Characterization and tribology of PEG-like coatings on UHMWPE for total hip replacements

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Abstract: A crosslinked hydrogel coating similar to poly(ethylene glycol) (PEG) was covalently bonded to the surface of ultrahigh molecular weight polyethylene (UHMWPE) to improve the lubricity and wear resistance of the UHMWPE for use in total joint replacements. The chemistry, hydrophilicity, and protein adsorption resistance of the coatings were determined, and the wear behavior of the PEG-like coating was examined by two methods: pin-on-disk tribometry to evaluate macroscale behavior, and atomic force microscopy (AFM) to simulate asperity wear. As expected, the coating was found to be highly PEG-like, with ~83% ether content by x-ray photoelectron spectroscopy and more hydrophilic and resistant to protein adsorption than uncoated UHMWPE. Pin-on-disk testing showed that the PEG-like coating could survive 3 MPa of contact pressure, comparable to that experienced by total hip replacements. AFM nanoscratching experiments uncovered three damage mechanisms for the coatings: adhesion/microfracture, pure adhesion, and delamination. The latter two mechanisms appear to correlate well with wear patterns induced by pin-on-disk testing and evaluated by attenuated total reflection Fourier transform infrared spectroscopy mapping. Understanding the mechanisms by which the PEG-like coatings wear is critical for improving the behavior of subsequent generations of wear-resistant hydrogel coatings. © 2009 Wiley Periodicals, Inc. J Biomed Mater Res 92A: 1500–1509, 2010

Key words: UHMWPE; poly(ethylene glycol); hip replacement; coating; wear

INTRODUCTION

Ultrahigh molecular weight polyethylene (UHMWPE) has been used as a bearing surface in total joint replacements (TJR) since 1962.1 Although it has proven to be an excellent material for TJRs because of its bulk biocompatibility and high wear resistance, UHMWPE components still produce millions to billions of wear particles per year in vivo.2 The particles, which are primarily submicron in size,2 can cause wear-mediated osteolysis, the primary reason for late-stage failure of TJRs.3,4 Consequently, decreasing the wear rate of UHMWPE has been a focus of TJR research for many years. Modifications to bulk UHMWPE have included reinforcement with carbon fibers, which resulted in numerous failures5,6; high pressure treatments to increase lamellar size, with mixed results7; and crosslinking to reduce lamellar orientation, a known precursor to wear particle formation.8 Although crosslinking does reduce wear, it also reduces the ultimate tensile9 and fracture properties10 of UHMWPE. As a result, some crosslinked UHMWPE acetabular cups have failed because of reduced material properties and poor implant design.11,12

Surface modification of UHMWPE offers the opportunity to improve surface wear behavior while retaining material properties such as toughness and fatigue resistance. A number of researchers have hardened the UHMWPE surface by ion bombardment/implantation, which generates surface crosslinking,13,14 or diamond-like coatings15,16 that can decrease wear and increase scratch resistance. A more biomimetic approach increases lubrication at
the UHMWPE-counterbearing interface by applying soft hydrophilic polymer coatings to the UHMWPE surface. Pavoor et al.\textsuperscript{17} dip-coated UHMWPE with polyelectrolyte multilayers (PEMs), which reduced the wear rate of the UHMWPE by forming a lubricious transfer film on the counterbearing. Such a mechanism is unlikely to be effective in the body, where synovial fluid may wash lubricious PEM fragments away from the articulating interface. Thus, covalently-bonded lubricious coatings seem more promising. Zhang et al.\textsuperscript{18} generated hyaluronan coatings on sintered UHMWPE microcomposites and found that they reduced the wear volume, but the sintering method used during coating produced inferior quality UHMWPE. This suggests that direct surface treatments, such as photopolymerization or plasma treatment, are preferable. Moro et al.\textsuperscript{19} photopolymerized 2-methacryloyloxyethyl phosphorylcholine (MPC) onto UHMWPE to covalently bond a brush layer to the surface. The MPC coating resists protein deposition,\textsuperscript{20} reduces particle immunogenicity, and decreases the wear rate of crosslinked UHMWPE.\textsuperscript{19}

The performance of the hyaluronan and MPC surfaces validates the use of covalently-bonded hydrogel coatings to increase lubricity and decrease wear of UHMWPE. This study investigates the efficacy of an alternative coating material similar to poly(ethylene glycol) (PEG), a flexible linear polymer made from CH\textsubscript{2}CH\textsubscript{2}O repeat units (see Fig. 1) that is hydrophilic, lubricious, biocompatible, and resistant to protein adsorption. It has been used for many other biomedical applications, such as conjugation to drugs to reduce antigenicity and enzymatic degradation,\textsuperscript{21,22} and to reduce phagocytosis of liposomes.\textsuperscript{23}

