VALIDATION OF A CROSS-SHEAR MODEL FOR ULTRA-HIGH MOLECULAR WEIGHT POLYETHYLENE (UHMWPE) WEAR

by

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ABSTRACT

The goal of this study was to validate a novel cross-shear model for predicting wear in UHMWPE bearings of artificial joints. To complete this goal, this thesis used microscopy techniques, pin-on-disk cyclic testing, and computational methods. Scanning Electron Microscopy (SEM) was used to visualize molecular realignment during unidirectional sliding with the goal of understanding the effect this molecular movement produced on UHMWPE wear. Pin-on-disk cyclic testing was completed to understand the effect of angular changes on cross-shear wear and determine if the cross-shear model assumption of a 90° angular change producing worst-case wear was accurate. Finally validation of the model was completed by comparing wear predictions from the model against published cross-shear wear test results, including the angular pin-on-disk testing completed. The validation involved implementing the cross-shear model as both a simplified MatLab algorithm and incorporating it into a complex Finite Element analytical model.

Validation of the cross-shear model focused on two key assumptions. The model assumes an overall wear coefficient, $\bar{k}$, can be used to calculate UHMWPE wear. This overall wear coefficient is composed of a unidirectional wear coefficient, $k_0$, and a cross-shear wear coefficient, $k^*$. These wear coefficients are material properties of UHMWPE, independent of cross-shear path. Equation 1 shows this relationship with $x^*$ being the cross-shear intensity factor determined by the cross-shear path. The model also assumes the elevated wear due to cross-shear can be characterized by an incremental weight factor, $m$, which takes into account the distance over which this elevated wear occurs and the effect of the cross-shear angular path change. Equation 2 shows this relationship with $\theta_{ij} - \theta_{i-j}$ calculating the angular change in sliding path and $mem$ representing the number of sliding increments that occur during elevated wear after an abrupt angular path change. The wear model follows finite element methodology by breaking the wear surface into discretized wear surfaces with locations described by $j = 1, 2, ..., N$ and time increments as the wear surface slides along a path defined by $i = 1, 2, ..., n$.

$$\bar{k} = k_0 + k^*x^*$$  \hspace{1cm} (1)
\[ m_{ij} = \sum_{s=1}^{m_{em}} \left(1/m_{em}\right) \left| \sin(\theta_{ij} - \theta_{j-i}) \right| \quad (i > m_{em}) \]  

(2)

Results from this thesis indicate the cross-shear model produces reasonable predictions of wear rates for UHMWPE pin-on-disk testing exposed to cross-shear, but some of the model assumptions may need to be reconsidered. Pin-on-disk testing indicates elevated wear from cross-shear occurs at angles as low as 40° and does not increase significantly as this angle increases. Statistically, testing determined no difference in wear rates for the 40°, 70°, and 90° cross-shear paths. Thus, the cross-shear model will produce low estimates of wear for cross-shear paths with angular turns between 40-70 degrees.

Empirical test results from Dressler et al. (2011) indicate elevated wear after an angular turn occurs in the first 5 mm of sliding. This thesis determined this elevated wear distance, and the following wear factors, produced reasonable estimates of wear when used in the cross-shear metric. For conventional UHMWPE, a unidirectional wear factor, \( k_0 = 1*10^{-11} \text{ mm}^3/\text{N*mm} \) and a cross-shear wear factor, \( k^* = 5*10^{-9} \text{ mm}^3/\text{N*mm} \) produce reasonable estimates of wear rates. Wear rates for crosslinked materials varied based on degree of crosslinking, but computational testing indicates a unidirectional wear factor, \( k_0 = 1*10^{-12} \text{ mm}^3/\text{N*mm} \) and a cross-shear wear factor, \( k^* = 1.5*10^{-9} \text{ mm}^3/\text{N*mm} \) for crosslinked materials below 50 kGy irradiation and a cross-shear wear factor, \( k^* = 2*10^{-10} \text{ mm}^3/\text{N*mm} \) for crosslinked materials above 50 kGy irradiation produce reasonable estimates of wear rates.
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CHAPTER 1
ULTRA-HIGH MOLECULAR WEIGHT POLYETHYLENE (UHMWPE) IN ORTHOPEDIC IMPLANTS

1.1. Introduction

Joint arthroplasty is used to replace damaged, arthritic, or degenerated joints with artificial prostheses. Knee and hip arthroplasty are considered some of the most successful surgeries available because they allow someone with little to no mobility to return to a normal lifestyle. Because of the potentially life-altering aspects of arthroplasty surgery, the demand has been rising exponentially in the US [1], with an increase in surgery on younger, more active patients. This growing demand produces an ethical and business incentive to produce better designed, longer lasting implants.

Most joint implants are composed of metal components embedded into the bone, separated by a polyethylene spacer or bearing that acts as a low-friction surface during joint movement. Figure 1.1 shows an example of a knee implant and how the metal components attach to the femur and tibia. Almost all artificial joints have a similar configuration where the metal components anchor the implant into the bones surrounding the joint and an ultra-high molecular polyethylene (UHMWPE) bearing separates the metal components, providing a low-friction surface for the metal to slide against during normal joint articulation. Figure 1.2 (A) shows the components of a fixed-bearing knee implant from Stryker Orthopedics (Mahwah, New Jersey).

**Figure 1.1:** Components of a knee implant showing attachment to a femur and tibia, referenced from [2]
USA); (B) shows the components of a SBIII CHARITÉ spinal implant, and (C) shows the components of a shoulder implant from Biomet, Warsaw, IN. As can be seen from the three figures, each UHMWPE bearing is shaped to meet the needs of individual implant, and in all cases, serves as the contact surface during motion.

**Figure 1.2**: Examples of contemporary implants. (A) Scorpio posterior-stabilized total knee prostheses, reference from [3] page 98, (B) SBIII CHARITÉ spinal implant, referenced from [3] page 172, (C) Comprehensive® Biomet modular hybrid glenoid shoulder implant, referenced from [3] page 123

Since its introduction in 1962 by Sir John Charnley [4], ultra-high molecular weight polyethylene (UHMWPE) has been the bearing material of choice for knee and hip prostheses bearings [3,5]. The material has excellent mechanical and biocompatibility properties including high strength and low wear, impact and abrasion resistant, low surface friction, and an inert chemical composition [3]. Despite these excellent properties, when the metal components of an implant slide against the UHMWPE bearing, often under load, the cyclic contact produces submicron wear debris [6]. This wear debris can have an adverse effect on surrounding biological tissue, often leading to osteolysis, a condition that can cause loosening of implant components and limit the clinical lifespan of the implant [7].
1.2. The Relevance of UHMWPE Wear Debris

UHMWPE is used almost exclusively as the bearing material for hip, knee, spinal, and other artificial implants. Despite its excellent material properties, wear debris in the form of micron (≥ 1 μm) and sub-micron (< 1 μm) particles continue to limit implant performance. During normal joint kinematics, wear debris particles are generated by articulating of the UHMWPE bearing against the metallic implant. These wear particles accumulate in surrounding tissue and cause inflammatory foreign-body reactions.

