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Wear behavior of bulk oriented and fiber reinforced UHMWPE

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Abstract

A study of the friction and wear properties of isotropic, fiber reinforced, and bulk oriented ultra-high molecular weight polyethylene (UHMWPE) was conducted on a reciprocating wear tester. The tests were carried out with a cobalt–chromium alloy cylinder sliding against a flat sample of UHMWPE in bovine serum at 1.5 Hz for over a million cycles. In the fiber reinforced material, layers of woven UHMWPE fibers were embedded in a UHMWPE matrix. Bulk orientation of UHMWPE was produced by channel die compression of standard UHMWPE. The fiber-reinforced samples were tested in one configuration and three different degrees of consolidation. The less consolidated samples failed catastrophically, and the more consolidated sample had a wear rate twice that of the unreinforced, standard UHMWPE. The channel die oriented samples were tested in various configurations and degrees of anisotropy. They all showed similar wear behavior as the standard, with a wear rate of approximately 1×10^{-7} mm^3/N m. The average values of the coefficient of friction of all the samples ranged from 0.08 to 0.11.

Keywords: Polyethylene composite; Orientation; Abrasive wear; Joint prosthesis

1. Introduction

Over the course of the past several decades, in attempts to improve the frictional and wear properties of ultra-high molecular weight polyethylene (UHMWPE) for total joint replacement prostheses, modifications in the molecular structure have been introduced and composites with this polymer fabricated. The objective of this study was to assess the wear behavior of novel, oriented and composite forms of UHMWPE.

Changes in the polymer structure of UHMWPE have included (1) increasing the chain length or molecular weight [1], (2) producing extended-chain crystals [1,2], and (3) introducing cross-links [3–7]. The increase in the average molecular weight of UHMWPE that has occurred over the past few decades has not been clearly documented [1], and its direct effect on wear properties difficult to determine because of other concomitant changes in catalysts used in polymerization and additives to the polymer (e.g., calcium stearate), as well as in component design. A few years ago a modified form of UHMWPE, with a higher degree of crystallinity and an increase in the thickness of the lamellae, was produced by applying elevated pressures and temperatures to the conventional polymer [1]. This form of the polymer, referred to as Hylamer, while displaying what might be expected to be favorable changes in certain mechanical properties, such as yield strength, also demonstrated alterations in other mechanical properties that might be considered to disfavor wear (e.g., an increase in the modulus of elasticity) [1]. Laboratory wear testing of Hylamer did not reveal improved tribological properties [2,8,9], and recent clinical findings have suggested less favorable performance than with conventional UHMWPE components [10–12]. Cross-linking of UHMWPE, first introduced several years ago for the fabrication of acetabular cups [5], has been the focus of several recent studies [5–7]. While the results of hip simulator tests and clinical

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trials [5,7] have been encouraging, additional work will be required before the benefits of this method of modifying the polymer are proven.

One method for modifying the organization of macromolecules of linear polymers that has only recently been applied to UHMWPE is chain orientation through channel die compression. Boontongkong et al. [13,14], have shown that the macromolecules of UHMWPE, like those of high density polyethylene (HDPE), can be oriented without cavitation by using a channel die to induce plane strain compression. It was determined that the UHMWPE crystallites were oriented to produce a chevron-like morphology and the macromolecules within crystallites oriented along the flow direction. This type of texturing was shown to take place monotonically with increase in compression ratio, λ (defined as the ratio of the initial height and the final height of the sample after compression). Substantial texturing occurred by a λ of 1.4. The potential value of selected chain orientation in arresting the propagation of microcracks associated with wear processes prompted the study of the wear and friction of the channel die oriented UHMWPE.

Other attempts at improving the wear performance of UHMWPE have led to the use of fiber reinforcement. Fabrication of composites with short carbon fibers, while initially yielding favorable results in the laboratory [15–18], proved to be unsuccessful in the clinic [19,20], with a higher wear rate than conventional UHMWPE. Recently, Suh et al. [21], produced a UHMWPE homocomposite, comprising continuous, high strength UHMWPE fibers in the UHMWPE matrix. When the fibers were uniaxially oriented normal to the sliding surface the mass loss due to wear in dry reciprocating sliding conditions was an order of magnitude lower than the standard isotropic UHMWPE. These observations confirmed earlier work by Sung and Suh [15], showing that uniaxially oriented fiber reinforced polymeric composites, such as oriented graphite fiber–epoxy and kevlar fiber–epoxy, exhibited lower wear rates when the fibers were oriented perpendicular to the sliding surface. It was proposed that the reduction in wear was due to the arrest of crack propagation parallel to the surface (delamination wear) by the fibers. The cracks in this case were involved with debonding of the fiber from the matrix to a certain depth, and for further crack growth the fibers had to be worn down. These positive findings prompted the present investigation of a biaxially oriented UHMWPE fiber reinforced UHMWPE composite.

