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SLIDING DIRECTION-DEPENDENCE OF POLYETHYLENE WEAR FOR METAL COUNTERFACE TRAVERSE OF SEVERE SCRATCHES

Liam P. Glennon^{*,†,§}, Thomas E. Baer^{*}, James A. Martin, Ph.D.^{*}, William D. Lack^{*,†,‡}, and Thomas D. Brown, Ph.D.^{*,†}

^{*} Department of Orthopaedics and Rehabilitation, University of Iowa, Iowa City, Iowa

[†] Department of Biomedical Engineering, University of Iowa, Iowa City, Iowa

Abstract

Third body effects appear to be responsible for an appreciable portion of the wear rate variability within cohorts of patients with metal-on-polyethylene joint replacements. The parameters dominating the rate of polyethylene debris liberation by counterface scratches are not fully understood, but one seemingly contributory factor is the scratch's orientation relative to the direction of instantaneous local surface sliding. To study this influence, arrays of 550 straight parallel scratches each representative of the severe end of the clinical range were diamond stylus-ruled onto the surface of polished stainless steel plates. These ruled plates were then worn reciprocally against polyethylene pins (both conventional and highly cross-linked) at traverse angles varied parametrically relative to the scratch direction. Wear was measured gravimetrically, and particulate debris was harvested and morphologically characterized. Both of the polyethylene variants tested showed pronounced wear rate peaks at acute scratch traverse angles (15° for conventional, 5° for cross-linked), and had nominally comparable absolute wear rate magnitudes. The particulate debris from this very aggressive test regime primarily consisted of extremely large and elongated strands, often tens or even hundreds of microns in length. These data suggest that counterface damage regions with preferential scratch directionality can liberate large amounts of polyethylene debris, apparently by a slicing/shearing mechanism, at critical (acute) attack angles. However, the predominant manifestation of this wear volume was in the form of particles far beyond the most osteolytically potent size range.

INTRODUCTION

Late aseptic loosening from wear-induced osteolysis remains a principal limitation to the longevity of metal-on-polyethylene total joint replacements. Well-engineered contemporary total hip arthroplasty (THA) and total knee arthroplasty (TKA) designs, coupled with technically well-performed surgeries in high-volume centers, nowadays consistently achieve survival rates in the range of 95% and above at ten years, and 90% and above at twenty years [1]. Although construct failure is thus restricted to a relatively small fraction of joint replacement patients, it remains of major concern to the orthopaedic community because of the substantial morbidity to the affected individuals. Likewise, it increases the overall socio-economic burden of revision surgery [2], given the very large absolute numbers of arthroplasty

Corresponding author: Thomas D. Brown, Ph.D., Orthopaedic Biomechanics Laboratory, 2181 Westlawn, University of Iowa Iowa, City IA 52242 (319), 335-7528, fax: (319) 335-7530, email: tom-brown@uiowa.edu.

[§]Zinsser North America, Northridge CA

[‡]School of Medicine, Harvard University, Cambridge MA

procedures being performed now and for the foreseeable future, in an increasingly resource-constrained health care system.

The propensity for aseptic loosening has been convincingly linked to wear debris burden [3]. Although most clinical and laboratory studies of wear rates for design/construct variants involve comparisons of group-wide mean values, in point of fact the wear rates within any given patient cohort tend to be highly variable [4] for reasons not yet definitively elucidated. One very plausible explanation for wear rate variability, however, is accrual of damage (surface roughening) of the bearing couple due to entrapped third-body debris from any of various sources [5,6,7]. Laboratory tribology data show dramatic wear rate accelerations from even modest bearing surface roughening or scratching [6,8,9,10], and controlled clinical series suggest that this effect may account for nearly half the wear rate variability seen within individual patient cohorts [11].