The size and shape of the particulates make them susceptible to localized biological macrophage responses. Studies indicate submicron wear particles lead “to a foreign body macrophage and giant cell reaction in the periprosthetic tissue” [8]. This adverse biological reaction can produce periprosthetic osteolysis, a condition that can lead to bone resorption causing aseptic loosening of implant components [7].

This physiological tissue response has been shown to be a function of the shape, size, concentration, and morphology of the particles [9,10]. Experimental results indicate particles with “a mean size of 0.24 μm to 7.2 μm are more proinflammatory,” [11] than larger or smaller particles. The shape of these particles varies with spheroid forms being the most common.

UHMWPE wear debris has emerged as the major reason for aseptic loosening, both in hip and knee implants, often leading to failure and the need for revision surgery [12-14]. Clinical studies of removed implants have found the “concentration of wear particles within periprosthetic tissues can extend into billions per gram of tissue” [10]. To understand the origins of this wear debris and to improve implant life, UHMWPE material characteristics and morphology must be understood.

1.3. Morphology and Material Characteristics of UHMWPE Wear

Tribological assessment of UHMWPE wear is a valuable method used to understand the morphological and material characteristics of UHMWPE wear. Medical grade UHMWPE is a high molecular weight polymer with unique chemical, molecular, and mechanical properties of high strength and low wear and an inert chemical composition that is highly biocompatible [3]. UHMWPE chains arrange themselves into both an amorphous structure, where the chains are intermixed and random, and a
crystalline-like structure, where the chains fold themselves into highly organized lamellae regions. This unique combination, along with a high molecular weight, is one of the reasons UHMWPE has not been replaced as the bearing material of choice for orthopedic implants.

Under unidirectional sliding conditions, microscopy has shown UHMWPE crystalline lamellae realign themselves in the direction of sliding [15-17], as shown in Figure 1.3. This molecular realignment is theorized as the cause of increased wear during multi-directional sliding [16,18-20]. Wang et al. [15,16] theorized that repetitive linear motion across a UHMWPE surface produces molecular realignment leading to directional strain-hardening in the principle direction of sliding, thus increasing wear resistance in that direction, while conversely decreasing wear resistance in the transverse direction. The present thesis theorizes molecular movement begins immediately after an angular change in sliding direction and it is this molecular movement, not directional strain-hardening, that leads to increased UHMWPE wear. The microscopy described in Chapter 2 details the methods used to analyze this theory.

1.4. Experimental Methods Used to Measure UHMWPE Wear

Wear in UHMWPE is complex to understand due to the numerous kinematic, material, and environmental factors that influence it. Figure 1.4 shows images of worn bearings that were removed from knee implants when the implant failed [3]. By studying
these and similar failures, wear mechanisms have been attributed to abrasive wear from surface defects and foreign particles, adhesive wear from the shearing off of protruding micro-asperities, and cyclic fatigue wear due to repetitive joint movement [16,21,22].

Figure 1.4: Worn Insall-Burstein (II) and Miller-Gallante (II) tibia bearings showing pitting and delamination wear and fatigue damage to the stabilizing post of a PFC Johnson & Johnson tibia bearing, referenced from [3], pages 102 and 113

Tribological conditions like contact area, contact stress, sliding distance, surface roughness, lubrication, and multidirectional sliding motion can all influence these wear factors and are often difficult to quantify. Different test methods including pin-on-disk testing, tribological assessment, whole system wear simulators, and clinical studies have been used to characterize and understand UHMWPE wear.

Comprehensive and accurate assessments of entire implant systems is done in vitro using hydraulic joint simulators. In these machines, all implant components are tested in physiologically accurate positions, with lubrication, kinematics, and loading that mimic in vivo conditions as closely as is possible. Figure 1.5 shows an example of one of these machines used in the Biomechanics Laboratory at the University of Nebraska Medical Center. Figure 1.6 shows an example of the realistic knee wear simulator inputs obtained from gate kinematic studies that are used in these kinds of studies [23].

Figure 1.5: Example of a hydraulic joint simulator used by Dr. Hani Haider’s Biomechanics Laboratory at the University of Nebraska Medical Center
Wear simulators are a critical part of the design cycle to evaluate system designs before clinical tests begin, to screen out design issues, and to provide design feedback. They are extremely valuable, but costly and time consuming to use. For example, to complete a 5 million cycle wear test operating at 1 Hz frequency with time added in for periodic weight loss evaluations, a study using an experimental simulator will require approximately two months [23]. In addition, it is impossible for any single in vitro test to evaluate all the environmental, loading, and kinematic conditions seen in vivo.

Pin-on-disk testing, where the surface of an UHMWE pin is loaded axially and slides against a polished metal surface, is less costly and thus has been used to vary individual parameters such as lubrication types, altering cross-shear paths, or experimenting with surface roughness to understand their contribution to UHMWPE wear [4,5,15,24-27]. Although this testing does not represent the physiological environment and kinematics of UHMWPE bearings in vivo, pin-on-disk testing has been used successfully to better understand individual wear factors.

Pin-on-disk studies have been used extensively to study UHMWPE wear versus sliding path [4,5,25-27]. A number of publications report on experiments varying cross-shear path [4,5,25-29] to determine its effects on UHMWPE wear, but the author was unable to find published studies that experimented with wear versus cross-shear angular change. This area of research is important because several computational models

Figure 1.6: Typical knee wear simulator inputs for flexion angle, axial force, anterior/posterior load, and internal/external torque, referenced from [23]
assume worst-case cross-shear wear occurs after an abrupt 90° angular turn. In this thesis, as detailed in Chapter 3, pin-on-disk testing was completed to compare how different angular turns affect cross-shear wear.

1.5. Predicting UHMWPE Wear Using Computational Methods

Laboratory and clinical testing are important methods for understanding UHMWPE wear in implants, but cost, ethics, and time constraints limit the practicality and appropriateness of these approaches. Computational biomechanical analysis tools, such as finite element analysis and empirically derived wear models, provide a faster and more cost-effective method for the analysis of design variations, material properties, and wear characteristics. Although unable to model all the parameters effecting UHMWPE wear, many of these empirically derived wear models include critical parameters like cross-shear, creep, contact load, and contact area [30-32] to quantify wear.