2. Materials

2.1. The standard and channel die compressed UHMWPE

The standard UHMWPE was obtained from Westlake Plastic (Lenni, PA). It was a 3-in. diameter ram extruded rod. The resin, Hostalen GUR 4150HP, manufactured by Hoechst Celanese, has a molecular weight of six million, with 53% crystallinity and a density of 0.932 g/cm^3. The melt flow index of this resin is essentially zero [13].

The textured samples were developed through channel die compression following previously reported procedures [13]. Samples were compressed in a channel die originally constructed by Lin and Argon [22]. The samples tested were produced with compression ratios of 1.70 and 2.75.

The crystallographic texture of channel die compressed UHMWPE has been characterized [13,14], and was shown to increase monotonically with compression ratio. In samples with compression ratio of 1.70 and 2.75, the macromolecules of UHMWPE within the lamella shaped crystallites were highly oriented along the flow direction, with the degree of orientation increasing with increase in compression ratio. The lamellar and molecular orientations, relative to the surfaces of the specimen, were different for the two compression ratios. For the compression ratio of 1.70, the molecules were oriented at approximately 30° from the flow direction, while they were aligned along the flow direction by a compression ratio of 2.75. In both cases, deformation resulted in reorientation of lamellar stacks so that their surface normals were oriented at 20–30° from the loading direction. The surface normals did not rotate further with high compression ratios. An earlier study on HDPE by Song et al. [23], provided transmission electron microscopic evidence for this chevron-type of lamellar morphology. There were three different surfaces for wear testing: the extruded or flow surface, the constrained surface, and the loaded surface (Fig. 1).

The loaded surface was tested with the cylinder sliding along the flow direction, (LD; Fig. 1). The predominant feature was that the molecules were parallel to the sliding surface. The constrained surface was tested along the flow direction (CD) and along the loaded direction (CD2). In both cases, the predominant feature was that the lamellar surface was perpendicular to the sliding surface and the molecules were parallel to the sliding surface. When tested

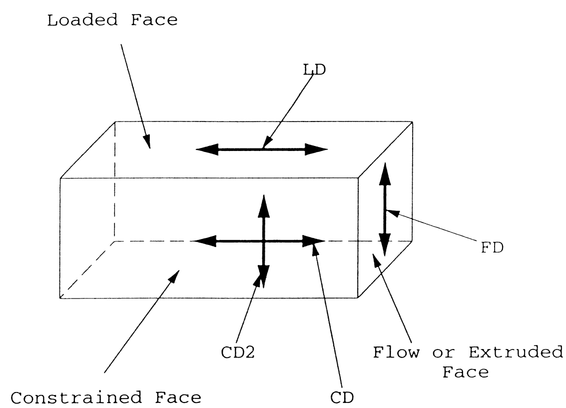

Fig. 1. Surfaces and directions tested on the compressed samples.

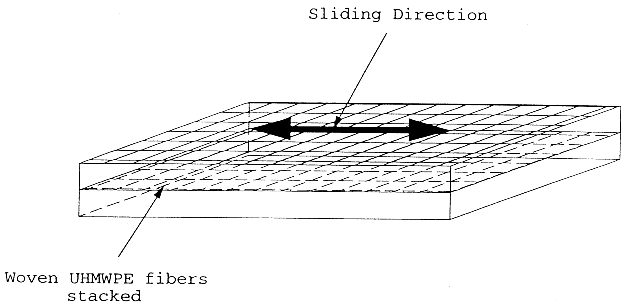

Fig. 2. Surfaces and sliding direction tested on the fiber oriented samples.

in the flow direction (CD) the lamellar surface normals were mainly 60–70° to the sliding direction, and the molecules were oriented along it. In the loaded direction (CD2) the molecules were oriented perpendicular to the sliding direction and the lamellar normals were 20–30° from the sliding direction. The flow surface was tested along the loaded direction (FD), with the lamellar normals oriented 60–70° from the flow surface and the molecules perpendicular to the surface.

2.2. Fiber reinforced UHMWPE

The fiber-reinforced polyethylene has been described previously [24]. It was comprised of layers of UHMWPE fabric in a UHMWPE matrix. The fibers of the fabric were Spectra 1000, Allied, and the matrix was Hostalen GUR4113, Hoechst. The external surface of the sample was melted and allowed to recrystallized in an unoriented form. The thickness of the unoriented layer and the degree of consolidation of the bulk of the sample were controlled during processing. Prior mechanical testing of this composite material [24] confirmed that the properties were limited by the cohesive properties of the matrix and not to failure at the fiber–matrix interface. Since Spectra fibers contain highly oriented UHMWPE macromolecules, for the purpose of this work the fiber-reinforced material will also be referred to as ''fiber-oriented'' UHMWPE.

For the purpose of the present work three different composite samples were tested: two having a fibrous bulk structure but unoriented polyethylene surface (MP-56 and MP-58), and one that was highly consolidated bulk and thick (approximately 2 mm) unoriented surface (MP-60). The samples had a void content of over 10%, resulting in a much greater absorption of water than observed in the standard or channel die compressed sample.

