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Wear Characteristics of Ultrahigh Molecular Weight Polyethylene (UHMWPE)

A. El-Domiaty, M. El-Fadaly, and A.Es. Nassef

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The wear of ultrahigh molecular weight polyethylene (UHMWPE) bearing against 316 stainless steel or cobalt chromium (Co-Cr) alloy was measured using a 12-channel wear tester especially developed for the evaluation of candidate materials for prosthetic joints. The coefficient of friction and wear rate were determined as a function of lubricant, contact stress, and metallic surface roughness in tests lasting 2-3 million cycles, the equivalent of several years use of a prosthesis. Wear was determined by the weight loss of the polyethylene (PE) specimens corrected for the effect of fluid absorption. The friction and wear processes in blood serum differed markedly from those in saline solution or distilled water. Only serum lubrication produced wear surfaces resembling those observed on removed prostheses. The experimental methods provided accurate reproducible measurement of PE wear. The long-term wear rates were proportional to load and sliding distance. Although the PE wear rate increased with increasing surface roughness, wear was not severe except with very coarse metal surfaces. The data obtained in these studies formed a comparison basis for the subsequent evaluation of potentially superior materials for prosthetic joints.

Keywords 316 stainless steel, friction and wear rate, total joint replacement, ultrahigh molecular weight polyethylene (UHMWPE)

1. Introduction

The majority of the total joint replacements currently in use have one component of ultrahigh molecular weight polyethylene (UHMWPE) bearing against a second component of either 316 stainless steel or a cobalt chromium (Co-Cr) alloy. The low friction and high wear resistance of these material combinations have been a major factor in the overall clinical success of prosthetic joints. However, a number of material-related problems remain to be solved. Polyethylene (PE) acetabular sockets in total hip prostheses have been observed to wear as much as 0.6 mm per year.[1] Unusually rapid wear of this magnitude can lead to a significant reduction in the range of motion of the prostheses, with subsequent loosening of the components from their anchorage to the underlying bone. The wear particles released to the surrounding tissues can generate adverse tissue reactions, including bone resorption, which also may contribute to loosening of the prosthesis.[2] In addition to the problem of wear, PE components are subject to gross deformation due to creep (cold flow at below the yield point) and ordinary plastic yielding, with subsequent instability of the prosthesis and, again, possible loosening.[3]

Although the metal component of a polymer-metal prosthesis is generally not subject to wear, plastic yielding and even fracture of the metal femoral stem are significant problems with both stainless and Co-Cr alloy total hip prostheses. These shortcomings have led to a number of attempts to identify superior materials for prosthetic joints through laboratory wear tests. A great variety of material combinations have been tested on machines, ranging from simple pin-on-disk devices to elaborate (and expensive) joint simulators. However, to date no polymer-metal combination has been consistently and reliably shown to have wear properties equal or superior to those materials already in use. Two polymers, poly(tetrafluoroethylene) (PTFE) and polyester, exhibited apparently adequate wear resistance in preliminary testing, but were found completely unacceptable in actual clinical use.[4,5] Prostheses using these polymers were subsequently removed from hundreds of patients.

The effect of sterilization methods on the wear of PE in a hip simulator was studied by Affatato et al.[6] Two different methods were used for sterilization. Gamma-sterilized PE acetabular cups show a total weight loss of 41.08 ± 11.02 mg (average ± standard deviation), whereas ETO gas PE acetabular cups show a total weight loss of 36.46 ± 15.66 mg. Walker et al.[7] introduced a simple wear test for evaluating wear and damage of material pairs when used in total knee replacement. The test consisted of an axially loaded metallic femoral indentor and a reciprocating UHMWPE flat disk that represented the tibial component.

Transfer film of UHMWPE was observed on the cobalt-chromium indentors for both serum and distilled water lubricants. The lowest wear rate was observed when oxidized zirconium was used on the femoral side, which was attributed to greater wettability, surface hardness, and immunity to oxidative wear.[7] The importance of pin geometry on screening wear testing of orthopedic bearing materials was studied by Besong et al.[8] They demonstrated that the design of the test system and components are important in determining the reliability of the comparative wear results, particularly when both bearing components are made of materials with high stiffness modulus.