In this thesis, analytical methods and empirical results were used to determine the parameter inputs for the cross-shear metric derived by Petrella et al. [30]. Once these parameters were determined, the cross-shear metric was validated by predicting wear in the angle testing described in Chapter 3 and comparing predictions to experimental wear data published in other pin-on-disk studies. Since the load over the surface of the pin varies with position, a Finite Element model, discussed in Chapter 4, was used to more accurately model surface pressure and edge effects from displacement. The pressure distribution from this model was then incorporated into the Petrella et al. [30] model to more accurately predict UHMWPE wear for the angle testing described in Chapter 3.

1.6. Aims of Study

The goal of the work detailed in this thesis was to validate the novel cross-shear wear model proposed by Petrella et al. [30] through experimental testing, computational analysis, and extensive review of published literature. Pin-on-disk testing was completed as a collaborative research project between Colorado School of Mines and the Biomechanics Laboratory at the University of Nebraska Medical Center. Surface profilometry, friction testing, and scanning electron microscopy was completed at Colorado School of Mines and used to visualize UHMWPE realignment after directional
sliding change. Test results were used to determine critical input parameters for the cross-shear model. Finally, validation of the cross-shear model was completed comparing empirical wear rates for different cross-shear paths with predictions from the model. The following describes the hypotheses and specific aims of this study.

1.6.1. First Hypothesis and Aim

It was hypothesized that worst-case cross-shear wear of UHMWPE will occur after an abrupt 90° angular sliding path change. This hypothesis is incorporated into cross-shear model developed by Petrella et al. [30], discussed in Chapter 4, where \( \sin(\theta_i - \theta_{i-1}) \) yields its highest value, 1, when the difference between two sliding path angles is 90 degrees. This hypothesis is in agreement with Wang et al. [15,16] and correlates well with test results from Kang et al. [28]. To validate that an abrupt 90° angular sliding path change produces worst-case cross-shear wear, pin-on-disk testing of UHMWPE crosslinked and conventional material was completed on an AMTI OrthoPOD™ machine. Testing, described in Chapter 3, consisted of pins sliding under load for a distance of 40 mm along a unidirectional path, rotating the pin with the load removed for a specific angle (each test used a different angle between 0° and 90°), and again sliding under load for 40 mm along a unidirectional path. Each test ran for 1 million cycles and during the testing, volumetric weight loss due to wear was measured every 250,000 cycles. Results from testing are discussed in Chapter 3 and compared to computational model predictions in Chapter 4.

1.6.2. Second Hypothesis and Aim

It was hypothesized that elevated wear of UHMWPE takes place during the first 3-8 mm of sliding after an abrupt angular sliding path change. After this distance, the wear rate drops back down to wear rates seen in unidirectional sliding with wear factors of the order of \( 10^{-8} \) mm³/N m [15,19,24]. Existing pin-on-disk published data for wear during repetitive square path sliding support the hypothesis that wear rate is elevated during the first 3-8 mm of sliding, after which wear returns to unidirectional wear rates. Dressler et al. [25] tested pins sliding under identical test parameters with only the square path varying (squares of 1 mm, 2 mm, 5 mm, 10 mm, and 100 mm) and found wear rate
for squares with sides longer than 10 mm remains fairly constant while wear decreases for square paths with sides smaller than 5 mm. Testing of rectangular sliding paths indicated worst case wear in paths with the smaller rectangle side between 3-5 mm and longer rectangle side between 5 – 7 mm [4,26]. Dressler et al. [27] graphically showed this elevated wear rate after cross-shear, as shown in Figure 1.7.

To estimate the distance for this high wear region, a detailed comparison of all pin-on-disk published data was completed, as detailed in Chapter 3. To validate the distance determined, computational analysis using the model developed by Petrella et al. [30] was completed, as detailed in Chapter 4.

1.6.3. Third Hypothesis and Aim

It was hypothesized that the sliding distance it takes to realign the surface layer of amorphous UHMWPE chains is the same distance that produces the worst-case cross-shear wear, described in section 1.6.2, and this molecular realignment is the cause for increased wear. To visualize molecular realignment, pin-on-disk sliding was analyzed using surface profilometry and microscopy. While published literature describes the successful use of microscopy to confirm molecular reorientation [26,33,34], to clearly visualize this phenomenon, surface etching and gold sputter coating must be used. Since surface etching would remove initial molecular realignment, only gold sputter coating was used to prove this hypothesis. Various microscopy techniques, as described in Chapter 2, were used with varying levels of success.

1.6.4. Fourth Hypothesis and Aim

It was hypothesized in the model by Petrella et al. [30], described in Chapter 4, that the UHMWPE overall wear coefficient, $k$ is composed of a wear coefficient that
represents wear due to unidirectional sliding, $k_o$, and a second material property for wear due to cross-shear, $k^*$. These two wear coefficients, $k_o$ and $k^*$, are material properties independent of wear path. Material wear coefficients $k_o$ and $k^*$ were estimated based on published literature and experimental testing. These values were verified by using the cross-shear model to predict UHMWPE wear of the angular pin-on-disk testing and wear rates from several different published literature testing with different cross-shear.

1.7. Summary

The following chapters detail the work completed to prove or disprove the hypotheses described above. Chapter 2 discusses UHMWPE material morphology and the work done to investigate if molecular realignment begins immediately after an abrupt 90° path change and if this molecular realignment effects elevated wear after the turn. Chapter 3 discusses the angular pin-on-disk testing completed to determine if worst-case cross-shear wear occurs after a 90° angular path change and how this cross-shear wear varies with smaller angular turns. Chapter 4 discusses the cross-shear metric proposed by Petrella et al. [30] and determines material properties for wear coefficients and elevated sliding distance that produces elevated cross-shear wear. These values are then used in both a simplified MatLab code and a complex Finite Element analysis to compare experimental wear rates to rates predicted by the cross-shear model. Finally, Chapter 5 summarizes the work and conclusions drawn and proposes future research areas based on unanswered questions from the work.

1.8. References Cited


Following a Change in Sliding Direction, 56th Annual Meeting of the Orthopaedic Research Society, Poster No. 2327.


CHAPTER 2
MORPHOLOGY OF ULTRA-HIGH MOLECULAR WEIGHT POLYETHYLENE (UHMWPE) ANALYZED USING MICROSCOPY

2.1 Introduction

Understanding the unique material properties of ultra-high molecular weight polyethylene (UHMWPE) and why these properties make it the material of choice for bearings in joint implants is critical to the understanding of how these bearings wear and fail. In this chapter, the material properties of UHMWPE are discussed with a focus on where this high molecular weight polymer has superior performance and where issues arise. After a discussion on both conventional and crosslinked UHMWPE, the reader is introduced to electron scanning microscopy and how this technology has been used to understand the mixed amorphous/crystalline structure of UHMWPE and to visualize molecular reorientation that occurs during unidirectional sliding.