The three fiber reinforced samples (MP-56, MP-58, MP-60) were tested in one direction only, on the surface parallel to the fabric like layers (Fig. 2). The composition of this surface was that of the melted layer comprising isotropic standard UHMWPE; the metallic counterface initially did not directly contact the woven fibers.

3. Methods

3.1. The wear tester apparatus

The reciprocating cylinder on flat wear tester used in this study has been used in a previous investigation of UHMWPE [21]. The uniaxial reciprocating movement had an excursion (or stroke length) of 28.58 mm (1.125 in.) and a frequency of 1.5 Hz. This test simulates certain aspects of the femoral–tibial and patello-femoral articulation in total knee replacement prostheses. A normal load of 890 N (200 lb) was applied which is approximately equal to the load applied on UHMWPE tibial plateaus during in vivo use. Wear tests were conducted at room temperature, 25°C. Assuming that the UHMWPE behaves like an elastic material, and using Hertzian contact stress analysis, the maximum contact stress for a 890-N load was approximately 15 MPa. The minimum sample size of the flat UHMWPE samples required for wear tests was $20 \times 35 \times 10$ mm, This required samples produced from the plane strain channel die compression, that were $11 \times 10 \times 76$ mm, to be clamped together. The normal of the mating surface was perpendicular to the sliding direction to minimize any affect on the wear tests (see Fig. 3). The cylindrical counterface was a cobalt–chromium (Co–Cr) alloy, American Society of Testing Materials (ASTM) F-75, as typically used in orthopedic applications. The Co–Cr cylinders of 28.6 mm diameter and 15.9 mm width were

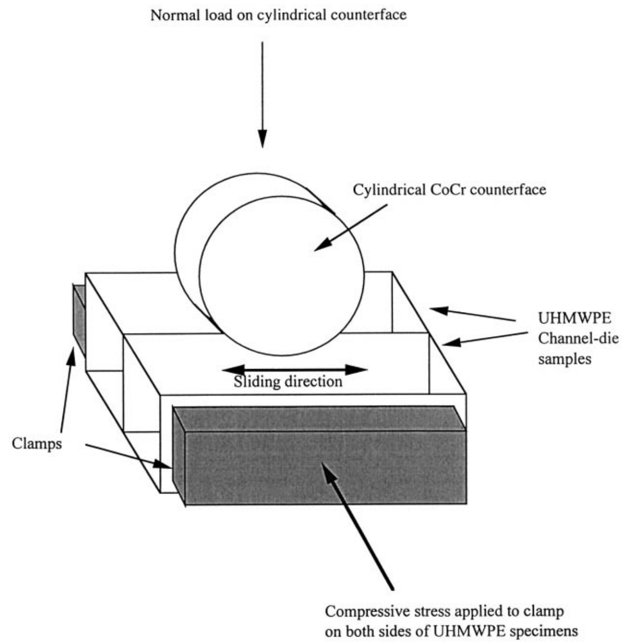

Fig. 3. Schematic showing the specimen and wear tester geometry.

polished on a lathe beginning with a 270 grit paper and slowly proceeding to a 600-grit silicon carbide polishing compound. The metal cylinder was then cleaned in an ultrasonic acetone bath for 10 min. The surface finish was measured with a P-10 Tencor Surface Profiler with a diamond tipped stylus. The counterface finish used in this experimentation reflected a roughness used in implants and in other in vitro wear tests; the *Ra* used was of 0.027 ± 0.002 μm (mean ± standard deviation). Bovine serum, (Sigma-Aldrich), was the lubricant used for all wear tests. To arrest bacterial growth the bovine serum was mixed with a 1% by volume aqueous solution of sodium azide (E. Merck Science) in a 2:1 proportion [25]. The water used to prepare the solution was triple filtered distilled water (E. Merck Science). During the wear test, the bovine serum was changed every four days because it denatures over time due to frictional heating at the contact point.

3.2. Test protocol for wear and friction

The UHMWPE wear samples were paired up, clamped, and machined with a fly cutter after being soaked for at least two to three weeks. Identical spindle speed, feed rate and fly cutter was used for all samples. The samples had an *Ra* of approximately 1 μm. The fiber-reinforced samples were not fly cut; the melted surface was used as the sliding surface. After fly cutting, the samples were cleaned with isopropyl alcohol and weighed to 0.01 mg of accuracy using a Mettler AT20 scale. Repetitive weighing was made until two measurements with an error of less than 0.03 mg were obtained.

A friction measurement was taken at the beginning of each test and after every 24 h. Both the normal load and the frictional force were recorded and their average was taken over a period of 30 s, these were used to calculate the coefficient of friction (μ).

Wear measurements where taken after approximately 15, 30, and 59 km of sliding (259,200, 518,400, and 1,036,800 cycles). The samples were weighed using the same procedure as in the initial weighing. Once weighed, the samples were returned to their original holder and the test was restarted on the same counterface. The mass loss was then converted to volume loss by using the density of UHMWPE. Archards wear equation was then used, and the data presented using the Dimensional Wear Coefficient (DWC). Water absorption was accounted for using load-soak controls as described by Lee and Pienkowski [25].