A. El-Domiaty, M. El-Fadaly, and **A.Es. Nassef,** Production Engineering and Mechanical Design Department, Suez Canal University, Faculty of Engineering, Port Said, Egypt. Contact e-mail: aeldomiaty@hotmail.com.

Currently, much interest exists in the characterization of wear debris from different types of artificial hip joints. The aim of the study carried out by Tipper et al.[9] was to compare the wear volumes and debris generated from three different types of hip prostheses under identical conditions in a hip joint simulator. The volumetric wear rate (in mm^3/million cycles ± 95% confidence limits) were 32 ± 4, 1.6 ± 0.8, and 0.05 ± 0.02 for UHMWPE/zirconia, cobalt-chromium/cobalt-chromium, and alumina/alumina, respectively. The study by Jackson et al.[10] examined the effect of both sterilization and cyclic loading on the stress relaxation behavior of UHMWPE. From their results, they conclude that the relaxation behavior of UHMWPE remains the same regardless of the loading history or method of sterilization.

The purpose of this study was to establish a laboratory test protocol for accurately and reliably assessing the wear properties of candidate prosthetic bearing materials. The wear of UHMWPE against 316 stainless steel and Co-Cr alloy was determined in long-term, multispecimen tests. In the tests reported here, PE wear was measured as a function of contact stress, lubricant, and metallic surface finish. The results of these tests provided valuable insight into the nature of PE-metal wear and established a basis for the comparative evaluation of alternate materials.

2. Experimental Procedure

2.1 Wear Screening Device

The polymer specimen consisted of a 12 mm diameter cylinder with one end tapered to form a contact area of 64 mm^2. When mounted in the wear-testing rig (Fig. 1), the polymer specimen was pressed end-wise against a flat metal counterface. Constant axial load up to 445 N (100 lb) was applied to each set of specimens by a pneumatic cylinder mounted above the wear chamber. The wear chamber was mounted on an oscillating table driven through a 25 mm stroke at a frequency of 100 cycles/min. The polymer specimen was held stationary while the counterface oscillated against it. The wear chamber was made of Plexiglas to allow the use of potentially corrosive fluids such as blood serum or saline solution. Frictional force between the polymer specimen and its counterface was monitored by strain gauges attached to the upper specimen holder. The absolute value of the friction on each set of specimens was averaged over several cycles and plotted continuously. The test temperature was kept at 20 ± 2 °C.

2.2 Wear Measurement

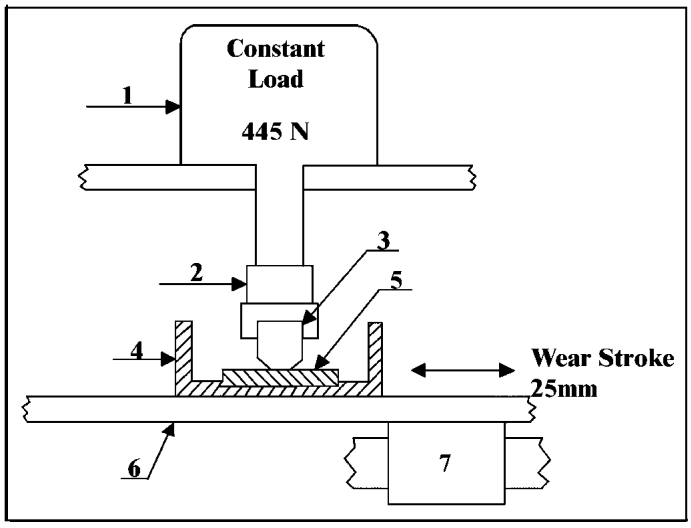
In this study the wear rates were determined by direct weighing of the PE specimens. However, it was soon discovered that the weight gain due to fluid absorption could actually be greater than the loss due to wear, causing a net increase in the weight of the specimens. Two different methods were used to correct fluid absorption.