In this thesis, a Field Emission Scanning Electron Microscope (FESEM) was used to analyze the wear surface of GUR 1050 UHMWPE pins, the same material pins used in the pin-on-disk testing described in Chapter 3. There is a discussion covering all testing completed and an explanation on why this technology proved inadequate in supporting the thesis hypothesis that the sliding distance it takes to realign the surface layer of amorphous UHMWPE chains is the same distance that produces the worst-case cross-shear wear, and this molecular realignment is the cause for increased wear.

2.2 Properties of Ultra-high Molecular Weight Polyethylene (UHMWPE)

Ultra-high molecular weight polyethylene (UHMWPE) has a unique combination of chemical, molecular, and mechanical properties, making it an ideal material for bearings in joint replacements [1,2]. Medical grade UHMWPE has high strength and low wear, is impact and abrasion resistant, has low surface friction, and has an inert chemical composition that is highly biocompatible [3]. Despite these excellent material properties, due to the release of micron and sub-micron sized UHMWPE wear particles into surrounding tissue during normal joint articulation, wear of implants continues to elicit clinical concern.
UHMWPE is a high molecular weight polymer (molecular weight exceeds $1 \times 10^6$ g/mole [4]) consisting of hydrogen (H) atoms extending from a carbon (C) backbone [3], as shown in Figure 2.1. In this figure, $C_2H_4$ is the ethylene group that makes up a single monomer, and the small n indicates UHMWPE is a repeating microstructure that combines with other ethylene monomers to form a polyethylene polymer chain. UHMWPE consists of hundreds of thousands of monomers attached with covalent bonds that form into a long linear chain. Each covalent bond is 109.5° to the next, as shown in Figure 2.2, causing the polymer chain to twist along its length, entangling itself with neighboring chains, but under stress, these twists can unkink and the molecules can elongate and align [5].

On a nanometer scale, UHMWPE is a two-phase viscoelastic semicrystalline composite [4]. The long polymer chains form into both an amorphous structure, where they are entangled with each other in a random arrangement, and a crystalline structure, where they fold themselves into highly organized crystalline units, called orthorhombic unit cells. Individual unit cells are approximately 0.255 nm x 0.494 nm x 0.741 nm in size [5], and when joined together, they form thick crystalline lamellae.

Medical grade UHMWPE contains a mixture of both amorphous and crystalline structures, as shown in Figure 2.3, with typically around 50% crystalline lamellae, although this percentage can vary based on manufacturing and post-processing methods. The degree of crystallinity can strongly influence

**Figure 2.1:** Chemical composition of a single polyethylene monomer, referenced from [3]

**Figure 2.2:** Fully extended polyethylene chain showing “sawtooth” geometry and relative size of hydrogen and carbon atoms, referenced from [5]

**Figure 2.3:** Amorphous and crystalline structure of UHMWPE, referenced from [6]
UHMWPE morphology and material properties [7], as shown in Table 2.1, but variations of crystallinity typically seen in medical grade UHMWPE are minor.

**Table 2.1:** Mechanical properties of UHMWPE varying with crystallinity, referenced from [7]

<table>
<thead>
<tr>
<th>Crystallinity ±3%</th>
<th>Tensile Modulus (MPa)</th>
<th>Yield Stress (MPa)</th>
<th>Ultimate Tensile Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48.3 %</td>
<td>225.2 ± 26.4</td>
<td>19.4 ±0.4</td>
<td>55.4±1.7</td>
</tr>
<tr>
<td>52.0 %</td>
<td>267.8 ± 26.0</td>
<td>19.2 ±0.1</td>
<td>49.1±0.7</td>
</tr>
<tr>
<td>45.9 %</td>
<td>255.0 ± 28.1</td>
<td>19.1 ±0.3</td>
<td>44.6±1.2</td>
</tr>
<tr>
<td>42.9%</td>
<td>227.3 ± 10.2</td>
<td>18.5 ±0.1</td>
<td>59.0±1.7</td>
</tr>
<tr>
<td>34.6%</td>
<td>186.0 ± 14.8</td>
<td>16.6 ±0.1</td>
<td>47.2±0.7</td>
</tr>
</tbody>
</table>

Low voltage scanning electron microscopy (SEM) and small-angle X-ray scattering were used to visualize and characterize the mixed amorphous/crystalline structure of UHMWPE. The crystalline lamellae range in thickness from 10-50 nm with a length between 10-50 μm and a typical distance between adjacent lamellae of approximately 50 nm [7]. Typically, UHMWPE crystalline lamellae are oriented randomly in the amorphous structure. Figure 2.4 shows how crystalline lamellae appear as branched structures surrounded by non-distinct amorphous regions. This picture was taken after the sample was etched for six hours with chlorosulfonic acid and stained with uranyl acetate [8].

The unique polymer structure and mixed amorphous/crystalline organization gives UHMWPE outstanding physical and mechanical properties, chemical inertness, natural lubricity, and resistance to both impact and abrasion. The high molecular weight compared to standard polyethylene, typically 2-6 million [3], has been shown to improve wear resistance [9] and the string-like chains contribute to its unique wear characteristics. At the same time, the polymer material has viscoelastic-plastic characteristics which produce a time dependent stress-strain relationship.
response and observable creep [10].

Chains of conventional UHMWPE have strong, covalent bonding between the individual monomers in the chain and weaker van der Waals bonding between adjacent chains. Deformation in conventional UHMWPE occurs when molecules slip past each other, breaking the weaker van der Waal bonds rather than the intermolecular covalent bonds [11]. This molecular movement produces plastic deformation of UHMWPE as the molecules rearrange themselves and adjust to external stress and energy. For example, in a manufacturing gel spinning processes, hot drawing polyethylene molecules through high draw ratios causes molecular chain elongation and slippage, causing polyethylene chains to realign themselves in the direction they are being drawn, producing a superior strength fiber with a high degree of molecular orientation [12].

When used in implant bearings, the microstructure and mechanical properties are affected by the manufacturing process [13]. Unlike most polymers, UHMWPE does not undergo a flow transition at higher temperatures because of the entanglement of its polymer chains [3] and thus thermoplastic processing techniques like injection molding or screw extrusion are not practical. Therefore, most UHMWPE bearings are fabricated from powder that is ram extruded into rods or compression molded into sheets and then machined into the desired shape [3,14,15]. One study using small-angle x-ray scattering analysis showed that “the orientation of crystalline lamellae in the ram extruded UHMWPE rod stock varied along the radial direction of cross-section of the rod” [13] and testing of these extruded rod stock resulted in wear that both depended on the radial location of the sample tested and the orientation of the crystalline lamellae.