3.3. Statistics

The sample size used was determined for an α of 0.05, a β of 0.05, and an alternative hypothesis of a dimensional wear coefficient of one tenth of the standard, 1.0×10^{-7} mm^3/N m [26]. From preliminary testing, it was found that the coefficient of variance was roughly 30%. A sample size of four was found to be sufficient. Two-tailed Student's *t*-test was used to determine the significance of the difference in the dimensional wear coefficient between selected groups.

4. Results

4.1. Solid and joined standard isotropic UHMWPE

No statistically significant difference was found in the wear values between the solid and joined samples of the standard UHMWPE (Table 1). Also, the friction data for both the joined and solid samples had similar values and overlap. Both started at average values of μ between 0.05 and 0.06 and leveled out to the final average values between 0.08 and 0.10 at 25–20 km of distance slid. Based on these data we concluded that joining two samples for

Table 1
Dimensional wear coefficient (DWC, mean ± standard deviation) and the coefficient of variance (CV) of each sample type

Sample	15-km Distance slid			30-km Distance slid			59-km Distance slid		
	DWC $\times 10^{-7}$ mm^3/N m	n	CV%	DWC $\times 10^{-7}$ mm^3/N m	n	CV%	DWC $\times 10^{-7}$ mm^3/N m	n	CV%
Std. Solid	1.07 ± 0.18	5	17	0.93 ± 0.12	5	13			
Std. Joined	0.97 ± 0.15	4	16	0.90 ± 0.13	6	14	1.25 ± 0.29	4	23
$\lambda = 2.75$ CD	1.26 ± 0.35	4	28	1.40 ± 0.36	4	25	2.27 ± 1.23	4	54
$\lambda = 2.75$ LD	0.90 ± 0.20	4	23	0.79 ± 0.24	6	31*	1.10 ± 0.31	4	28
$\lambda = 1.70$ CD	1.04 ± 0.15	4	14	1.28 ± 0.22	4	17*	1.86 ± 0.68	4	37
$\lambda = 1.70$ LD	0.77 ± 0.23	4	30	1.00 ± 0.24	4	24	1.65 ± 1.19	3	72
$\lambda = 1.70$ FD	1.40 ± 0.15	4	11	1.46 ± 0.13	4	9**	3.43 ± 2.57	4	75
$\lambda = 1.70$ CD2	1.26 ± 0.16	4	13	2.56 ± 1.94	4	76	7.11 ± 7.87	4	111
MP-60	1.97 ± 0.21	3	11	1.97 ± 0.36	3	18	2.08 ± 0.26	3	12

*$P < 0.1$ for comparison with the standard UHMWPE at the same distance slid.
**$P < 0.05$ for comparison with the standard UHMWPE at the same distance slid.

the wear test did not meaningfully affect the results, and thus was a valid test setup.

4.2. Fiber oriented composite samples

The MP-56 was the least consolidated of the three types of specimens. It failed in less than 2 km of sliding. The top surface completely sheared off at the interface between woven layers. Once the melted top surface was removed, the Co–Cr cylinder plowed through the subsequent layers. The MP-58 sample failed similarly, but after 30 km of sliding. Because of the early failure of these two types of specimens a complete analysis of all samples was not performed. For the MP-60 samples that were more consolidated and had a thicker melted (unoriented) surface layer, catastrophic failure did not occur. In one of the three samples tested there was a large excess of water absorption resulting in negative mass loss, eventhough there was visible surface damage. This data point was not included in the analysis. The dimensional wear rate was relatively constant within the distance slid (Fig. 3) and was on average 2×10^{-7} mm^3/N m. This was approximately twice the average value found for the standard UHMWPE control.

The average frictional value of MP-60 started out at a higher value, 0.075, than the standard, 0.05–0.06, and remained relatively constant throughout the test reaching a final value of 0.085. This behavior differed from the standard, for which the final value was 50% higher than the initial value.

4.3. Channel die compressed specimens

Previous work has shown that the degree of molecular orientation varied throughout the specimen [14], particularly for the samples with low compression ratio (i.e., $\lambda = 1.70$). By visual inspection, isotropic UHMWPE was white and opaque in appearance, while the anisotropic UHMWPE was more translucent. In the larger samples, there were areas that were translucent and others that were opaque. The samples for wear testing were generally taken from the middle of one of the halves of the compressed sample where the sample was translucent.

