 1 μm and most of them are granular. Fig. 7(b) shows the debris generated by the test on the ZrO_2 disc R_a = 0.22 μm. The debris were almost flake-like, the size is about 10–20 μm. Only 10% of the debris are granular and the size of them is below 5 μm. The debris size is similar to those retrieved from the tissues or synovial fluid removed during the revision of total hip or knee replacement [6,22,23]. According to Rabinowicz's minimum energy criterion [24] for particle formation by adhesion and material transfer, the sizes of UHMWPE particles would be in the range of a few millimeters. The volume and size of debris are critical factors in osteolysis [25]. The size of the most biologically active particles in the phagocytosable is in the range of 0.3–10 μm. Therefore, the debris size should be considered.

The SEM micrographs of UHMWPE transfer film found on TZP disc (R_a = 0.22 μm) are shown in Fig. 8 which show the clean surface of zirconia, Fig. 8(b) was the surface near the inside track and Fig. 8(c) was middle part of the track. It demonstrates that the distribution of transfer film is not uniform. The thickness was decreasing from inside to outside of ring and disc contact track. It had a relationship with the accumulation of UHMWPE debris in the center of the ring. The debris near the rim slipped into the interface, then the third particle were pressed and ground repeatedly. Finally, the debris formed a thick transfer film near inside track. The cracks can be observed on Fig. 8(b). It may be that the UHMWPE undergo a period of drying, the crack form, or repeatedly shear force acted on the thick transfer film causing the crack formation. In addition, the debris collected inside the ring slide into the interface can treated as the third body of the UHMWPE and disc, affect the wear behavior.

Fig. 9 shows the SEM micrographs of UHMWPE transfer film found on Al_2O_3 disc (R_a = 0.034 μm). The morphology is similar to that on TZP disc. But the thickness of transfer film was thinner than that on the TZP disc, the microstructure of the matrix can be observed.

3.4. Effect of lubricant

The consistency of human synovial fluid is similar to egg white. The fluid moistens and lubricates the smooth catilaginous surface within the joint [26]. Hyaluronic acid, one component of the synovial fluid, shows very good lubricating property. It has been reported [7] that adding 0.3 wt.% hyaluronic acid in saline can reduce the friction coefficient from 1.5 to 2 times, and the wear factor can be reduced from 1.5×10^{-8} mm^{3}N^{-1} m^{-1} to 1.2×10^{-8} mm^{3}N^{-1} m^{-1}. Similar result was shown in the experiment of Jay et al. [27]. They also found that hyaluronate appears closely isotribologic properties with 0.9% NaCl saline. Because of difficulty of getting hyaluronic acid, we used saline with 0.9% NaCl as a lubricant in this research. The results of the wear test in saline and distilled water are shown in Fig. 10. It appears that the initial friction coefficient in saline is about 0.100 and is closed to those in distilled water. The average friction coefficient of stable period and wear factor are about 0.046 and 1.68×10^{-8} mm^3 N^{-1} m^{-1} smaller than those in distilled water. But the different is not significant.

3.5. Effect of contact surface properties

Wear behavior was profoundly affected by the conditions of contact surface [8,20]. UHMWPE transfer film generated on the matrix was considered relevant to a reducing of friction coefficient. In order to realize how the contact surface properties affect the wear result, we pre-coated a thin transfer film on ceramic before test and adopt different UHMWPE surface to test. The results are shown in Fig. 11. The initial friction coefficient is 0.10, the stable friction coefficient 0.057, and the wear factor 1.98×10^{-8} mm^{3}N^{-1} m^{-1} when the R_a of