Possibly because of the nebulous nature of third-body particle generation and the seeming randomness of subsequent bearing surface damage, systematic investigations of the mechanisms governing the potency of scratch-induced polyethylene wear acceleration have been relatively infrequent. However, since data from several laboratories now suggest that recent dramatic advances in polyethylene wear resistance against smooth counterfaces do not carry over fully comparably to situations of counterface roughening [12–16][†], osteolysis-prone outlier wear situations arguably will continue to occur frequently, despite the major improvements [18,19] in cohort-average wear rates achieved by cross-linked materials. Given the likely continued occurrence of third-body challenges, it is therefore important to understand what aspects of counterface scratch interaction are responsible for accelerated debris liberation, both for conventional and cross-linked polyethylenes, especially for guiding process improvements to achieve improved wear performance.

Work to date with scratch parameter-dependence of polyethylene wear has concentrated primarily on the effects of scratch morphology and has documented that the geometrical characteristics of the raised scratch lip dominate the wear process [8]. Such experimental work, along with the supporting body of computational simulations of scratch/polyethylene interaction [20], has largely assumed that the scratched metal counterface traverses the polyethylene in a direction perpendicular to the scratch axis. Such a scenario intuitively represents the most destructive interaction locally in terms of the scratch lip directly plowing through the polyethylene, but it is plausible that when scratches traverse obliquely, very different local polyethylene failure mechanisms would ensue from slicing/shearing interaction, and possibly involve even more exuberant material liberation than occurs for straight-ahead plowing. There is a large literature documenting the importance of local engagement angles for polymer surface damage occurring due to articulation against local asperities [21,22]. And, of course, slicing/shearing is an efficient material removal mechanism that is deliberately exploited by rake angle optimization in machining processes [23].

Since scratches on metal surfaces of orthopaedic joint replacement implants arise predominantly from entrapped third body particulates whose traverse loci within the bearing depend upon the complex sliding kinematics of the motion cycle [24,25], it seems unavoidable that a given site on the polyethylene surface would habitually encounter a wide variety of scratch traverse directions, some presumably much more critical than others in terms of wear process exacerbation. The present study was undertaken to explore the potential traverse direction-dependence of polyethylene removal by metal counterface scratches, under kinetic conditions nominally representative of contemporary total hip and knee replacements.

[†]Under certain conditions [17] cross-linked polyethylene performs comparably to - or perhaps even worse than - conventional polyethylene, when articulated against badly damaged counterfaces.

MATERIALS AND METHODS

The highly cross-linked polyethylene (HXPE) (DePuy Marathon, Warsaw, IN) used in this study was produced from ram-extruded ultrahigh molecular weight polyethylene (UHMWPE) bar stock, GUR 1150, irradiated to 5Mrads at room temperature, and remelted at 155 °C for 24 hours. The conventional polyethylene (CPE) used in this study was ram-extruded GUR 4150 HSS/Poly Hi/Hoechst Reference UHMWPE Material [26]. The as-received rods of both types of polyethylene were machined into lengths and diameters of approximately 30 mm and 25.4 mm, respectively, for testing purposes. (Edge effects were negligible for this diameter, based on preliminary finite element modeling.) The plugs were first rinsed with tap water to remove bulk contaminants and then washed in an ultrasonic cleaner in a 1% solution of surfactant detergent (RBS[®], Fisher Scientific, Inc.) for 15 minutes. The plugs were again rinsed in distilled water and then in an ultrasonic cleaner in distilled water for 5 minutes. The plugs were each dried with lint-free tissue, and each specimen was placed in an individual bag filled with fetal bovine serum (FBS) (Invitrogen Corporation, Grand Island NY) and stored for 35 days to reach a steady-state level of fluid sorption (ASTM Standard F 2025-00). The FBS used for this purpose was treated with 10 mM ethylenediaminetetraacetic acid (EDTA) and 0.01% sodium azide to prevent microbial growth.