2.3 Method A: Dry Weighing

The PE wear specimens and a set of controls were washed in an ultrasonic cleaner, vacuum-desiccated for 3 days, and weighed prior to wear testing. The control specimens were soaked separately during the wear test. Finally, the wear specimens and controls were re-cleaned and desiccated for 2 weeks to remove as much of the absorbed lubricant as possible. This method gave large variation in the control soak specimens; therefore, a more accurate weighing method was needed.

2.4 Method B: Wet Weighing

To minimize fluid absorption during the wear tests, the wear specimens were presoaked in serum for several weeks. After the specimens were soaked, they were washed, rinsed, dried with alcohol, and then weighed. At intervals during the wear test, the wear and control soak specimens were re-cleaned and



1. Pneumatic Load Cylinder
2. Friction Transducer
3. Polymer Specimen
4. Plexiglas Chamber and Lubricant
5. Metal and Ceramic Plate
6. Oscillating Table
7. Linear Bearing

Fig. 1 Wear testing set up

weighed. The average net gain (or loss) in weight of the control specimens relative to the start of the wear test was added to (or subtracted from) the apparent weight loss of each wear specimen to correct for fluid absorption. In long-term tests, the weight of the control specimens eventually stabilized at a fixed value. The error in this method was about ±50 μg. The sequential weighing provided accurate indication of wear as a function of sliding distance. The overall wear rate was taken as the slope of a straight line fit to the wear data, using the method of least squares linear regression.

The total height loss (due to creep and wear combined) was measured for each of the PE specimens at five points on the wear surface in a special jig fitted with a dial indicator accurate to ±1 μm. The same points were measured before and after the wear test. The resultant loss was taken as the average loss for these five points. A control creep test was performed with three PE specimens. These were placed under a load of 6.9 MPa for 1 week without wearing. The result was a permanent height loss of about 50 μm, or 0.4% strain (Fig. 2).

2.5 Materials

PE specimens were machined from a 25 mm diameter bar of extruded UHMWPE. The 316 stainless steel counterfaces were machined from 41.2 mm diameter wrought bars. Each specimen was lapped, polished with a slurry of 0.05 μm alumina, cleaned and degreased ultrasonically, and finally passivated in nitric acid before being used in the wear test. The surface roughness was about 0.05 μm root mean square (R_{ms}), typical of prosthetic components.

The Co-Cr alloy counterfaces were prepared from disks of cast cobalt-chromium-molybdenum alloy. These were treated similarly to the stainless steel counterfaces except that four grades of surface finish were prepared: 0.03-0.05 μm (prosthesis quality), 0.08-0.13 μm (produced using 600 grit silicone carbide paper), 0.20-0.30 μm (240 grit paper), and 0.75-0.86 μm RMS (60 grit paper). Again, the surfaces were passivated after final polishing.

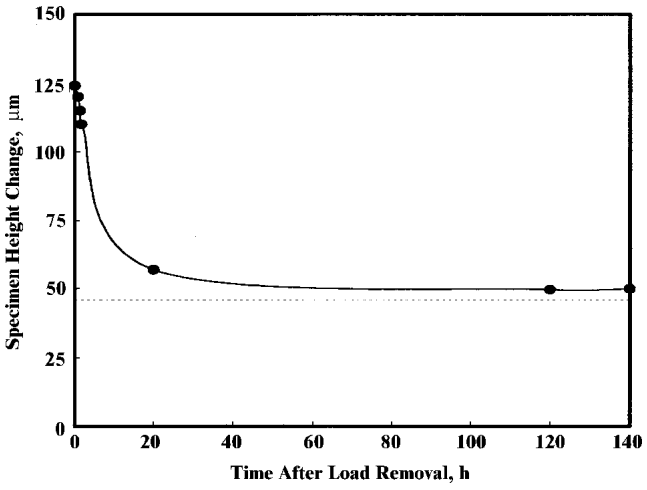


Fig. 2 Residual height loss (creep) of polyethylene specimens as a function of time after load removal. A constant pressure of 6.9 MPa was applied for 1 wk.