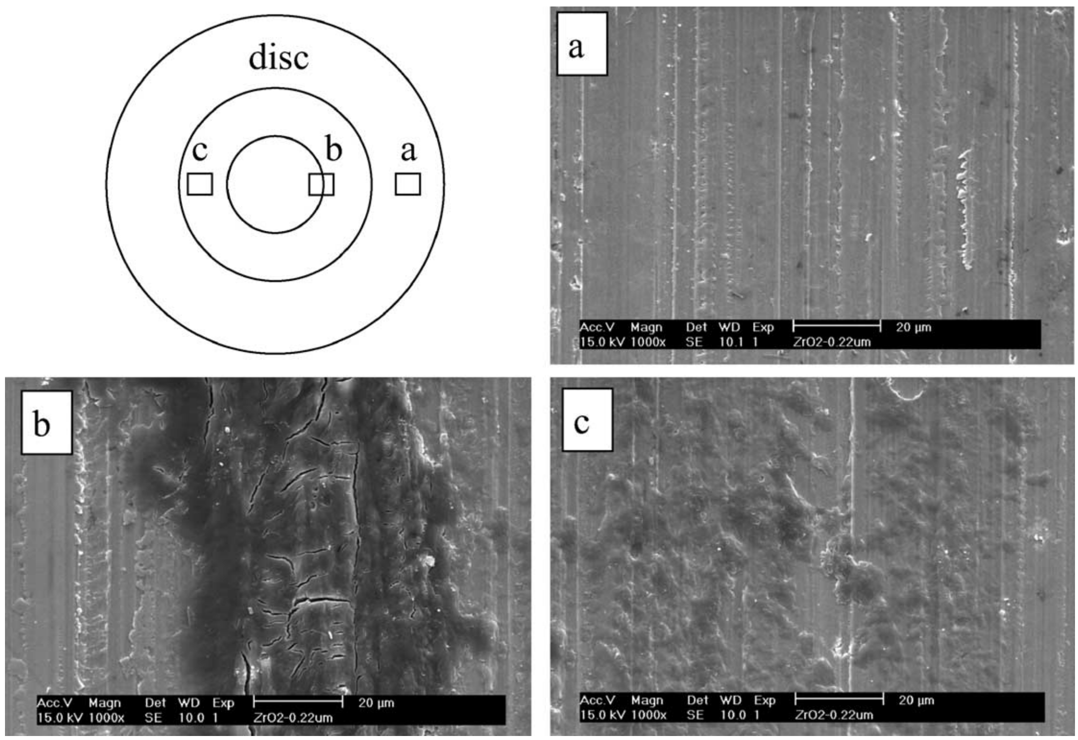

Fig. 8. SEM micrographs of UHMWPE transfer film found on ZrO_2 rough (R_a = 0.22 μm) contact surface of testing in distilled water. (a) Clean surface (b) near inside track (c) middle part of the track.