Conventional HMWPE is a homopolymer, meaning it is a single, long polymeric chain with hydrogen (H) atoms attached to a carbon (C) backbone, but when conventional UHMWPE is exposed to ionizing radiation, the C-H and C-C bonds break apart, forming free radicals that recombine to form crosslinks, or branches [3]. These new monomer combinations link long polyethylene chains together, forming a lattice structure, as shown in Figure 2.5. Crosslinked UHMWPE exposed to

![Figure 2.5: Loosely crosslinked UHMWPE chains, referenced from [6]](image-url)
radiation doses between 10 kGy (1 MRad) to 50 kGy (5 MRad) have shown an 83-85% reduction in wear [16] and higher radiation doses up to 100 kGy (10 MRad), have shown an almost 98% reduction in pin-on-disk wear [17] in addition to improved creep resistance. Testing of crosslinked UHMWPE shows an increase in the material’s modulus of elasticity, impact resistance, and rigidity [5,18], but also shows reductions in ductility, fatigue, fracture resistance, and ultimate tensile and yield strength [18], as shown in Table 2.2. Despite these drawbacks, limited crosslinking (between 50 and 100 kGy) is now standard in most hip and knee implant bearings [3,19] because of the reduction of wear particles produced from the material.

### Table 2.2: Effect of crosslinking on material properties of GUR1020 and 1050 resin as reported by Sobieraj and Rimnac, reproduced from [18].

<table>
<thead>
<tr>
<th>Dose</th>
<th>Irradiation</th>
<th>GUR resin</th>
<th>Sheet or Bar</th>
<th>Yield strength (MPa)</th>
<th>Ultimate tensile stress (MPa)</th>
<th>Elongation at break (%)</th>
<th>Izod impact (kJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>None</td>
<td>1020 Sheet</td>
<td>23.6 ± 0.1</td>
<td>42.1 ± 0.7</td>
<td>396 ± 10</td>
<td>101.3 ± 1.9</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>μ</td>
<td>1050 Sheet</td>
<td>23.6 ± 0.1</td>
<td>37.2 ± 6.4</td>
<td>376 ± 52</td>
<td>130.5 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>μ</td>
<td>1020 Sheet</td>
<td>22.5 ± 0.1</td>
<td>43.8 ± 3.5</td>
<td>358 ± 20</td>
<td>93.7 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>γ</td>
<td>1050 Sheet</td>
<td>22.3 ± 0.4</td>
<td>40.0 ± 5.0</td>
<td>353 ± 33</td>
<td>97.9 ± 2.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td>1050 Bar</td>
<td>20.4 ± 0.1</td>
<td>36.7 ± 5.8</td>
<td>284 ± 49</td>
<td>90.1 ± 1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td>1020 Bar</td>
<td>21.0 ± 0.1</td>
<td>43.6 ± 6.8</td>
<td>340 ± 32</td>
<td>86.8 ± 1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td>1020 Bar</td>
<td>21.3 ± 0.0</td>
<td>41.6 ± 3.7</td>
<td>315 ± 18</td>
<td>87.4 ± 3.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td>1050 Bar</td>
<td>22.5 ± 0.2</td>
<td>45.3 ± 5.0</td>
<td>336 ± 24</td>
<td>88.1 ± 1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>γ</td>
<td>1020 Bar</td>
<td>21.1 ± 0.2</td>
<td>36.7 ± 0.7</td>
<td>279 ± 5</td>
<td>74.6 ± 2.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>γ</td>
<td>1020 Bar</td>
<td>35.4 ± 0.8</td>
<td>278 ± 8</td>
<td>74.3 ± 1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td>1050 Bar</td>
<td>20.4 ± 0.1</td>
<td>36.9 ± 3.8</td>
<td>264 ± 15</td>
<td>73.3 ± 1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td>1050 Bar</td>
<td>21.2 ± 0.2</td>
<td>39.5 ± 3.1</td>
<td>276 ± 21</td>
<td>70.6 ± 1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td>1050 Bar</td>
<td>20.1 ± 0.1</td>
<td>33.2 ± 1.2</td>
<td>247 ± 5</td>
<td>73.0 ± 1.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>γ</td>
<td>1020 Bar</td>
<td>20.6 ± 0.1</td>
<td>31.6 ± 1.0</td>
<td>243 ± 8</td>
<td>72.0 ± 0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>γ</td>
<td>1020 Bar</td>
<td>21.4 ± 0.1</td>
<td>33.3 ± 1.7</td>
<td>212 ± 7</td>
<td>56.7 ± 0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td>1050 Bar</td>
<td>21.3 ± 0.3</td>
<td>31.1 ± 2.1</td>
<td>215 ± 9</td>
<td>59.6 ± 1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td>1050 Bar</td>
<td>20.6 ± 0.2</td>
<td>34.1 ± 4.0</td>
<td>209 ± 15</td>
<td>60.9 ± 2.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td>1050 Bar</td>
<td>21.2 ± 0.2</td>
<td>36.6 ± 3.2</td>
<td>227 ± 14</td>
<td>57.5 ± 2.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>γ</td>
<td>1050 Sheet</td>
<td>20.6 ± 0.1</td>
<td>30.2 ± 1.6</td>
<td>188 ± 7</td>
<td>49.9 ± 1.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>γ</td>
<td>1050 Sheet</td>
<td>21.0 ± 0.1</td>
<td>29.2 ± 1.0</td>
<td>185 ± 5</td>
<td>51.4 ± 0.6</td>
<td></td>
</tr>
</tbody>
</table>

Numerous chemical and process-related alterations have been explored to improve UHMWPE wear characteristics including increasing crystalline content and incorporating various fillers like kaolin, quartz, hydroxyapatite, Al-Cu-Fe powder, short carbon fibers, carbon nanotubes, and carbon nanofibers [20]. Most of these have been found to improve a specific characteristic at the cost of another, for example carbon fiber reinforcement increases creep resistance but compromises the articulating surface friction coefficient [4].
2.3 Scanning Electron Microscopy (SEM)

Microscopy has been used to study UHMWPE to help clarify morphological changes due to wear. Traditional reflected light microscopes and polarized light microscopy have been used to study surface defects, cracking, and subsurface shear strains [9], but this technology is limited to a resolution around 0.2 μm [21]. Scanning Electron Microscopy (SEM) increase resolution to 2-10 nm but unfortunately this resolution drops significantly with non-conductive materials [21]. Non-conductive materials like UHMWPE tend to gather a surface charge from the electron beam, causing scanning faults. Field emission scanning electron microscopes (FESEM) place the sample in an ultra-high vacuum chamber which allows for lower accelerating voltage ranges (0.5 -2 kV are common) and thus reduces negative charge buildup on non-conductive specimen surfaces. Despite the ultra-high vacuum, clear images showing UHMWPE crystalline lamellae reorientation usually require altering the surface through some type of etching process (permanganate, argon plasma), and sputter-coating the surface with a conductive material (gold or gold-palladium) [7,22]. Transmission electron microscopes (TEM) improve resolution to between 0.1 – 1 nm, but require the sample under investigation to be sliced into very thin, electron-transparent samples [21], making it unusable for pin-on-disk cross-shear testing where the surface of the pin must remain intact.