3. Results

3.1 PE Wear in Various Lubricants

The first test compared the wear of UHMWPE against 316 stainless steel in distilled water, physiological saline (Ringer's solution), and bovine blood serum. The weight loss of the PE specimens was measured using method A; that is, the specimens and soak controls were vacuum-desiccated and weighed before and after the wear test.

The friction, amount of wear, and most importantly the nature of the wear process varied in each of the lubricants. The three specimens lubricated with distilled water showed an increase in weight of 50, 60, and 120 μg, respectively. Subtracting 150 μg, the average gain of the soak controls, gave a net loss of 100, 90, and 30 μg, respectively. The same correction was applied to the serum- and saline-lubricated specimens. Weight loss was converted to equivalent wear depth by dividing by the density and apparent contact area of the PE specimens (0.936 gm/cm^3, 64.5 mm^2). Friction and wear for the three lubricants are compared in Table 1.

Transfer layers of PE gradually formed on the surface of the saline- and water-lubricated counterfaces, accompanied by an increase in the coefficient of friction. Transfer layers normally were not present on the serum-lubricated counterfaces. However, polymer transfer did occur during a temporary period of unusually high friction, which often occurred about 1 h after a test was restarted with fresh serum. During this period, a sudden increase in the coefficient of friction to as high as 0.35 (Fig. 3) was accompanied by the rapid formation of a dense layer of PE on the metal counterface, similar to those which formed in distilled water and saline solution.

3.2 PE Wear Against 316 Stainless Steel and Co-Cr Alloy

PE specimens were run against stainless steel and Co-Cr counterfaces lubricated with commercial serum to compare the wear rate for these two alloys using method B. The influence of contact stress on wear rate was examined at two load levels in the range thought to occur in vivo on a total hip prosthesis.[11,12]

Wear was very low for both counterface materials, such that 2-3 million cycles were necessary to clearly establish the pattern of wear in each test (Fig. 4). The long-term wear rates and coefficient of friction are compared in Table 2. In many of the tests, the wear rate did not stabilize until after the first 0.5 million cycles. The wear rate and correlation coefficient were therefore calculated excluding the initial data point (0,0) to minimize the effect of this wearing-in period on the values obtained for the long-term wear rates. The correlation coefficients ranged from a low of 0.93 (for specimen CC-1) to a high of 0.998 (for specimen SS-6), the latter value indicating a very constant wear rate over the duration of the test.

PE wear against stainless steel increased with load, such that the average wear rate at 6.90 MPa was double that at 3.45 MPa. The average wear rate against Co-Cr alloy was less than that with stainless steel at the same load (Table 2). However, this difference was probably not significant because the individual values overlapped considerably. Each of the metal specimens

had surface scratches running the length of the contact area. This scratching was more extensive on the stainless steel than Co-Cr and tended to increase as the test progressed. As in the previous tests with serum, PE transfer layers did not form on these counterfaces.

Although the total frictional force increased with load, the coefficient of friction decreased; that is, frictional force did not increase in proportion to load. Several of these specimens experienced a temporary slight increase in the coefficient of friction, to about 0.15, when the serum bath was changed. However, this did not appear to affect the overall wear rate.

3.3 Surface Roughness Effect

Table 3 lists the wear rates for PE against Co-Cr counterfaces having surface roughness ranging from "grade A" (prosthesis quality, R_{ms} = 0.03-0.05 μm) to "grade D" (rough surface, R_{ms} = 0.75-0.76 μm). These specimens were also subject to the temporary increase in friction that sometimes occurred after the serum was changed. The magnitude of the increase in friction was greater for the rougher surfaces, as indicated by the peak values in Table 3. The friction on the roughest grade D counterfaces was very high throughout the test. The polymer specimens wore very rapidly and were removed at less than 0.25 million cycles.