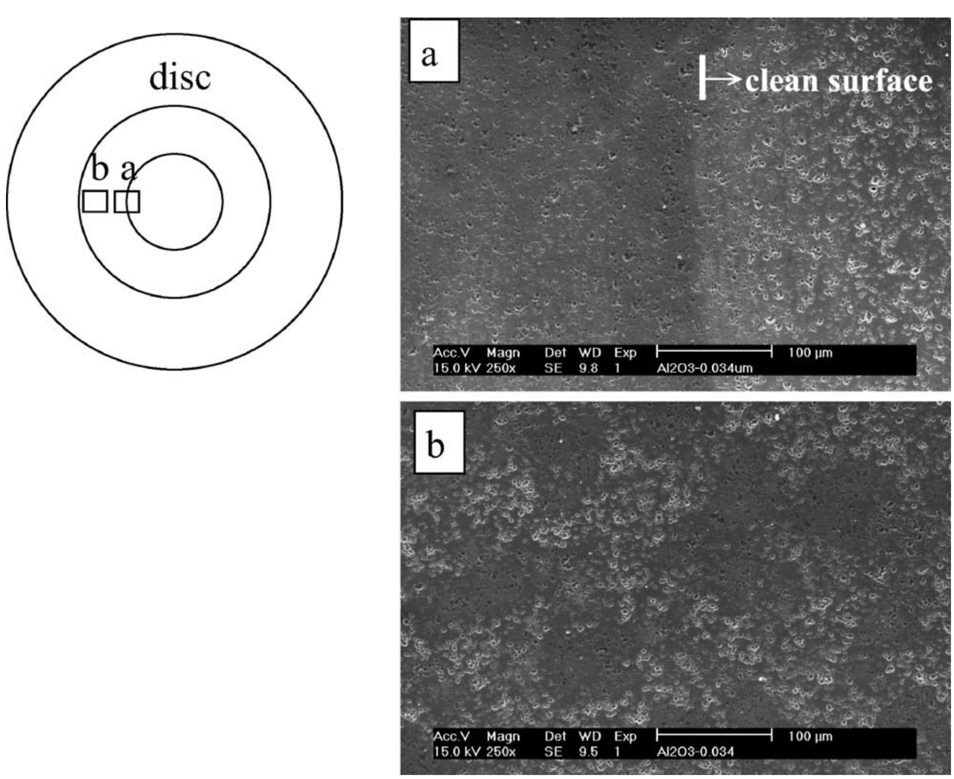

Fig. 9. SEM micrographs of UHMWPE transfer film found on Al_2O_3 (R_a = 0.034 μm) contact surface of testing in distilled water. (a) The interface of transfer film (b) middle part of the track.

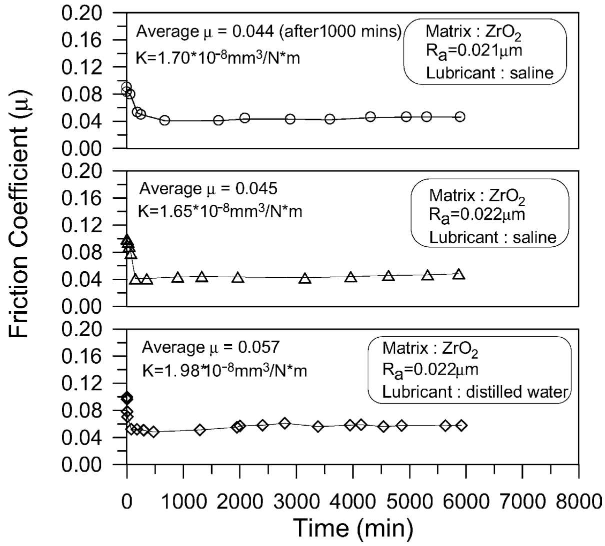

Fig. 10. The difference of wear behavior between tests in distilled water and saline.

UHMWPE ring and TZP disc is 0.71 and 0.022 μm, respectively. While the R_a of ring is reduced to 0.26 μm (the ring underwent 100 h wear test), the initial friction coefficient (μ = 0.085) and wear factor ($k = 1.66 \times 10^{-8}\,mm^3\,N^{-1}\,m^{-1}$) are smaller than those in prior test. But the stable friction coefficient is similar. If a thin transfer film is pre-coated on the disc, the friction coefficient is increased to 0.110 from 0.060 and then decreased to a stable value of 0.450. The wear factor is $1.56 \times 10^{-8}\,mm^3N^{-1}\,m^{-1}$ which is slightly better if with a transfer film.

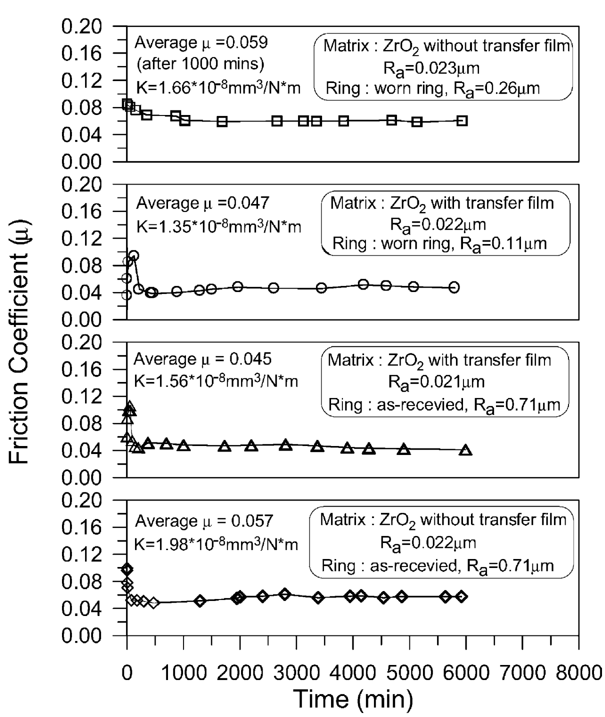

Fig. 11. The wear behavior of different contact surfaces tested in distilled water.