A scanning electron microscope (SEM) bombards the surface of a sample material with a high energy beam of electrons and uses the electrons scattered from the material’s surface to form a high-resolution image of the sample’s surface. The output from SEM imaging contains information about the surface topography and material compositional contrast. Magnification resolution is typically between 20x to 50,000x with a depth of field factor of about 300 [23]. Consequently, electron microscopy has become a powerful tool to better understand UHMWPE morphology and wear, especially crystalline lamellae reorientation after unidirectional sliding.

2.4 Molecular Reorientation After Unidirectional Sliding

In the 1970’s, Pooley et al. [24] and Tanaka et al. [25] studied molecular orientation of PTFE-based composites sliding unidirectionally against metal and glass
surfaces. Their results showed molecular polymer reorientation along the sliding direction. Later, Minn et al. [26] studied molecular orientation, crystallinity, and changes in friction for a UHMWPE film sliding against a silicon nitride ball. Their results indicate “during the initial sliding process the molecules on the top layer of the film get plastically deformed and oriented in the direction of sliding” [26]. Using Field Emission Scanning Electron Microscopy (FESEM) techniques, as shown in Figure 2.6, this study showed how the surface morphology changed and aligned with sliding direction as the number of unidirectional sliding cycles increased. Although Minn et al. [26] was able to demonstrate molecular reorientation after significant unidirectional sliding, the study could not identify molecular realignment during initial sliding, as seen in Figure 2.6 (b).

Further research used microscopy to verify this molecular realignment during multi-directional or cross-shear sliding [13,27,28] to try and understand its importance in UHMWPE wear. Korduba et al. [29] used SEM to compare the surface morphology and molecular realignment of conventional UHMWPE pins exposed to rectangular cross-shear paths that ranged from 5 mm x 5 mm square to varying aspect ratio rectangles, including a linear sliding path used as a control. Figure 2.7 shows how the more linear motion paths have crystalline lamellae that have reoriented in the direction of sliding.
It has been theorized that molecular realignment is one of the main reasons that cross-shear sliding, or sliding perpendicular to the realigned direction, significantly increases UHMWPE wear [28,30-32]. Scanning Electron Microscopy (SEM) and tribological friction testing have helped visualize this unusual phenomenon, but a precise molecular understanding of how molecular reorientation effects UHMWPE wear is still under investigation.

2.5 Experimental Methods and Results

Testing was completed as a collaborative effort that included the Colorado School of Mines Metallurgical & Materials Engineering Department, the Biomechanics Laboratory at the University of Nebraska Medical Center (UNMC), and the author. The Biomechanics Laboratory at the University of Nebraska Medical Center (UNMC) provided six pins, three machined from ram extruded rods of conventional GUR 1050 UHMWPE and three from gamma irradiated GUR 1050 (95.7 kGy). The pins were machined from the same bar stock used in the pin-on-disk testing described in Chapter 3. The raw material was generously donated by Orthoplastics Limited of Lancashire England. Material data sheets have been reproduced in Appendix A.

Figure 2.7: SEM micrographs with a scale bar of 1 \( \mu \)m comparing molecular reorientation in square and rectangular sliding paths, referenced from [29]
Visualization and characterization of all conventional pin surfaces was completed on a JEOL JSM-7000F Field Emission Scanning Electron Microscope (FESEM), pictured in Figure 2.8.

Initial visualization, using a working distance of 4.0 mm and operating at 1.0kV was completed to confirm no noticeable defects in the surface of the pins, as shown in Figure 2.9. This initial visualization showed surface morphology indicative of a machined surface with machining marks clearly visible.

After initial visualization, conventional UHMWPE pins were mounted in a TEER ST2200 Scratch and Wear Tester and translated unidirectionally for 40 mm under a 20 N load against a polished #8 finish stainless steel substrate (Ra between 0.08-0.19 microns). The loading was lower than planned due to limitations in the TEER tester. The first pin was exposed to 5234 cycles for a total unidirectional sliding distance of 209 m. The
second pin experienced 20 cycles for a total unidirectional sliding distance of 0.8 m. A third pin was not translated and used as a control. The goal of this initial test was to confirm molecular reorientation could be observed on the first pin (with the sliding distance of 209 m) and to determine if molecular reorientation was observable after the shorter, .8 m sliding distance.

After translation, the pin surfaces were sputter coated with gold using a Hummer VI sputter system. Pins were placed in a vacuum environment below 100 torr and coated for 30 seconds at 15 milliamps, as shown in Figure 2.10.

After sputter coating, pin surfaces were once again characterized using FESEM operating at 2kV and a working distance of 4.0 mm. Figure 2.11 shows the surface of the pins, each image with a scale of 100 μm in the right corner, allowing the visualization of most of the surface exposed to sliding. As can be seen from the figure, the machining marks are still clearly visible on all surfaces and there is no clear difference between the surfaces exposed to unidirectional sliding and the control surface. Figure 2.12 shows three microscopic views of the pin’s surfaces after unidirectional sliding, each image with a scale of 1 μm in the right corner, indicating surface defects from machining have not been worn down. Surface morphology showing crystal lamellae, like that shown by Korduba et al. [29] in Figure 2.7, were not visible.
Because molecular reorientation was not visible, a renewed search of published literature was undertaken. The author found that all published microscopy studies examined \[7,8,14,15,24,26,29,31,33\] used SEM, TEM, and AFM to document and visualize crystal lamellae reorientation after extended unidirectional sliding, not amorphous chain realignment. This thesis hypothesized initial molecular realignment of the UHMWPE would first occur in the more mobile amorphous chains on the surface, not the crystal lamellae which are much larger than the random amorphous chains. This raised questions about the viability of using SEM technology to visualize reorientation of UHMWPE amorphous chains.