Surfaces made from plasma-polymerized tetraglyme have similar chemistry to PEG, and are also hydrophilic and protein resistant. These coatings have been characterized chemically\textsuperscript{24} and evaluated as antithrombogenic surfaces.\textsuperscript{25} Plasma deposition offers many advantages over surface grafting or adsorption, producing coatings that are conformal, continuous, sterile, and covalently bonded to even unreactive surfaces like UHMWPE.\textsuperscript{26} In addition, plasma-deposited coatings are crosslinked, which should increase the mechanical strength and wear resistance of the material relative to an uncrosslinked, end-grafted brush layer like MPC.

This study examines the chemical composition, hydrophilicity, protein resistance, and wear behavior of plasma-polymerized tetraglyme coatings on UHMWPE. The wear behavior was observed on three different length scales—millimeter, tens to hundreds of microns, and less than 10 microns—to elucidate the tribological mechanisms occurring at each level. This understanding should enable superior design decisions regarding future iterations of PEG-like coatings, as well as other hydrogels used for similar purposes, to tailor their wear behavior.

**MATERIALS AND METHODS**

**Materials**

UHMWPE substrates were cut from 250 µm thick sheets [x-ray photoelectron spectroscopy (XPS), attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR), contact angle, and protein deposition] or rod stock [atomic force microscopy (AFM), wear pins, and ATR-FTIR mapping], both from McMaster-Carr. The AFM samples and wear pins were microtomed using a Reichert Ultracut E with a glass blade. All substrates were then cleaned by successive sonication in 1% Aquet solution (Bel-Art Products), deionized water 3×, acetone, and isopropanol (Sigma-Aldrich).

**Plasma deposition**

Clean UHMWPE substrates were coated with tetraglyme (Sigma-Aldrich) using a Plasma Science PS0500 parallel-plate reactor with a 13.56 MHz, 550 watt RF generator heated to 50°C. High-power argon treatment (400 W, 250 sccm, 3 min) was used to activate the UHMWPE surface to promote covalent bonding of the coating. Tetraglyme was then plasma polymerized onto the surface at 50 W, 30 sccm argon, with 6 mL/h tetraglyme flow through a 130°C heated tube, for 20–40 min to generate a range of coating thicknesses.
X-ray photoelectron spectroscopy

XPS was performed on a Surface Science Instruments S-probe spectrometer with a monochromatized Al source at a 55° take-off angle. For each plasma deposition batch, survey and high-resolution C 1s spectra were collected at two spots on two samples. High-resolution C 1s spectra were peak fit with the Service Physics ESCAVB Graphics Viewer to resolve the hydrocarbon, ether, and carbonyl peaks.

Contact angle goniometry

The relative hydrophilicity of the surfaces was measured using a custom-made contact angle goniometer with a variable-magnification InfiniVar video microscope (Infinity Photo-Optical), a 1.45 megapixel Sony XCD-SX910 camera, and LabView 7.1 software. Deionized water (5 l L) was pipetted onto the surface, and the drop was imaged in LabView and fit to a sphere. Two spots on two samples per plasma deposition batch were tested.

Attenuated total reflection-Fourier transform infrared spectroscopy

ATR-FTIR spectra were collected using a Nicolet Avatar 360 with an Omni-Sampler ATR accessory (Ge crystal, single-bounce beam path, 45° incident angle, 32 scans, 4 cm⁻¹ resolution). An advanced ATR correction was applied to all spectra, and the region from 1800 to 900 cm⁻¹ was peak fit using Omnic 7.3 software. The area under the most prominent ether peak at ~1115 cm⁻¹ was used to compare the relative thickness of different coatings.

ATR-FTIR mapping

ATR-FTIR maps were collected with a ThermoNicolet Nexus 870 FT-IR ESP with a Nicolet Continuum XL FT-IR Imaging Microscope (15× objective) and a Ge ATR crystal (single-bounce beam path, 32 scans per spot, 25 μm spot size, 37.5 μm step size, 4 cm⁻¹ resolution). All spectra were truncated to 1800-900 cm⁻¹, baseline corrected, and an advanced ATR-FTIR correction was applied, again using Omnic 7.3. Profiles of the ether/hydrocarbon ratio (the ratio of the area under the ether peak normalized by the area under the carbonyl peak) were constructed to evaluate the coating thickness across the mapped region.