Scratched metal counterfaces were prepared from initially square (10 cm x 10 cm) 0.8 cm-thick 316L stainless steel plates, lapped and polished (Double-Disc Grinding Company, 7225 W. Wilson Avenue, Harwood Heights, IL) to a surface roughness Ra of approximately 100 nm (vendor's unpublished data). Arrays of clinically representative [20] parallel scratches were then ruled at 150 µm intervals on these steel plates, increasing the regionally averaged Ra to approximately 1.2 µm. Formation of these scratches was via a rake-like row of eleven diamond styli (Gilmore Diamond Tools, Inc., East Providence RI) of tip radii 50µm, spaced at 8 mm intervals (Figure 1). The styli were each spring-loaded to 3N against the metal surface, and were driven across the surface using the automatic feed of a Bridgeport milling machine. After each passage of the milling machine carriage, the perpendicular-direction purpose-built plate holder was incrementally offset by 150µm. This process was repeated for 50 passages until an 8 x 8 cm area of the plate surface was uniformly scratched. This method resulted in 550 nominally identical scratches, having lip heights, lip widths and furrow widths of approximately 1.3, 22, and 23 µm, respectively (Figure 2), creating a "ruled" plate. The square plate was then mounted in a lathe and its edges turned to the 9.5 cm diameter circular dimension of the housing in which it would be mounted for wear testing.

Wear testing was conducted using a Bionix 858 biaxial loading frame (MTS Eden Prairie, MN). To isolate the parameter of interest (relative motion directionality), the experimental design adopted single-direction reciprocal motion relative to the scratch axis. For this purpose a "Scotch yoke" reciprocating mechanism was utilized (Figure 3). The ruled circular metal plate was fastened into the base plate by a bolt in the bottom, and the parallel scratches were aligned at the desired orientation with respect to the direction of motion, using a protractor. Dental wax was used to water-seal the plate edge, after which 50% FBS was poured over the plate. A plastic splash guard fixed on top of the lubricant pool ensured that no bovine serum sloshed out over the edges. Coolant water was circulated just beneath the plate through channels bored within the mounting base, to minimize plate heating from friction-induced temperature elevations at the contact surface between the plug and the plate. (Flash temperature elevations, very locally from scratch lip friction, nevertheless probably occurred.) The polyethylene plug was inserted into a housing fixture connected to the MTS crosshead. The housing had two set screws for securing the plug in place.

The plug was initially brought lightly into contact (approximately 3N load) with the scratched plate. After initial engagement, the pin axial load was increased to approximately 1269 N before

motion was initiated, and was held at this value for the duration of the wear test, producing a nominal contact stress of 2.5 MPa. The duty cycle consisted of the scratched counterface plate being temporally driven sinusoidally at a frequency of 0.75 Hz against the polyethylene plug through a distance of approximately 44.6 mm, corresponding to average linear speed of approximately 72 mm/sec. This nominal contact stress and sliding speed were toward the low end of the *in vivo* range, in order to minimize local frictional heating.

The plug was induced to parametrically traverse the ruled plate at a specific angle of either 0°, 2.5°, 5°, 10°, 15°, 20°, 30°, 45°, 60°, or 90° relative to the scratch orientation. The accuracy of angle setting was approximately 0.5°. Three replicate trials were conducted for both polyethylene material variants for each direction tested, leading to a total of 60 parametric trials (10 directions x 2 materials x 3 replicates). Tests were typically run for 3 increments of 30,000 cycles each, totaling 90,000 cycles per trial, with the order of testing randomized among angles. CPE and HXPE plugs were run on separate plates. Wear was measured gravimetrically for specimens in the as-tested condition, typically with 30 minutes of specimen removal from the apparatus, using a Mettler AE163 balance whose rated precision was 100 micrograms. For each gravimetric assessment, the plug was weighed three times and the average recorded. Both wear rates and cumulative wear were assessed. Wear tests were also done on an as-received (i.e., non-roughened) lapped/polished plate (Ra value of approximately 100 nm), and on a plate randomly roughened by hand with 180-grit emery cloth, for both material variants. Tare compression tests (3 hours of load application) carried out on three non-worn HXPE plugs, to control for load-induced exudation of absorbed serum, showed immeasurable weight change.