The wear rates with the grade B and C surfaces (Table 3) tended to decrease significantly over the period from 0.5-1 million cycles. Both the early and late values of the wear rates were calculated. Examination of the contact area on these counterfaces revealed that the rubbing action of the PE had caused a general smoothing of the initial surface texture. These specimens exhibited long scratches running parallel to the wear direction, similar to those produced on the grade A surfaces.

The wear rate with one specimen (C-4) increased over the test run. This specimen exhibited very high wear (450 μm/million cycles) during the period from 1-1.2 million cycles, with the coefficient of friction as high as 0.24 and a heavy transfer layer covering about 50% of the contact area. Eventually the transfer material was rubbed away and the friction returned to its normal level (Table 3). The wear rate for the remainder of the run was about 15 μm/million cycles.

Table 1 Wear of Polyethylene in Different Lubricants (a)

Lubricant	Number of Specimens	Average Wear, μ/10^6 Cycles (b)	Friction Summary, μ = Coefficient of Friction
Serum	4	0.65 (±17%)	μ = 0.07-0.12 normally, μ = 0.35 during temporary high friction; polymer transfer onto metal counterfaces occurred only during the high-friction phase
Distilled water	3	0.08 (±60%)	μ = 0.07-0.13 at start; a heavy polymer transfer layer formed by 0.3 million cycles, μ then ranged from 0.14-0.18; the transfer layer remained intact for the duration of the test
Saline solution	3	5.2 (±17%)	μ = 0.07-0.1 at start; heavy, orange-colored transfer layers formed increased to 0.27; these layers occasionally broke up and μ dropped to the initial level

(a) Vertical axes are names of the materials (Fig. 5).
(b) Range in parentheses.

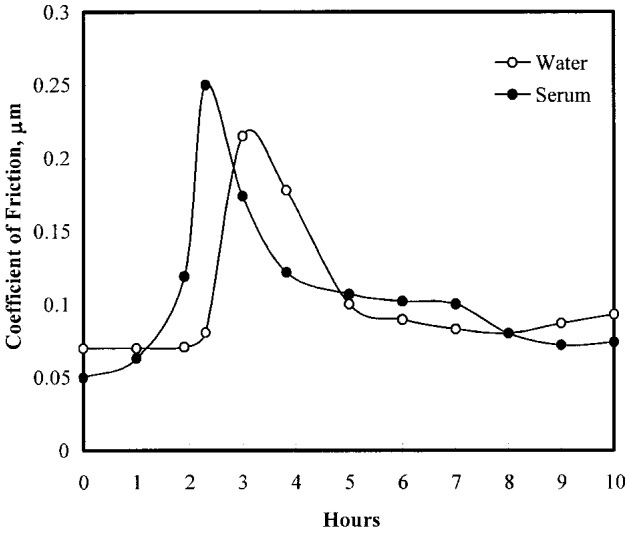


Fig. 3 Coefficient of friction vs time for specimens lubricated with water and serum

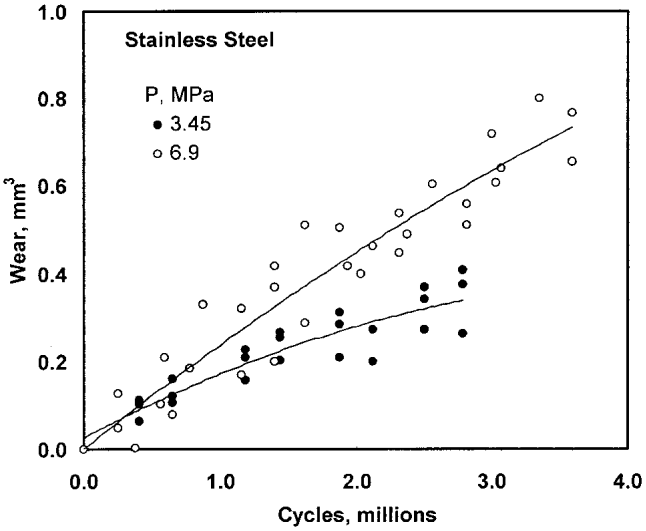


Fig. 4 Wear of UHMW polyethylene as a function of sliding distance (one cycle 50 mm), using serum lubrication and highly polished counterfaces for specimens S1-S6