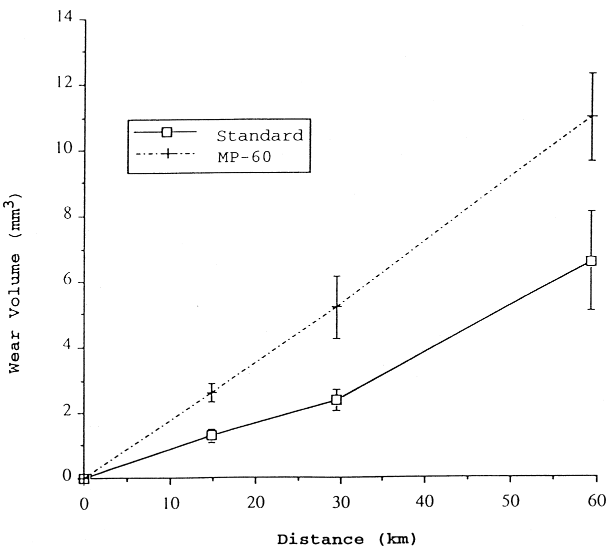

Fig. 4. Wear of sample MP-60. Only two data points were obtained for MP-60. Error Bars represent one standard deviation.

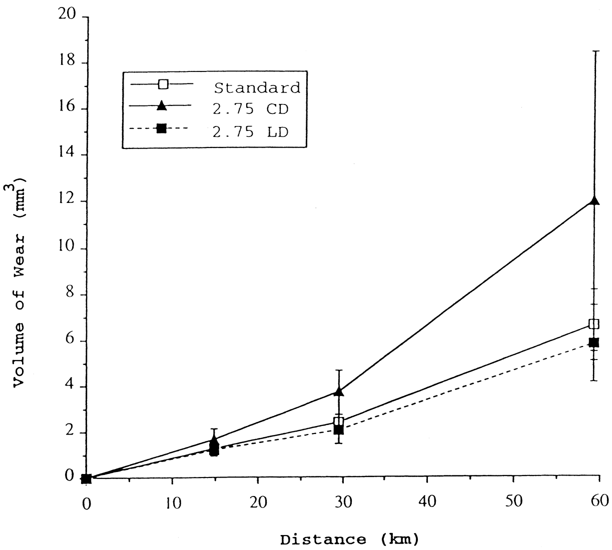

Fig. 5. Wear of samples with a $\lambda = 2.75$ in CD and LD. Error Bars represent one standard deviation.

The samples with λ of 2.75 could only be tested in the LD and CD configuration. Therefore, the values for mass loss at a sliding distance of 15 km were from a different group than the values reported at 30 and 59 km. The wear volumes reported for the latter two are from the same wear run, with data collected only after 4 and 8 days (30 and 59 km of sliding; Fig. 4). The wear rate of the samples with λ of 2.75 tested on the LD and CD surfaces increased from 30 to 59 km of sliding. The 2.75 LD sample showed only a 20% increase, as did the standard UHMWPE sample, but the 2.75 CD sample showed a 64% increase at 59 km over the 30 km value. The dimensional wear coefficient of 2.75 CD after 59 km of sliding was approximately double that of the standard (Table 1). Also from the friction data, both the compressed and the standard samples had an average initial frictional value between 0.05 and 0.06, and leveled off between 15 and 20 km of sliding to values between 0.08 and 0.10.

Samples, compressed at a ratio of 1.7, like the standard, showed an increase in the wear rate after 30 km (Figs. 5 and 6). Their increase in wear rate from 30 to 59 km was much higher than that for the standard; for samples of λ of 1.70 in the FD, CD2, CD and LD orientations (Fig. 7), the values were 178%, 135%, 45%, and 65%, respectively.

The initial wear rate was slightly higher in the channel die compressed samples than in the standard, but not statistically significantly different. The final wear rate of 1.70 CD2 and 1.70 FD samples were considerably higher than the standard, but did not reach a statistical significant difference owning to the large coefficient of variance.

The average frictional values all started between 0.05 and 0.06, except for 1.70 CD which started between 0.04 and 0.05. In all cases, it leveled off after 20 km to values between 0.08 and 0.11.

4.4. Average values of the dimensional wear coefficient

The wear rate of UHMWPE did not behave in a linear fashion as can be seen in Figs. 4–6; it varied depending on the distance slid. Archard's wear equation, however, was used for first approximation. The average values for the dimensional wear coefficients and coefficients of variance are given in Table 1 for the different sliding distances. All the samples, except for the fiber oriented (MP-60), showed an increase in the wear rate between 30 and 59 km. Also, from these values it can be observed that the coefficient of variance, CV, increased dramatically in the samples worn in the CD, FD and CD2 configuration after 30 km. This was due to certain samples in the group showing a dramatic increase in their wear rate, particularly, a sample in the 1.70 FD group and two samples in the 1.70 CD2 group. Though the general trend was for a higher wear rate.

After 59 km of sliding, all of the mean DWC values for the 1.70 channel die compressed samples and the 2.75CD specimen were higher than the standard UHMWPE (Table 1). Only the 2.75LD sample displayed a DWC less than the control value, although the difference was not statistically significant. While the DWC of the channel die compressed samples decreased as the compression ratio increased from 1.70 to 2.75, when tested in the LD direction, the DWC increased when tested in the CD direction.