Protein adsorption

Uncoated and PEGylated UHMWPE substrates were soaked in 5 μg/mL bovine serum albumin (the most common protein in synovial fluid) conjugated to AlexaFluor 488 (BSA-AF, Invitrogen) in phosphate-buffered saline (PBS; Gibco; pH 7.4) for 30 min, then rinsed three times with PBS. The surfaces were visualized with a Zeiss AxiolMager M1 fluorescence microscope with a Zeiss Plan-Neofluar 20× air objective, NA = 0.50, using a 450 to 490 nm excitation filter and a 500 to 550 nm emission filter (both band pass). Five areas on each sample were imaged with a Photometrics Quantix KAF1401E CCD camera and iVision 4.0 software (BioVision Technologies). The fluorescence intensity was calculated as the mean of the brightness of the 1.4 million pixels of each image.

Pin-on-disk testing

Uniaxial wear tests were performed on a custom-built pin-on-disk tribotester. UHMWPE pins with a 2 mm diameter flat end and RMS roughness ~0.030 μm were articulated against a CoCr disk, Rₐ 0.027 ± 0.001 μm, at 36 mm/sec, at room temperature, in bovine calf serum (HyClone) diluted 1:1 v/v with deionized water and 0.1% wt/v sodium azide (Sigma-Aldrich). The serum volume was replenished with deionized water at 1.0 mL/h using a syringe pump (Cole-Parmer). The contact pressure was either 3 or 21 MPa to simulate conditions in the hip or knee, and the sliding distance was 2500 or 500 m, respectively. After testing, the pins were rinsed in deionized water and examined by ATR-FTIR to determine coating survival.

Atomic force microscopy scratch testing

AFM scratching was used to evaluate both coating thickness and microscale wear behavior. AFM was performed with an Asylum Research MFP-3D using silicon cantilevers (Nanosensors FM tips, spring constant ~2 nN/ nm) in PBS (Gibco, pH 7.3). As shown in Figure 2, the surface was sequentially imaged nondestructively in tapping mode (image size: 8 μm × 2 μm); lithographed in contact mode to produce a rectangular defect (10 passes along the lithography path; normal force, 1–2 μN); and scratched in

![Figure 2. The AFM scratch process. The surface was sequentially imaged, lithographed, imaged, scratched (which also generated a real-time image of the wear box), imaged, rescratched, and reimaged.](image)
contact mode (1–2.5 lN) inside the 4 μm × 1 μm wear box enclosed by the lithographic defect. The surface was reimaged after lithography (which was omitted from some sequences to evaluate the behavior of fully intact coatings) and again after every 1 to 4 scratches. During scratching, the AFM also recorded images, which show the real-time scratching behavior of the coatings.

Image analysis was performed using MPD-3D software and Igor Pro 6.02A. The first image taken served as a reference for all tapping-mode images. After scratching and reimaging, the reference image was subtracted from each subsequent image to highlight wear-induced damage. The smooth region surrounding the wear box is unworn coating. The height of the unworn area was used as the zero point for calculation of the volumetric wear rate of the coating.

RESULTS

XPS

All plasma-treated samples exhibit PEG-like surface chemistry (Table I). The plasma-deposited surfaces have an oxygen content of 31.0 to 31.5% and they are 82.1 to 83.2% ether (C—O). For comparison, pure PEG has 33.3% oxygen content and is 100% ether. The hydrocarbon content likely represents crosslinked or branched chains, whereas the carbonyl derives from side reactions during plasma polymerization. These results correlate very well with both the expected chemical structure and the literature24. In addition, the ether content of coatings produced with different plasma deposition times are not significantly different (p < 0.05). Therefore, plasma deposition time, which was used to control coating thickness, did not impact coating chemistry.