4. Discussion

4.1 Effect of Creep and Fluid Absorption on Wear Measurements

Creep deformation is 4-13 times greater than the height loss due to wear. Creep deformation is the property of PE that makes it virtually impossible to accurately quantify wear, knowing only the total deformation of the specimens. Some investigators[13-15] have attempted to eliminate the error caused by PE creep by continuously recording the specimen deformation or wear track depth. Because the creep rate decreases exponentially with time after the load is applied, eventually a point should be reached where additional deformation is due primarily to wear. This method may be satisfactory, provided that the test is of sufficient duration and the instrumentation is capable of accurately measuring wear depth as small as 1-2 μm/million cycles.

Wear rates determined from specimen weight loss are accurate only if the effects of fluid absorption are controlled. For example, the highest wear rate with serum lubrication (specimen S-3) corresponded to a weight loss of only 210 μg over 1 million cycles. If a PE specimen is not presoaked, the gain due to absorption during the same period can be as high as 400 μg, making weight measurement useless for determining wear (Table 4).

4.2 PE Wear in Different Lubricants

Although PE wear has been examined previously in each of the lubricants used in this study, there is currently no agreement about which lubricant is most suitable for use in determining the wear properties of candidate prosthetic materials. Distilled water or saline solution was used in earlier studies primarily because it was easily obtainable in large quantities. Neither liquid was subject to bacterial degradation, nor did it tend to corrode metal components of the test apparatus as readily as did serum or synovial fluid. However, the results of our tests indicated that distilled water or saline solution had fundamentally different lubricating properties. The most apparent of these differences relates to the formation of PE transfer layers.

It has often been suggested that the PE transfer film on the metal counterface serves to reduce the wear rate by masking any rough asperities on the metal. Lancaster,[16] working with carbon fiber-reinforced PE bearing against a comparatively rough steel counterface (0.15 μm c.l.a.), found that transfer films formed under dry sliding conditions, but were quickly rubbed away when the surfaces were immersed in water, with a simultaneous increase in friction and wear rate. In our tests with highly polished counterfaces (0.05 μm R_{ms}), the transfer films that formed in distilled water and saline solution were associated with an increase in both the coefficient of friction

Table 2 Wear of Polyethylene With Serum Lubricant

PE Specimen No.	Counterface Material	Load, MPa	Wear Rate, μm/10^6 Cycles	Correlation Coefficient	Average Rate (a)	Friction Coefficient
S-1	316 Stainless Steel	3.45	1.2	0.96	1.6 (±20%)	0.04-0.16
S-2			1.7	0.994		
S-3			1.7	0.97		
S-4		6.90	2.6	0.98	3.1 (±15%)	0.03-0.09
S-5			3.1	0.98		
S-6			3.6	0.998		
C-1	Co-Cr alloy		2.3	0.93	2.6 (±23%)	0.05-0.11
C-2			2.3	0.98		
C-3			3.3	0.97		

(a) Range in parentheses.

Table 3 Wear of Polyethylene for Counterfaces With Varying Surface Roughness

Specimen No.	Counterface Roughness, μm RMS	Coefficient of Friction		Wear Rate, μm/10^6 cycles	
		Steady Range	Peak Value	0-0.5 Million Cycles	1-2 Million Cycles
C-1	Grade A 0.03-0.05	0.06-0.11	0.15	3.6	2.3
C-2				7.6	2.2
C-3				1.2	2.9
C-4	Grade B 0.07-0.012	0.07-0.12	0.20	5.3	14.6
C-5				7.4	3.6
C-6				9.5	3.9
C-7	Grade C 0.20-0.30	0.11-0.15	0.23	22.3	7.8
C-8				73.8	12.9
C-9				86.8	10.5
C-10	Grade D 0.75-0.76	0.22-0.30	0.30	3 000	Grade D tests stopped at least than 0.25 million cycles due to excessive wear
C-11				20 000	
C-12				8 700	