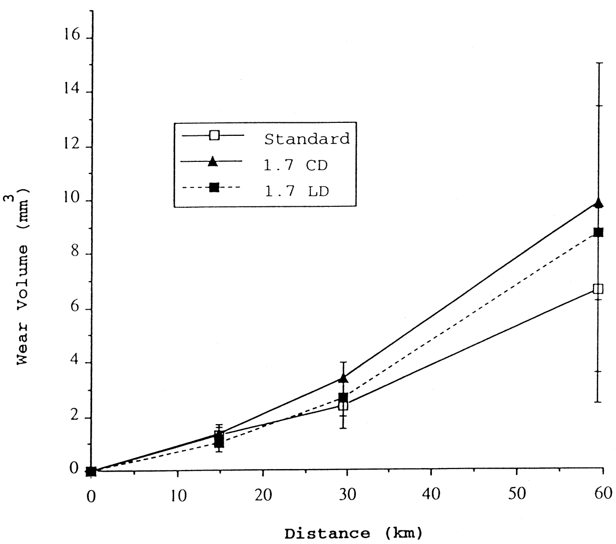

Fig. 6. Wear of samples with a $\lambda = 1.70$ in CD and LD. Error Bars represent one standard deviation.

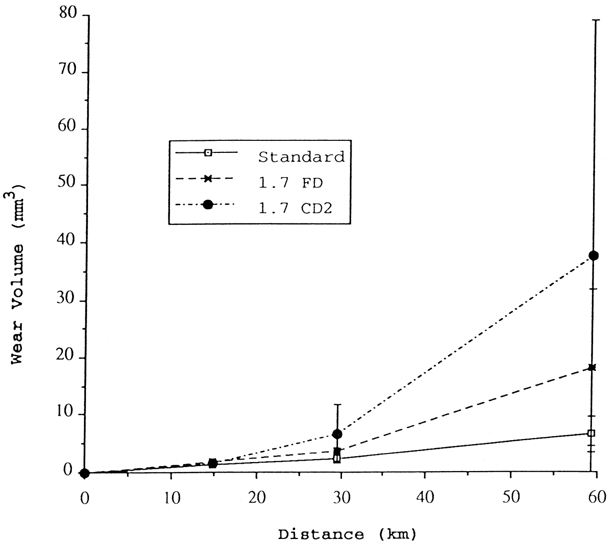

Fig. 7. Wear of samples with a $\lambda = 1.70$ in FD and CD2. Error Bars represent one standard deviation.

5. Discussion

5.1. Fiber-oriented composite samples

The premature failure of two forms of the fiber-reinforced samples, MP-56 and MP-58, precluded their extensive evaluation. The wear of this material in the orientation and condition tested was significantly higher than the standard UHMWPE. Examination of the failed samples revealed what appeared to be debonding of the fiber from the bulk polyethylene, indicating that failure took place at the interface between two woven layers, parallel to the surface. The plastic strain most likely accumulated at a certain depth, between plies of the material, causing the eventual shearing of the top layer.

The MP-60 specimens did not display catastrophic failure, but presented problems in the measurement of the mass loss. The fiber-oriented samples had a relatively high void content, approximately 10%, favoring the uptake of water. A reliable measurement of mass loss could not be made, eventhough the samples were soaked for more than a month. The fibers of the woven material had a crystallinity of 99–98%, which made them impermeable to water. The woven layer would not allow the water to reach the inner voids of matrix polyethylene of the sample. Once the wear tests were begun, however, the fibers may have been rearranged thereby allowing water to reach these regions. This unaccounted water absorption caused an underestimation of the mass loss.

From visual examination of the worn MP-60 samples it was concluded that the material being removed was only the melted unoriented UHMWPE, and that the Co–Cr cylinder had not worn into the woven layers. Its wear rate was of the same order of magnitude as the standard, though slightly higher in value.

For this material friction and wear appeared to increase concurrently. The friction data were within the range of that reported for UHMWPE sliding against Co–Cr, [21,26]. The average frictional values remained constant throughout the duration of the test, unlike the standard and channel die compressed samples. This behavior was reflected in the approximately constant wear rate. However, it is likely that if the melted surface layer had been completely worn off, the sample would have failed in a similar fashion as the MP-56 and MP-58 samples. The higher wear rate for samples with fibers oriented parallel to the surface, likely due to poor bonding of the fibers and the bulk matrix, has been reported previously by Sung and Suh [15] for fibers and matrix of different materials.

The fiber-oriented material was not tested on the surface with the fibers normal to it. A recent publication has shown a lower wear rate in a homocomposite tested on the surface with the fibers normal to it [21]. It was not possible to test this configuration in this study because of the lack of samples with the appropriate dimensions for the wear test.

The potential risk for catastrophic failure of the MP-60, coupled with the fact that the wear rate was found to be of the same order of magnitude as the standard sample, indicates that improvement in the fabrication of the fiber oriented UHMWPE composite is needed before this material could be suitable for the use in total joint replacement applications.