Additionally, recovered debris from representative testing variants was compared. For this purpose, the entire volume (approximately 100 ml) of the lubricant fluid was collected from above the test plate after wear test completion and was treated with 5M KOH for two days, and then filtered through a 90 mm diameter Milipore Steriflip Express Plus 0.22 µm pore cellulose membrane vacuum filter unit (Nalgene Inc., Rochester NY) for subsequent wear particle isolation and visualization. After initial filtration, 200 ml of filtered water was passed through the apparatus in the same way, to remove any residual FBS. The membrane was then air-dried overnight. The filter was removed from the filtration unit and cut into sections 6 x 6 mm, which were mounted on stubs for SEM (scanning electron microscope) scanning. The filter sections were gold sputter-coated in a 0.07 mbar vacuum chamber and imaged in a Hitachi S-4000 SEM. Owing to the very different particle morphologies present, particle detection by automated image analysis was impractical. Individual polyethylene particles were therefore manually cursor-delineated, and their nominal longest dimension (length), shortest dimension (width) and apparent out-of-plane dimension (thickness) were visually estimated based on the SEM display scale. Particle aspect ratios and equivalent circular diameter (ECD) were calculated for a morphological comparison of the recovered debris.

RESULTS

For all traverse angles, the steady state wear rate for all angles was reached by approximately 60,000 cycles. Unlike HXPE's major performance differential against undamaged surfaces [18,19], the absolute volumetric wear rates for crosslinked polyethylene were of comparable magnitude to those of the conventional material in this particularly abusive test regimen, where the ruled scratches greatly dominated the surface engagement tribology. Scratch orientation was a critical factor in the overall wear rate. The highest wear rates were found at a 15° traverse angle for CPE and at 5° for HXPE (Figure 4), measured relative to the scratch axis. This suggests that at these two respective critical angles, large amounts of material were efficiently sliced off as the pin traveled across the scratch lips. The volume of material removed from both polyethylene variants by the scratch plate wear tests, with the exception of these 5° and 15°

maxima for cross-linked and conventional polyethylene, respectively, otherwise followed no apparent pattern of angle dependence.

The debris recovered was primarily in the form of very small numbers of very large particles (tens or hundreds of microns in characteristic dimension, Figure 5) rather than the large number of very small (micron or sub-micron sized) particles characteristic of UHMWPE wear against non-roughened surfaces [27]. The emery-roughened plate (of interest mainly for particle morphology, see below) produced slightly less volumetric wear than that produced by the ruled plates. Non-roughened plate wear tests yielded vanishingly small amounts of debris in 90,000 cycles, suggesting that the datum surface finish of the plates (while less smooth than typical clinical implants) was amply smooth for the present study.

Various geometrical models have been incorporated to aid in particulate morphological and volume calculations through SEM images, motivated by situations in which the gravimetric approach is untenable [28,29]. Images recovered from the emery-roughened plate yielded about 1200 identifiable particles, which were visually measured (Table 1, Figure 6). As an approximate check on particle recovery completeness for one particular survey case, the summation of estimated volumes for all identified particles (0.00375 mm^3) times polyethylene density (0.945 g/cc) led to an inferred total particle weight of 0.0033 grams, a value which compared reasonably (i.e., within a factor of 2) to the corresponding direct gravimetric pin weight loss measurement of 0.0067 grams.

Particles recovered from both HXPE and CPE ruled-plate tests were mostly tens of microns in length, and in some cases hundreds of microns long, typically with ribbon-like or flake-like morphology (Figures 5a-d). Such particles, however, were very few and far between, and tended to be clumped together on an otherwise sparsely populated filter surface. The tiny quantity of debris recovered from the non-roughened plate wear tests was in the form of particles that were much smaller, i.e. submicron in size, and markedly different in shape, viz. more blunt and globular in form (Figure 5e). Particles recovered from the emery roughened-plate test (Figure 5f) were also blunt and globular in shape, but were in size ranges characteristic of both the non-roughened plate and ruled plate debris, with dimensions ranging from less than one micron to twenty-plus microns.