and the wear rate. Apparently, wear was initially due to adhesion between the polymer and metal. The particles of polymer that were pulled out eventually formed a nearly complete transfer layer on the metal surface. Synovial fluid might provide an even closer replication of the physiological environment; it is difficult to obtain in other than minute quantities. Furthermore, there appears to be little difference in the lubricating properties of serum and synovial fluid, probably because of their similar protein content.

The high friction condition that often occurred just after the serum was changed appeared to be due to a temporary failure of the lubricating mechanism, with a subsequent rapid buildup of a dense transfer layer (adhesive wear) and a corresponding increase in friction. A similar effect may have been encountered by Seedhom et al.[10] In their wear tests with synovial fluid lubrication, heavy PE transfer layers sometimes formed on the stainless steel counterface. Wear was higher in those tests where transfer occurred. Because the high friction step occurred only if the chambers were rinsed and fresh lubricant was introduced, it seems unlikely that this type of wear occurs in vivo. Investigators using blood serum in wear tests to evaluate prosthetic bearing materials should therefore take care to ensure that their results are not unduly influenced by this anomalous wear mode.

4.3 Effect of Surface Finish on PE Wear

Table 3 shows that polymer transfer layers did not form in our tests with roughened counterfaces lubricated with serum. The decrease in the PE wear rate with the grade B and C surfaces was apparently due to a gradual polishing of the surface scratches. These results indicate that surface finish studies in particular should be performed with physiological lubrication to avoid the masking effect of the transfer layers that form on water-lubricated specimens. In addition, the tests should be of sufficient duration to detect gradual alterations of the initial surface texture.

These tests were designed to determine the overall sensitivity of PE wear to metallic surface scratching. Although polymer wear tended to increase with surface roughness, the long-term wear rates were relatively low (less than 15 μm/year) on all but the roughest counterfaces. It appears that super-smooth, mirror-like metal finishes are not critical for acceptably low PE wear. The possibility remains that a specially textured counterface might serve to reduce the PE wear below that with mirror-finished specimens. However, it is questionable whether the achievement of a wear rate less than 2-3 μm/year would constitute a significant improvement in the overall performance of prosthesis.

It is generally believed that a high-quality, mirror-like surface finish on the metal component is essential for minimizing the PE wear in prostheses.[12,13,17,18] Oonishi[19] compared the wear of PE cups in a joint simulator using prosthetic heads with standard polishing, as well as a variety of surface treatments. Seedhom et al.[11] measured PE wear against a stainless steel disk with five degrees of roughness ranging from 0.05-0.27 μm, with synovial fluid as a lubricant. They reported that the PE wear rate generally increased with metal surface roughness. However, the results are difficult to interpret because other conditions such as sliding speed, test duration, and specimen temperature (due to dry running) varied in the different tests. Milleret al.[14] examined PE wear against titanium alloy counterfaces with surface roughness specified as 0.05, 5, and 15 μm, and using Ringer's solution as a lubricant. Although the initial wear was lowest with the smoothest counterface, the

Table 4 Comparison of Wear and Creep of Polyethylene Specimens

Specimen No.	Load, MPa	Height Loss Due to Wear, *h*, μm	Total Height Loss, *H*, μm	Unrecovered Creep, *D* = *H* − *H*, μm	Creep/Wear Ratio, *D*/*h*
S-1	3.45	4	61	57	14
S-2		6	61	55	9
S-3		6	69	63	11
S-4	6.90	11	74	63	6
S-5		12	71	59	5
S-6		12	58	46	4
C-1		4	75	71	18
C-2		7	64	58	7
C-3		6	65	59	10