5.2. Channel die oriented samples

Despite the difference in the crystallite and chain orientation between the channel die compressed and standard UHMWPE there were generally no meaningful differences in tribological behavior under conditions of abrasive wear, as these test conditions reflected. The wear rate of the die compressed samples tested in the LD direction decreased with increasing compression ratio, with the 2.75 sample demonstrating less wear than the standard UHMWPE. While this finding was not statistically significant, it warrants follow up investigations.

The average initial frictional value for the compressed and the standard UHMWPE sample was 0.05–0.06, except for 1.70 CD, which had an average initial value 0.043. Average frictional values for all the compressed and standard samples leveled off between 15 and 20 km of sliding to an average that ranged from 0.08 to 0.11. These values were similar to others reported in the literature [21,26]. The sliding distance at which the frictional values level off was consistent with the estimated end of the run-in period, where there would be a larger contact surface and other wear mechanisms, such as adhesive and delamination wear, would begin to play a greater role.

The average wear rate of the standard and the compressed samples changed after 30 km of sliding. There was an increase in the wear rate by at least 20%. The change in wear rate was consistent with the earlier leveling off of the frictional value and removal of the machining marks. The run-in period, which was generally characterized by abrasive wear probably, had a lower wear and friction because there was a lower contact area. However, once the run-in period ended and the contacting surfaces became more conformal, the wear rate and friction increased. The samples were visually inspected each time they were removed from the wear tester for mass loss measurement. Some remnants of the machining marks could be observed on the worn surface after 15 km of sliding. After 30-km machining marks were no longer found. Therefore, the end of the run-in period when the worn surface had become conformal, probably occurred between these two sliding distances.

Since the long term goals of this study was to evaluate wear characteristics of oriented polyethylene for use in knee prostheses, the length of the wear test was chosen so that sufficient wear debris was produced to be considered detrimental in the body. Worn surfaces of the samples did not reveal any evidence of cracking or surface fatigue that could induce delamination wear. Therefore, we conclude that the main wear mechanism within the sliding distance tested was abrasive wear. Under test conditions that favor delamination wear, the effect of chain orientation may have been more important.

Polyethylene is a considerably softer material than Co–Cr. Therefore, any change in surface hardness of the oriented UHMWPE would be minimal compared to the difference in hardness between the UHMWPE and the Co–Cr. Consequently, regardless of the orientation of the UHMWPE, asperities of the Co–Cr could easily plow through the material. The worn surface of the standard sample was similar to that reported by others [27,28]. All specimens had similar grooves in the middle of the wear track, suggesting that the primary mechanism of wear was abrasive wear.

The roughness of the Co–Cr cylinder was measured at the end of wear test for some samples. There was a wide variability of the final *Ra*, ranging from approximately 0.03 to 0.35μm. There was insufficient data to determine whether there were material factors that the roughening of the Co–Cr was dependent on, but there was a general trend toward increasing roughness of the counterface. One possible source of roughening of the counterface could be the presence of polishing compound, which may have remained despite thorough rinsing of the counterface after polishing. This progressive roughening of the counterface would have an impact on the wear rate at higher sliding distances, i.e., the primary mode of wear could continue to be abrasive wear. Thus, a major limitation of our experimental conditions is that longer sliding distances would have little effect in revealing differences between standard and oriented UHMWPE, as might be possible when wear occurs primarily by the mechanisms of fatigue wear, such as delamination wear. It must therefore be emphasized that these results reflect the performance of oriented UHMWPE under conditions of wear that primarily represent the mechanism of abrasive wear

6. Conclusion

Molecular orientation of UHMWPE through channel die compression up to a λ of 2.75 does not improve the abrasive wear performance of the polymer in the conditions employed in this work. The topography of the worn surface of certain samples in which the molecular chains were oriented by channel-die compression indicates some differences in the plastic behavior. A difference in wear behavior may be found for a more prolonged test for which the primary mode of wear becomes delamination wear.

The failure of the less consolidated fiber oriented composites were due primarily to poor bonding between the UHMWPE fibers and the bulk matrix. The more consolidated samples did not show any improvement on the wear rate compared to the standard under the conditions tested. Further investigation is required to determine whether better matrix–fiber bonding will improve the wear performance of such self-reinforced composites.