DISCUSSION

Although the duty cycle kinetic parameters for the present specialized testing protocol were nominally representative of a low demand range of total hip/knee function *in vivo*, the experiment was not designed to mimic the clinical service environment in terms of predicting absolute wear rates for implanted patients. Obviously, the high volumetric wear rates measured in this deliberately very aggressive testing regimen would be intolerable clinically, but they were useful in terms of affording expeditious replicate samplings of a large number of scratch traverse directions.

The experimental data showed that the greatest wear rates for the two different types of polyethylene occurred from scratches oriented at two specific highly acute angles, i.e., at 5° for highly cross-linked and at 15° for conventional polyethylene. This is suggestive of a slicing modality, in which large amounts of material were removed as the pin sheared across the scratch lips. (This shearing/slicing modality occurs on a substantially larger size scale than the cross-shearing effect associated with multi-directional motions that dominates micro-meter range particle liberation in abrasive/adhesive wear.) Also, the measured direction-dependence of wear for these relatively severe scratches is not necessarily representative of that for smaller/milder scratches, where different mechanisms for wear particle liberation might be operative. Similarly, the present directional relationships are not necessarily representative of those for

yet larger-size macro-scratching damage, such as occurs in situations of dislocation or forced relocation [30,31]. Factors governing wear rate acceleration from macro-damage presently are not well understood, but presumably the interplay between macro-scratch location, macro-scratch orientation, and articulation kinematics and kinetics is a major consideration.

In this protocol, the wear rates for cross-linked and conventional polyethylene were in the same general range. While cross-linking has major efficacy in reducing wear against highly polished surfaces, it has been recognized that this relative benefit can be substantially reduced when the counterface is appreciably roughened [17]. Elucidating the fundamental mechanism(s) responsible for liberation of UHMWPE debris due to counterface scratching was beyond the scope of this study, but presumably the details of local stress concentration near the scratch lip are the major determinant.

In the present series, recovered debris morphology did not differ appreciably between either of the two types of polyethylene, or for any of the testing directions, for the ruled-plate wear tests. Comparisons between ruled plates and emery-roughened plates did, however, yield clear differences in both shape and size. Particles recovered from the ruled-plate wear tests were predominantly elongated in nature, and in some cases were many hundreds of microns in length (Figure 5c,d). By contrast, the emery-roughened plate and non-roughened plate wear tests produced much smaller debris, although of course the quantity was much greater for the emery-roughened plate. The emery-roughened plate debris (from CPE) was dominated primarily (90%) by particles having an aspect ratio of nominally unity (Figure 6). The size of the debris recovered from the present ruled-plate wear tests was consistently much larger than the submicron debris that is known to be most potent for causing osteolysis [32]. Therefore, the present high volumetric wear rates (and possibly those seen clinically due to third body challenge) probably should not be interpreted directly in terms of correspondingly elevated osteolytic potency. At the spacing utilized, the local micro-mechanics of scratch/polyethylene engagement for a given scratch was not influenced by neighboring scratches [33]. Effectively, therefore, the experiment produced wear at nominally 550 times what would have been expected for a single *in vivo* scratch of similar morphology.,

The present testing protocol, involving purely reciprocal motion, aimed to elucidate the dependency of polyethylene wear upon direction of articulation relative to highly anisotropic counterface scratches. Such surface engagement effectively includes crossover (except at 0°) due to the scratches passing transversely to the motion direction. A unidirectional reciprocating test was the only viable approach to determine an orientation-specific wear relationship. The testing configuration did, however, utilize clinically realistic scratch dimensions, albeit clearly a worst-case scenario regarding the number and concentration of scratches.

Nominal wear values were, as expected, much greater per cycle in this experiment than in a typical roughened THA/TKA construct due to the usage of the large number of scratches. This particular test regimen aimed to amplify the differences due to scratch orientation in the interest of clearly accentuating a plausibly angle-dependent relationship. Since a given site on the polyethylene surface engaged hundreds of nominally identical scratches during each cycle of counterface traverse (depending on the specific test direction), the number of individual scratch encounters during a full 90,000-cycle trial was of order 10^7 . The number of isolated (large) particles, however, was only of order 10^4 or less. Thus, liberation of one of these individual elongated particles was a relatively rare event, occurring only after the overpassage of many hundreds or thousands of scratch lips at a given polyethylene site. This is suggestive of a fatigue-like local failure mechanism, even within the slicing/shearing modality of debris liberation.