ATR-FITR

Figure 3 shows the full ATR-FTIR spectra of cleaned, uncoated UHMWPE, and UHMWPE plasma-treated with tetraglyme. As expected, the untreated UHMWPE exhibits only peaks associated with hydrocarbons, namely the C–H stretch and bend, whereas the PEGylated surface also displays a cluster of large ether peaks, a small carbonyl stretch,

### TABLE I

<table>
<thead>
<tr>
<th>Tetraglyme Deposition Time (min)</th>
<th>Composition</th>
<th>C1s bonding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% C (285 eV)</td>
<td>% O (533 eV)</td>
</tr>
<tr>
<td>0 (uncoated UHMWPE)</td>
<td>96.6 (0.6)</td>
<td>3.5</td>
</tr>
<tr>
<td>20</td>
<td>68.8 (0.6)</td>
<td>31.2</td>
</tr>
<tr>
<td>30</td>
<td>69.0 (0.1)</td>
<td>31.0</td>
</tr>
<tr>
<td>40</td>
<td>68.5 (0.3)</td>
<td>31.5</td>
</tr>
</tbody>
</table>

Standard deviations are displayed in parentheses; n = 4 for all deposition times. For all XPS metrics, the coated samples are not statistically distinguishable, regardless of deposition time (p > 0.05), but all coated samples are different from uncoated UHMWPE (p < 0.05).

Figure 3. The full ATR-FTIR spectra of (a) untreated UHMWPE and (b) UHMWPE plasma-treated with tetraglyme. The inset in (b) shows the primary ether peak for coatings with three deposition times: 20 min (light grey); 30 min (darker grey); and 40 min (black). The increase in ether peak area indicates that the coatings thicken with increasing deposition time.
and a low, broad hydroxyl (O–H) stretch. The ether peak enlarges as the plasma deposition time increases, confirming that the coating thickness increases with deposition time. These results confirm that coatings are predominantly PEG-like with a small amount of carbonyl, which agrees well with the XPS results. In addition, the hydroxyl stretch suggests that the coatings either contain some −OH groups or have absorbed some water from the air.

**Contact angle goniometry and protein adsorption**

Uncoated UHMWPE has a mean contact angle of 90.3°, whereas the PEG-like coatings are much more hydrophilic, with mean contact angles of 44.8° to 50.0°. The PEGylated surfaces also resist protein adsorption substantially more than uncoated UHMWPE (Fig. 4), with most areas of the coated surfaces exhibiting fluorescence levels just above the background fluorescence of uncoated UHMWPE. Although one sample deposited for 20 min adsorbed more protein than the other coated surfaces, this likely stemmed from imperfections or contamination on this individual sample as the ATR-FTIR and XPS analyses indicated that all coatings tested exhibited similar chemistry. In addition, the moderate variations in surface hydrophilicity across the coated samples did not correlate to the variations in protein adsorption (see Fig. 4). In general, the coatings resisted protein adsorption, which suggests that, in contrast to UHMWPE particles, fragments of the PEG-like coating are less likely to cause an immune response *in vivo*.

**Pin-on-disk testing: microscale and mesoscale coating tribology**

Pin-on-disk tribotesting was used to determine the conditions under which the coating could survive; survival was defined as the presence of the main ether peak at 1115 cm⁻¹ in ATR-FTIR spectra of the entire pin surface taken after the wear test ended. 21 MPa, 500 m tests were used to mimic the contact pressure found in the knee whereas 3 MPa, 2500 m tests were used to mimic the hip. Longer runs were used for the 3 MPa experiments after preliminary results indicated that the coatings readily survived shorter tests. The results are shown in Table II. No coatings survived the tests conducted at 21 MPa, regardless of coating thickness (>140, 210, and >250 nm). During the lower-pressure tests, two pairs of pins with different initial coating thicknesses (210 nm and >250 nm) were evaluated. Of the three coatings that survived, two had an initial thickness of >250 nm, and one had an initial thickness of 210 nm.

To determine the mesoscale wear mechanisms of the coatings that survived, the pins subjected to the 3 MPa, 2500 m wear tests were then examined in more detail by ATR-FTIR mapping. Instead of recording a single spectrum of the entire 2 mm diameter pin surface, ATR-FTIR mapping took spectra of 25 µm-diameter spots 37.5 µm apart over an area several hundred microns on each side. The resulting maps (Fig. 5) show the ratio of the area under the ether and hydrocarbon peaks. The ether peak derives from the PEG-like coating; the hydrocarbon