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References

[1] S. Li, A.H. Burstein, Ultra-high molecular weight polyethylene, J. Bone Jt. Surg. 76-A (1994) 1080–1090.
[2] H. McKellop, B. Lu, S. Li, Effect of increased density and crystallinity on the wear of UHMW polyethylene acetabular cups, Trans. World Biomaterials Congress, Berlin, Germany, 1992, p. 117.
[3] J.R. Atkinson, R.Z. Cicek, Silane cross-linked polyethylene for prosthetic applications: Part 1. Certain physical and mechanical properties related to the nature of the material, Biomaterials 4 (1983) 267–275.
[4] J.R. Atkinson, R.Z. Cicek, Silane crosslinked polyethylene for prosthetic applications: II. Creep and wear behavior and a preliminary moulding test, Biomaterials 5 (1984) 326–335.
[5] H. Oonishi, Y. Takayama, E. Tsuji, In vivo and in vitro wear behavior on weight bearing surfaces of polyethylene sockets improved by irradiation in total hip prostheses,The Institute of Materials, 1992.
[6] D.C. Sun, A. Wang, C. Stark, J.H. Dumbleton, Development of stabilized UHMWPE implants with improved oxidation resistance via crosslinking, 63rd Annual Meeting of the American Academy of Orthopaedic Surgeons 1–5 (1996).
[7] B. Wroblewski, P. Siney, P. Dowson, S. Collins, Prospective clinical and joint simulator studies of a new total hip arthoplasty using alumina ceramic heads and cross-linked polyethlene, J. Bone Jt. Surg. 78-B (1996) 280–285.
[8] J.A. Davidson, R.A. Poggie, A.K. Mishra, A. Salehi, M.E. Harbaugh, Increased wear and contact stress from increased polyethlene stiffness in prosthetic knee and hip articulation, in: 7th International Conference on Biomedical Engineering, Singapore, 1992.
[9] A. Wang, A. Essner, V.K. Polineni, C. Stark, Lubrication and wear of ultra-high molecular weight polyethylene in total joint replacements, Tribol. Int. 31 (1998) 17–33.
[10] M.J. Chmell, R. Poss, W.H. Thomas, C.B. Sledge, Early failure of Hylamer acetabular inserts due to eccentric wear, J. Arthroplasty 11 (1996) 351–353.
[11] B.J. Livingston, M.J. Chmell, M. Spector, R. Poss, Complications of total hip arthroplasty associated with the use of an acetabular component with a Hylamer liner, J. Bone Jt. Surg. 79-A (1997) 1529–1538.
[12] M.D. Ries, A. Bellare, B.J. Livingston, R.E. Cohen, M. Spector, Early delamination of a Hylamer-M tibial insert, J. Arthroplasty 11 (1996) 974–976.
[13] Y. Boontongkong, Orientation of channel-die compressed Ultra-high molecular weight Polyethylene, MSc, Massachusetts Institute of Technology, June, 1997.
[14] Y. Boontongkong, R.E. Cohen, M. Spector, A. Bellare, Orientation of plane strain-compressed UHMWPE, Polymer 39 (1998) 6391–6400.
[15] N. Sung, N.P. Suh, Effect of fiber orientation on friction and wear of fiber reinforced polymeric composites, Wear 53 (1979) 129–141.
[16] D.L. Bartel, V.L. Bicknell, T.M. Wright, The effect of conformity, thickness, and material on stresses in ultra-high molecular weight components for total joint replacement, J. Bone Jt. Surg. 68-A (1986) 1041–1051.
[17] E. Sclippa, K. Piekarski, Carbon fiber reinforced polyethylene for possible orthopedic uses, J. Biomed. Mater. Res. 7 (1973) 59–70.
[18] R.D. Tetik, J.O. Galante, W. Rostoker, A wear resistant material for total joint replacement-tissue biocompatibility of an ultra-high molecular weight (UHMW) polyethylene–graphite composite, J. Biomed. Mater. Res. 8 (1974) 231–250.
[19] T.M. Wright, D.J. Astion, M. Bansal, C.M. Rimnac, T. Green, J.N. Insall, R.P. Robinson, Failure of carbon fiber-reinforced polyethylene total knee-replacement components. A report of two cases., J. Bone Jt. Surg. 70 (1988) 926–932.
[20] T.M. Wright, C.M. Rimnac, P.M. Faris, M. Bansal, Analysis of surface damage in retrieved carbon fiber-reinforced and plain polyethylene tibial components from posterior stabilized total knee replacements, J. Bone Jt. Surg. 70-A (1988) 1312–1319.
[21] N.P. Suh, M. Mosleh, J. Arinez, Tribology of polyethylene homocomposites, Wear 214 (1998) 231–236.
[22] L. Lin, A.S. Argon, Macromolecules 25 (1992) 4011.
[23] H.H. Song, A.S. Argon, R.E. Cohen, Contact pressure dependence of wear rates of ultra high molecular weight polyethylene, Macromolecules 23 (1990) 870.

[24] Y. Cohen, D.M. Rein, L. Vaykhansky, A novel composite based on ultra-high-molecular-weight polyethylene, Compos. Sci. Technol. 57 (1997) 1149–1154.
[25] K.Y. Lee, D. Pienkowski, Reduction in the initial wear of ultrahigh molecular weight polyethylene after compressive creep deformation, Wear 203–204 (1997) 375–379.
[26] V. Saikko, Wear and friction properties of prosthetic joint materials evaluated on a reciprocating pi-on-flat apparatus, Wear 166 (1993) 169–178.
[27] A. Wang, D.C. Sun, C. Stark, J.H. Dumbleton, Wear mechanisms of UHMWPE in total joint replacements, Wear 181–183 (1995) 241–249.
[28] W. Rostoker, E.Y.S. Chao, J.O. Galante, The appearence of wear on polyethylene — a comparison of in vivo and in vitro wear surfaces, J. Biomed. Mater. Res. 12 (1978) 317–335.