Worn ring (R_a = 0.11 μm) was repeatedly test on pre-coating transfer film disc. The initial friction coefficient was smaller (μ = 0.035), but it had the same trend that shown an increase to a high value (μ = 0.094) then reducing to a stable state (μ = 0.047). It is because the distribution of transfer film between the contact surfaces was not smooth (this has been discussed in prevision section). When the contact surfaces suffered relative motion, the transfer film will redistributed to a smooth and steady condition, then the friction coefficient decreases. After the wear test, the R_a of UHMWPE ring is increased to 0.23 μm. This is the evidence that the UHMWPE surface has worn. The wear factor ($1.35 \times 10^{-8}\,mm^3\,N^{-1}\,m^{-1}$) is smaller to that of the test with R_a = 0.71 μm ($1.56 \times 10^{-8}\,mm^3\,N^{-1}\,m^{-1}$). Therefore, decreasing the initial roughness of UHMWPE ring or pre-coating a transfer film on disc before wearing test can reduce wear factor.

4. Conclusion

The wear behavior of UHMWPE rings sliding on TZP or Al_2O_3 ceramic discs was investigated. The friction coefficient and the wear factor measured by a reciprocal-contact-wear test were closely related to the roughness and surface cleanness of disc under constant load condition. The wear mechanism of UHMWPE was either surface fatigue wear or abrasive wear which took place on the surfaces with a roughness (R_a) either smaller or greater than a critical value 0.10 μm. The wear factor of UHMWPE sliding on TZP and Al_2O_3 discs were nearly identical with a smooth surface (R_a < 0.10 μm). But the latter showed higher friction coefficient and wear factor than that sliding on zirconia. It should be caused by the grain pull-out defect on the Al_2O_3 surface.

The surface of the UHMWPE was worn to smother roughness as the surface roughness of the discs increased. The reattachment of various worn debris was the major cause for the modification of the surfaces of wearing parts. In addition, the debris generated inside the center of the ring was not easy to transude. The distribution of resulted transfer was thicker near the inside track of the contact area. But the film was hardly found on the middle part of the track.

The wear factor and friction coefficient of using saline as lubricant were smaller than those testing in distilled water, but the different is not significant. Reducing the initial roughness of UHMWPE ring, and pre-coating a transfer film on disc can slightly decrease the wear factor of the ring on ceramic disc.

Acknowledgements

The authors would like to express their appreciation for the financial support of this research provided by National Science Council (NSC) in Taiwan under the contracts NSC87-2622-E-002-014.