<table>
<thead>
<tr>
<th>Samples</th>
<th>Pin-On-disk conditions</th>
<th>Outcome (Measured By ATR-FTIR of Entire Pin Surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEG-like coating &gt;140 nm thick</td>
<td>Mean contact Pressure (MPa) 21</td>
<td>Coating wore off completely: 5</td>
</tr>
<tr>
<td></td>
<td>Sliding Distance (m) 500</td>
<td></td>
</tr>
<tr>
<td>PEG-like coating &gt;200 nm thick</td>
<td>Mean contact Pressure (MPa) 3</td>
<td>Coating present: 3 (2 &gt;250 nm thick, 1 210 nm thick)</td>
</tr>
<tr>
<td></td>
<td>Sliding Distance (m) 2500</td>
<td>Coating wore off completely: 1 (210 nm thick)</td>
</tr>
<tr>
<td></td>
<td>Clinical Scenario Knee</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of Pins 5</td>
<td></td>
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</table>

*Fig. 4. Protein adsorption resistance and contact angle goniometry results.* Most spots on the coated samples exhibited fluorescence levels only minimally greater than the background fluorescence of the UHMWPE substrate. Resistance to protein adsorption did not relate to surface hydrophilicity, as measured by contact angle goniometry.

![Figure 4](https://example.com/figure4.png)
peak is primarily from the UHMWPE substrate. The ratio normalizes for differences in the signal from the curvature of the ATR crystal. Maps of unworn PEG-like coatings show that the thickness of the coatings varies moderately across the surface. After pin-on-disk testing, the coatings exhibited two primary morphologies: relatively constant thickness across the mapped regions of the PEG-like layer initially 210 nm thick and wear (both smooth and rougher) combined with significant coating removal in the >250 nm thick coatings.

AFM scratching: microscale tribology

AFM was used to mimic the asperity wear behavior of the PEG-like coatings by repeatedly scratching the coatings with a sharp AFM tip (~10 nm radius) in contact mode, which produced real-time images of the wear box during scratching. The surface was nondestructively imaged after every 1–4 scratches to track the progression of surface damage. Four different coating thicknesses, ranging from 125 nm to >250 nm, were tested.

During nanoscratching, uncoated UHMWPE consistently formed ripples with an average period of ~1 μm perpendicular to the direction of wear. This behavior, which appears in Figure 6, is very similar in both appearance and period to the surface texture that develops on UHMWPE in reciprocating wear tests and hip joint simulators.2,30–32 At the microscale level, the PEG-like coatings exhibited three different damage behaviors—roughening, thinning, and deep tearing—all distinctly different from the characteristic ripples formed by uncoated UHMWPE. Individual surfaces usually failed as a result of combinations of behaviors, and all behaviors occurred in coatings of at least three different thicknesses, suggesting that they are intrinsic to the PEG-like material, rather than related to the coating thickness.

Roughening, shown in Figure 7, consisted of shallow tears on the coating surface. Most wear particles probably were not completely removed, such that there was no measurable loss of coating volume in the worn region. Roughening usually occurred early in the wear process, on samples without a lithographic defect or with a shallow/incomplete defect. In a few cases, roughening took place after successive thinning; this likely resulted from a lithographic defect that did not penetrate the full thickness of the coating, such that the coating thinned until it reached the bottom of the defect and then roughened like a defect-free surface again. Roughening could have occurred by two mechanisms—adhesive wear and microfracture. During adhesive wear, a small area of one articulating surface sticks to a small area of the countersurface, and the harder/stiffer surface pulls a particle out of the softer/less-stiff surface. During microfracture, subsurface cracks form in one material as it articulates against the countersurface. When a crack normal to the surface intersects a subsurface crack, a wear particle forms.
Thinning, shown in Figure 8, occurred when a uniform layer of material was removed from the coating surface, generating a smooth-bottomed wear box of consistent depth. In most cases, successive scratches deepened the worn area without roughening it, although deep tearing often eventually occurred in localized spots (see Fig. 9). Thinning appeared to result from an adhesive wear mechanism. The average adhesive wear factor $k$ was calculated for each of the three coatings that thinned according to Archard’s Law for adhesive wear,

$$k = \frac{V}{Lx}$$

where $V$ is the wear volume, $L$ is the normal load, and $x$ is the sliding distance. As expected, all three coatings exhibit similar wear factors, which are statistically indistinguishable ($p > 0.05$; see Table III). The high standard deviations result from the fact that the wear rate often decreased over the course of the AFM scratching experiments, possibly because the much stiffer UHMWPE substrate began to support