Figure 2.13 shows a low voltage SEM image of an UHMWP surface that has been etched to reveal the crystal lamellae structure. The non-distinct dark regions surrounding the crystal lamellae are the amorphous chains. Electron microscopy enables clear visualization of lamellae orientation because of its distinct topological characteristics, but gives no clear detail about the amorphous regions. In addition, to produce images like the one shown in
Figure 2.1, the surface must both be etched and gold sputter-coated. Acidic etching “preferentially etches the amorphous part of the polymer” [33], removing amorphous chains on the surface. Finally, because of the non-conductive nature of UHMWPE, gold sputter coating of the surface is needed to obtain clear FESEM images without errors from charge buildup. Initial molecular reorientation on the scale occurring during the first few millimeters of cross-shear sliding would be masked by this additional material layer.

Because of these reasons, it was determined that electron microscopy technology would not be adequate to visualize whether or not molecular realignment occurs during the first 3-8 mm of sliding after an abrupt angular path change. Therefore, testing in this area was discontinued.

2.6 Discussion

Understanding the material and morphological changes occurring due to UHMWPE wear is difficult because of the complex amorphous and crystalline structure of the polymer and the “evolving micro-mechanical state due to applied external loads” [34]. These microscopic changes are attributed to adhesive, abrasive, third-body, and fatigue wear [35] at the microscopic level during the normal kinematics seen in the UHMWPE bearings of knee, hip, spine, and other implants. Microscopy has shown crystalline lamellae reorientation after extended unidirectional sliding [26,28,29] and pin-on-disk testing has shown multidirectional sliding, or cross-shear, a major contributor to wear in UHMWPE [13,27-29]. Cross-shear testing demonstrates a significant increase in wear occurring in an “elevated wear zone” during the first 3-8 mm after a change in sliding direction [29,30,36,37], but a clear, molecular understanding on why this elevated wear zone occurs was not found.

Microscopy has become a useful tool to visualize and quantify molecular realignment, especially crystalline lamellae realignment after significant unidirectional sliding, but visualization of amorphous regions of UHMWPE is more complicated. It has been theorized that molecular realignment plays a role in the increased wear seen after cross-shear [15,28,30] but the author of this thesis was unable to locate research that validated if molecular realignment, specifically amorphous UHMWPE chains, realign
immediately, during initial elevated wear, or gradually, after significant unidirectional sliding. The difficulty of visualizing this amorphous molecular realignment is due to several factors including the non-conductive nature of UHMWPE making it more difficult to analyze in an electron microscope, and the size of individual UHMWPE chains.

SEM can and has produced interesting images of UHMWPE lamellae structure and reorientation [7,8,26] and has also provided visualization of micro-wear patterns [38], but despite these advances, the technology is not able to produce images which visualize reorientation of individual amorphous chains during initial cross-shear sliding. Due to the non-conductive nature of UHMWPE, surfaces must be sputter-coated with a conductive material such as gold which produces excellent visualization of surface morphology at scales similar to those in Figure 2.11 and 2.12, but when magnification is increased an order of magnitude, as seen in Figure 2.14, the gold coating acts like a ‘blanket of snow’ and interferes with clear visualization of finer molecular structure. In addition, according to Dr. Chandler, an expert on FESEM images at the Colorado School of Mines, the lines and cracking in the image (shown by arrows) are actually a cracking of the gold coat due to distortion of the UHMWPE surface caused by heating of the surface from the electron beam. This surface movement ‘breaks’ the smooth gold coating, further reducing visibility of fine features. Because of these defects, this thesis feels that FESEM technology cannot be used to identify amorphous molecular realignment during the first 3-8 mm of cross-shear sliding.

![Figure 2.14: Conventional UHMWPE pin surface image with a gold sputter coat and a corner scale of 100 nm](image)
Several researchers have hypothesized molecular realignment plays a large role in elevated wear from cross-shear [15,28,30]. Sobieraj et al. [15] reported lamellar alignment “within the subsurface damage layers of retrieved UHMWPE joint replacement components” and theorized molecular realignment occurs in the first 4-9 μm below the wear surface, as shown in Figure 2.15. Wang et al. [30] theorized that unidirectional sliding induced UHMWPE strings to reorient along the axis of sliding and produced directional strain-hardening in the principle direction of sliding, thus increasing wear resistance, but conversely, decreasing wear in the transverse direction. Finally, Minn et al. [26] theorized that the surface molecular chains become plastically deformed and reorient in the direction of principle sliding.

Wang’s theory [30] on directional strain-hardening assumes a ‘stress-induced anisotropy’ caused by molecular realignment during unidirectional sliding. This theory does an excellent job of explaining low wear during unidirectional sliding. During cross-shear, Wang [30] theorizes “rupture or splitting of the oriented molecules in the perpendicular direction” which assumes wear occurs before molecular reorientation begins in the new direction of sliding. This leaves molecular reorientation to occur.
during the low wear rates seen in unidirectional sliding and indicates the molecular movement has little effect on wear. The theory proposed by the author, that molecular realignment on the wear surface occurs during the elevated wear distance after an abrupt angular path change and this molecular movement is the cause of the elevated wear was neither supported nor disputed via FESEM analysis. Future research is needed to better understand this UHMWPE plastic flow and the effect it has on wear.

2.7 Conclusion

This study attempted to use FESEM techniques to understand and quantify molecular reorientation in the first 3-8 mm of sliding after a 90° angular change in order to understand why experimental results demonstrate increased wear during this sliding distance. By visualizing when molecular reorientation begins, it was hoped a better understanding of the mechanisms of wear could be obtained. Although the study was unable to identify successfully when molecular realignment begins, through the literature review, a clearer understanding of material morphology and its effect on wear has been obtained. The hypothesis of molecular realignment within the first 2-8 mm of cross-shear sliding is still plausible, but proving it will require testing and technologies not considered in this thesis.

2.8 Acknowledgements

The author would like to thank David Lusk from the University of Nebraska Medical Center Biomechanics Laboratory for machining the pins and John Jezek from Colorado School of Mines for assistance machining the pin holders. A special thanks to Dr. Jianliang Lin for assistance with unidirectional pin testing, Dr. John Chandler and Gary Zito for instruction and assistance in the Colorado School of Mines Electron Microscopy Laboratory, and Colorado School of Mines PhD student Grant Hudish for reviewing the chapter for accuracy.

2.9 References Cited


Following a Change in Sliding Direction, 56th Annual Meeting of the Orthopaedic Research Society, Poster No. 2327.


3.1 Introduction

Quantifying wear of UHMWPE bearings used in implants is difficult because of the complex interaction between the numerous factors affecting wear. Literature has attributed UHMWPE wear to abrasive wear from surface scratches and foreign particles that cut and plough the UHMWPE surface, adhesive wear from microscopic asperities on the UHMWPE surface plastically shearing when they contact the harder metallic surface asperities, and fatigue wear due to cyclic loading conditions [1-4]. Wear from any single mechanism is rare due to the complexity of joint kinematics and the varied tribological conditions experienced by implants [5]. Tribological conditions such as contact area, contact stress, sliding distance, surface roughness, lubrication, cross-shear motion, contact angle, and material properties all affect wear rates. In addition, experimental methods, manufacturing processes, and surgical factors can also contribute to UHMWPE wear. To accurately understand UHMWPE wear, each of these factors must be understood.