References

[1] D. Dowson, A comparative study of the performance of metallic and ceramic femoral head components in total replacement hip joint, Wear 190 (1995) 171–183.
[2] B. Derbyshire, J. Fisher, D. Dowson, C. Hardaker, K. Brummitt, Comparative study of the wear of UHMWPE with zirconia ceramic and stainless steel femoral heads in artificial hip joints, Med. Eng. Phys. 16 (1994) 229–236.
[3] A. Chanda, A.K. Mukhopadhyay, D. Basu, S. Chatterjee, Wear and friction behavior of UHMWPE-alumina combination for total hip replacement, Ceram. Int. 23 (1997) 437–447.
[4] H.C. Amstutz, P. Campbell, N. Kossovsky, I.C. Clarke, Mechanism and clinical significance of wear debris-induced osteolysis, Clin. Orthop. Rel. Res. 276 (1992) 7–18.
[5] D.H. Sochart, Relationship of acetabular wear to osteolysis and loosening in total hip arthroplasty, Clin. Orthop. Rel. Res. 333 (1999) 135–150.
[6] M. Kernick, C. Allen, The sliding wear of UHMWPE against zirconia in saline containing proteins, Wear 203–204 (1997) 537–543.
[7] Y. Sawae, T. Murakami, J. Chen, Effect of synovia constituents on friction and wear of ultra-high molecular weight polyethylene sliding against prosthetic joint materials, Wear 216 (1998) 213–219.
[8] D.M. Tetreault, F.E. Kennedy, Friction and wear behavior of ultra-high molecular weight polyethylene on Co–Cr and titanium alloys in dry and lubricated environments, Wear 133 (1989) 295–307.
[9] A. Wang, A. Essener, C. Stark, J.H. Dummbleton, Comparison of the size and morphology of UHMWPE wear debris produced by a hip joint simulator under serum and water lubricated conditions, Biomaterials 17 (1996) 865–871.
[10] P. Eyerer, M. Kurth, Characterization of UHMWPE hip cups run on joint simulators, J. Bio. Mater. Res. 21 (1987) 275–291.
[11] ROC, Patent 365,812, 1999.
[12] J.R. Cooper, D. Dowson, J. Fisher, Macroscopic and microscopic wear mechanism in ultra-high molecular weight polyethylene, Wear 162–164 (1993) 378–384.
[13] J. Fisher, D. Dowson, H. Hamdzah, H.L. Lee, The sliding velocity on the friction and wear of UHMWPE for use in total artificial joints, Wear 175 (1994) 219–225.
[14] M.H. Huang, The analysis of frictional heating effect of UHMWPE in total joint arthroplasty, National Yan-Ming University, Master Thesis, 1999.
[15] P.C. Wang, The optimization of colloidal process and mechanical properties of Alumina, National Taiwan University, Master Thesis, 1998.
[16] ISO 6474, Implants for surgery-ceramic materials based on high purity alumina, 1994.
[17] F.Y. Ho, The colloidal process and sintering properties of Y-TZP, National Taiwan University, Master Thesis, 1997.
[18] ASTM F732-82, Standard practice for reciprocation pin-on-flat evaluation of friction and wear properties of polymeric materials for use in total joint prostheses, 1991.
[19] W.H. David, L.W. Debra, L.P. Nancy, Characterization of submicron polyethylene wear debris from synovial-fluid of revised knee replacements using a light-scattering technique, J. Bio. Mater. Res. 31 (1996) 355–363.
[20] K.Y. Lee, D. Pienkowski, Reduction in the initial wear of ultra-high molecular weight polyethylene after compressive creep deformation, Wear 203–204 (1997) 375–379.
[21] J.G. Lancaster, D. Dowson, G.H. Isaac, J. Fisher, The wear of ultra-high molecular weight polyethylene sliding on metallic and ceramic counterfaces representative of current femoral surfaces in joint replacement, Proc. Instn. Mech. Engrs. 211 (Part H) (1997) 17–24.
[22] A. Kobayashi, W. Bonfield, Y. Kadoya, T. Yamac, The size and shape of particulate polythylene wear debris in total joint replacement, Pro. Inst. Mech. Eng. 211 (Part H) (1997) 11–15.
[23] D.W. Hahn, D.L. Wolfarth, N.L. Parks, Characterization of submicron polyethylene wear debris from synovial-fluid samples of revised knee replacement using a light-scattering technique, J. Bio. Mater. Res. 31 (1996) 355–363.
[24] E. Rabinowicz, Friction and Wear of Materials, second ed., Wiley, 1995.
[25] T.R. Green, J. Fisher, M. Stone, B.M. Wroblcwski, E. Ingham, Polyethylene particles of a critical size are necessary for the induction of cytokines by macrophages in vitro, Biomaterials 19 (1998) 2297–2302.
[26] W.H. John, A.K. Karen, Anatomy, Wm. C. Brown Publishers, 1991, pp. 192–193.
[27] G.D. Jay, K. Haberstroh, C.-J. Cha, Comparison of the boundary-lubricating ability of bovine synovial fluid, lubricant, and Healon, J. Bio. Mater. Res. 40 (1998) 414–418.