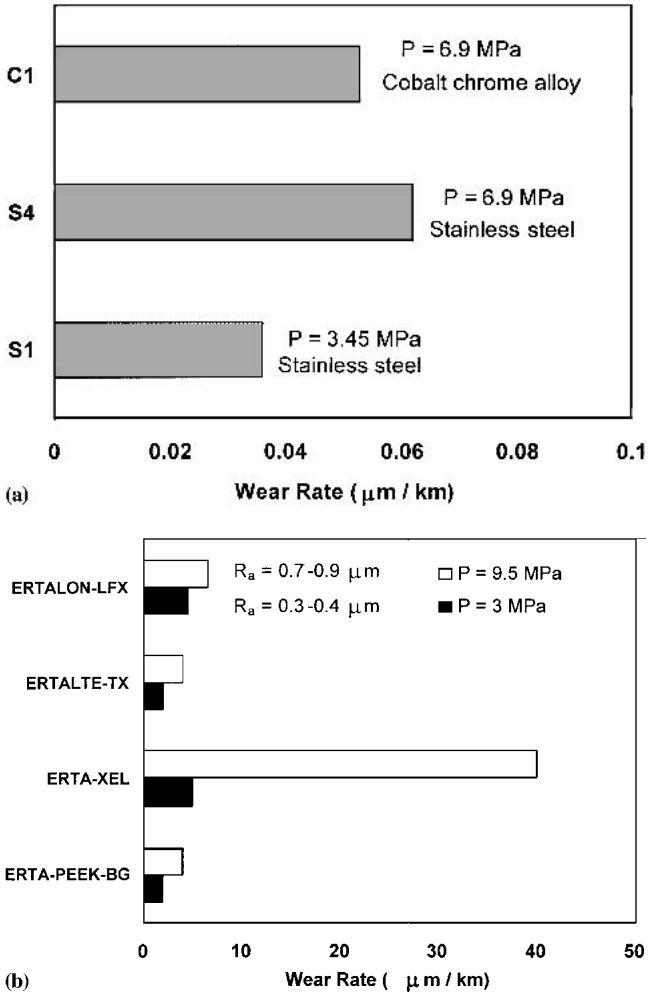


Fig. 5 Wear rate of different UHMW polyethylene. **(a)** Results of the present work; **(b)** results from Ref. 20

final rates were similar for each of the specimens. Heavy polymer transfer layers formed on the metal counterfaces. It is possible that the transferred PE tended to mask the underlying roughness of the metal, accounting for the similarity of the long-term wear rates.

4.4 Comparison Between Wear Rates

Some results of the wear rates obtained in the present work are shown in Fig. 5(a). These results give the wear rate of UHMWPE in micrometers per kilometer against two materials (stainless steel and Co-Cr alloy) under two different contact pressures (3.45 and 6.9 MPa). These data were specially selected to make possible the comparison between them and the results obtained from Ref. 20. The conditions of the test results shown in Fig. 5(b) are nearly similar to the present work results shown in Fig. 5(a). The major difference between the results shown in Fig. 5(a) and (b) is the testing technique, which is the standard disk and pin for the results.[20] The comparison between the results shown in Fig. 5(a) and (b) demonstrates that the wear rate obtained in the present work (Fig. 5a) is much lower than that obtained in Ref. 20, which is given in Fig. 5(b).

5. Conclusions

The PE wear rates developed in this study form a basis for the comparative evaluation of alternate materials for prosthetic joints. It is desirable to have as low a wear rate as possible to minimize the amount of debris that must be tolerated by the surrounding tissues. However, the use of a material that wears slightly faster than PE under ideal conditions may be justified if greater resistance to creep deformation or acrylic abrasion offers a significant improvement in the overall performance of prosthesis in actual use. The wear rate obtained in the current study is much lower than that obtained by other investigators.[21-23] Conventional UHMWPE wears at a rate of 100 μm/year, with the assumption that the average patient walks about 1 million cycles/year.[21] The wear rate obtained in this work is much lower than 10 μm/million loading cycles.

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