Considerable variability occurred among replicate trials in the ruled-plate test series, a phenomenon commonly encountered in laboratory wear testing. Since this type of study is logistically burdensome, investigations performing parametric wear testing normally are restricted to just a very few replicates (typically 3–6) per test group. Contemporary studies from leading research centers [34,35,36,37,38] commonly show variability (standard deviation/mean) in the range of 0.13 to 0.39, values generally consistent with the average replicate variability of 0.38 in the present series.

In conclusion, under a specialized experimental setting in which UHMWPE was induced to articulate at a range of specific traverse angles relative to scratches ruled in an apposing metal counterface, the highest wear rates occurred when the motion direction was at a small acute angle (5–15°) relative to the scratches. Debris were apparently liberated by a shearing/slicing mechanism, which operated similarly for both the conventional and cross-linked polyethylene. Both variants of polyethylene wore at nominally comparable rates, with wear particles being far larger than the typical osteolytic size range.

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1a**1b****Figure 1.**

Figure 1a. Rake-like scratching apparatus, having 11 spring-loaded scribes, positioned atop a lapped/polished plate.

Figure 1b. Close-up of a diamond-tipped scribe. Tip radius is 50 μm .

Figure 2. Zeiss LSM 510 confocal microscope reconstruction of a typical scratch profile. Note that each axis is on a different scale, which exaggerates scratch severity for purposes of visual emphasis.

Figure 3. Custom-built Scotch yoke pin-on-plate fixture. The articulating couple (25.4 mm diameter UHMWPE pin above, scratch-ruled plate below) was housed within the fixture.

Figure 4.

Wear rate versus angle between scratches and motion direction, for cross-linked versus conventional polyethylene. (Dispersion bars indicate standard deviations, for three replicate tests.) Statistically significant wear rate differences ($p < 0.05$, by paired t-test) were achieved only for 5° for HXPE, and only for 15 ° for CPE.

Figure 5.

(a) Typical particle from a 15° CPE ruled plate wear test. Note curling and twisting of polyethylene. (b) Ribbon-like particle recovered from 15° CPE ruled plate wear test. (c) 90° CPE scratch orientation ruled-plate wear test debris. (d) Flake-like particle recovered from 15° CPE ruled plate wear test. (e) Debris from a non-roughened plate wear test using CPE. (f) 180-grade emery-roughened plate wear.

Figure 6.
Comparison between ruled-plate and emery-roughened plate particulate frequency, and associated aspect ratios.

Morphology information on recovered debris from emery-roughened plate tests. Nominal Length (L) and Width (W) were directly inferred visually. Thickness (T) was inferred indirectly, from apparent out-of-plane particle appearance. Equivalent Circle Diameter (ECD) is $s\ 2\sqrt{\pi LW}$. All dimensional units are μm .

The thickness values for all particles were inferred from images that showed evidence of twisting. These twists enabled a view of the thickness of each strand of polyethylene.

Table 1

L	W	T	Volume	Aspect Ratio (L/W)	ECD	Number of Particles Identified	Frequency of Aspect Ratio
10	10	10	1000	1	11.29	450	88%
25	20	5	2500	1	25.24	150	88%
20	15	5	1500	1	19.55	225	88%
20	20	20	8000	1	22.57	200	88%
2	2	5	20	1	2.26	23	88%
4	2	5	40	2	3.19	26	7.5%
40	20	5	4000	2	31.92	35	7.5%
200	100	20	400000	2	159.62	30	7.5%
30	10	5	1500	3	19.55	14	2.5%
25	10	5	1250	3	17.85	15	2.5%
20	5	5	500	4	11.29	2	1%
40	10	5	2000	4	22.57	10	1%
25	5	5	625	5	12.62	11	1%