Figure 7. Roughening of the wear box in coatings with (c, d) and without (a, b) lithographic defects. (a): The real-time images of the contact-mode 1 μN scratch that caused the roughening in (b), the tapping-mode image of the wear box and surrounding unworn region. Superficial tearing appears throughout the scratching image and is highlighted by the arrows. (c): A very shallow lithographic defect around an unworn wear box. (d): The same wear box after 2 scratches of 1 μN. The 210 nm thick coating was produced in the same plasma deposition batch as the 210 nm thick coatings subjected to pin-on-disk testing and ATR-FTIR mapping (see Fig. 5). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 8. Successive thinning of a PEG-like coating with initial thickness >250 nm. The images were taken after (a) 2 scratches of 2 μN and (b) 4 additional 1 μN scratches. (c–e): The height distributions in the wear box plus a small area of unworn coating, outlined in red in (a) and (b). From top to bottom, the histograms correspond to images taken after (c) 2 scratches of 2 μN (image a), (d) 2 additional 1 μN scratches, (e) 2 additional 1 μN scratches (image b; 6 scratches total). This coating was produced in the same plasma deposition batch as the >250 nm surfaces subjected to pin-on-disk testing and ATR-FTIR mapping (see Fig. 5). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]
more of the load as the coating was removed, changing the effective stiffness of the system.

Deep tearing, shown in Figure 9, removed large pieces of the coating from either the entire wear box (a–c), or localized areas, producing deep wells (d–g). The localized tears often occurred at the corners of wear boxes with initial defects. This suggests a delamination mechanism, with subsurface cracks or tears intersecting the lithographic defect to liberate sections of coating over 100 nm deep and <0.5–4 μm (the full width of the wear box) long and wide.

**DISCUSSION**

The concept of lubricating the UHMWPE surface of TJRs with soft hydrophilic polymer coatings is relatively new. To date, only three other hydrogel coatings have been investigated: PEMs,¹⁷ hyaluronan,¹⁸ and MPC¹⁹. This study introduces an alternative—PEG-like coatings. Unlike all prior hydrogel coatings, these surfaces combine the strongest molecular architecture—a crosslinked network—with the strongest attachment to UHMWPE—covalent bonding. The coatings are PEG-like, with greater than 80% ether content, and they are both hydrophilic and resistant to protein adsorption. Tribological analysis determined the wear mechanisms occurring at the macro-, meso-, and microscales.

Two sets of PEG-like coatings (210 nm and >250 nm thick) were examined at all three scales. The macroscale results, which are the most clinically-relevant, were promising: the PEG-like coating survived contact pressure similar to that of total hip replacements on three of the four wear pins. The mesoscale results were somewhat surprising. The thicker coatings exhibited significant delamination—on both pins, the coating survived in places but also wore away to expose regions of bare UHMWPE hundreds of square microns in area. Microscale AFM modeling of asperity contact found that the >250 nm thick coating failed by either pure delamination or a combination of delamination and adhesive wear. A combined process would readily explain the mesoscale results.

The 210 nm coatings behaved quite differently. Only one of the two surfaces survived the 3 MPa pin-on-disk wear test, but the coating that did survive remained intact and smooth at the mesoscale, suggesting that it either thinned or did not wear at all.

<table>
<thead>
<tr>
<th>Coating Thickness (nm)</th>
<th>k (nm²/μN)</th>
<th>Number of Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>243 ± 122</td>
<td>6</td>
</tr>
<tr>
<td>&gt;140</td>
<td>196 ± 96</td>
<td>12</td>
</tr>
<tr>
<td>&gt;250</td>
<td>211 ± 102</td>
<td>5</td>
</tr>
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</table>
all. However, during AFM scratch testing, the 210 nm coating never thinned; it only delaminated. This supports the theory that the pin coating did not wear during the pin-on-disk test. It also suggests that if delamination could be delayed or prevented, perhaps by increasing covalent bonding at the UHMWPE-PEG interface (see Johnston et al.24), this coating could be appropriate for clinical use.

CONCLUSIONS

The coatings examined in this study represent the first generation of PEG-like materials evaluated as lubricious surfaces for UHMWPE in TJRs. The PEGylated surfaces are hydrophilic and resist protein adsorption. In addition, the coatings can withstand a contact pressure of 3 MPa, comparable to the loading in total hip replacements. Tribological studies of the wear behavior of the PEG-like coatings determined that they sustain damage predominantly by a combination of adhesive wear and partial or total delamination, which occurs more readily at sites with a surface defect. These results suggest a few strategies to improve coating wear resistance. To prevent delamination, the plasma deposition conditions should be altered to promote increased covalent bonding between the substrate and the coating. Second, increased crosslink density should strengthen the coating and has the potential to improve resistance to both thinning and delamination within the bulk of the PEG-like coating.

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