In the early 1950’s, Archard [6] published a wear theory for a deformable material sliding unidirectionally under pressure against a flat, non-deformable material. Archard’s experimental results indicated that wear of the deformable material was proportional to contact pressure and sliding distance. Archard theorized that the contact area between contacting surfaces was limited to protruding asperities on the surface of the deformable material and these asperities increased in both number and size (radius) as contact pressure increased [6]. For many years, Archard’s testing and results were used to quantify the wear of UHMWPE bearings sliding against Cobalt-Chromium, the materials used in most joint replacement hardware.

Failure of joint replacement implants due to molecular wear particles spurred additional research and in 1982 Robert Fusaro published a paper examining the effect of sliding speed and contact stress on the tribological properties of UHMWPE [7]. In Fusaro’s study, surface wear morphology was observed using optical microscopy and surface profilometry. He found the coefficient of friction increased with sliding speed.
and sliding distance [7], concluding wear rate did not depend on sliding speed, but wear mechanisms changed from an adhesive wear to a fatigue-like wear process with longer sliding distances. One of the interesting observations made by Fusaro was “the UHMWPE material appears to have flowed across the rider contact area,” [7]. This observation led to later theories of molecular movement and realignment, as previously discussed in Chapter 2.

Early wear tests were conducted with unidirectional sliding paths and direct contact between surfaces. These tests showed the development of a thin UHMWPE transfer film deposited on the counterface surface that effected wear. A UHMWPE transfer film was not observed in clinically removed inserts and it was hypothesized this was due to the synovial fluid, a naturally occurring protein-based lubricant separating insert components [8]. This discovery caused laboratory testing to change from direct contact sliding to lubricated sliding using a protein-based lubrication such as bovine serum. Wang et al. investigated lubrication protein concentration’s effect on UHMWPE wear rate and concluded, “a slight increase in protein concentration in the lubricant resulted in a drastic increase in wear rate” with the wear rate peaking at a protein content between 10 and 30 mg/ml, the typical range of protein content found naturally in synovial fluids in joints” [2].

Unfortunately, during extended cyclic testing, protein-based lubrications have been observed to form a solid precipitate which can lodge between the sliding surfaces and act like third-body debris. Third-body debris, or debris formed from materials independent of the UHMWPE bearing and Co-Cr insert, have been shown to be a concern in clinical studies where loose particulates of bone and bone cement have been found embedded in the UHMWPE bearing surface [8]. This third-body debris can produce scratching on the surface of the Co-Cr polished surface, which leads to additional wear issues.

In 1993, Cooper et al. determined the roughness of the counterface, the surface finish of the Co-Cr insert sliding against the UHMWPE bearing, was an important factor affecting wear and that a “single defect in the counterface can also cause a dramatic increase in the wear” [9]. Wang et al. [2] reported a 50 fold increase in wear resulting from increasing the average counterface surface roughness from 0.01 μm to 0.10 μm.
This increased wear is attributed to surface-to-surface contact between the two materials as asperity contact increases.

The studies by Cooper et al. [9] and Wang et al. [2] showed how surface defects on the polished Co-Cr counterface increased wear, yet despite these findings, clinically retrieved hip implants showed high clinical wear rates “not only on components that showed gross damage or extensive scratching, but also on components that exhibited excellent surface finish, i.e. polishing” [2, 10,11]. Other wear mechanisms beside surface finish were obviously at work.

Because increased asperity contact occurs both with increased surface pressure and increased contact area, experimentation to understand and separate the effect on wear from each of these parameters was completed [12-16]. Surprisingly, correlation between wear and contact pressure has yielded varied results. As would be expected, several pin-on-disk and implant studies reported that as contact pressure rose, so too did the wear rate [12,13], but a surprising number of studies did not confirm this finding [14-16]. Instead, these studies found either a weak correlation or no correlation between contact pressures and wear. This result brings into question the accuracy of using Archard’s Law, which is based on contact pressure, as a model to predict wear.

In contrast to the results on varying surface pressure, experimental results show strong correlation between wear and contact area with increased contact area causing increased wear [2,15-17]. Figure 3.1 shows a reproduction of the data reported by Ernsberger et al. [16]. In this study, pin-on-disk wear testing was completed on conventional UHMWPE pins with diameters varying from 2.97 – 8.4 mm and

![Figure 3.1](image-url)
loads varying between 69 – 208 N. All pins slid along a 10 mm square path. The results indicate a direct correlation between increased surface area and increased wear.

By the mid-to-late 1990’s, several studies published pioneering work on the effect of multidirectional sliding or cross-shear motion on UHMWPE wear [18-23]. These studies determined that UHMWPE wear was sliding path dependent and that wear significantly increased after an abrupt angular change in sliding path. This discovery was a major breakthrough, both in understanding wear and predicting it. Including repetitive, multi-directional sliding, or cross-shear, as seen in normal joint kinematics, in laboratory experimentation produced wear rates comparable to those observed in failed orthopedic implants [3,23-25].

Other factors affect wear including the material, morphological, and manufacturing conditions discussed in Chapter 2 and surgical techniques which are beyond the scope of this work. Due to the numerous complex factors influencing UHMWPE wear, simplified pin-on-disk testing is often used to quantify individual wear factors.

3.2 Pin-on-Disk Testing of UHMWPE Wear

Pin-on-disk testing utilizes a UHMWPE pin with a flat end pressed under load against a flat, polished Cobalt-Chromium disk such that the bottom surface of the pin slides against the top surface of the disk. This sliding motion follows a pre-determined path where often other parameters (load, lubrication, counterface roughness, etc.) are held constant. The sliding motion is repeated cyclically for anywhere from 10,000 cycles to several million, depending on the intent of the test. Hip and knee implants see millions of cycles of repetitive motion paths during daily walking, but time constraints usually limit the number of cycles in a test. To reduce error from lubrication precipitates, the testing is interrupted regularly to measure gravimetric weight loss and refresh lubrication.

Significant pin-on-disk testing published in the literature, including the work documented in this thesis, was completed using an AMTI Ortho-POD™ Friction and Wear Testing Machine [26] as shown in Figure 3.2. The Ortho-POD™ is a six-station pin-on-disk machine that can provide suitable test motions, environments, and loads to produce wear rates similar to those encountered in physiologically correct testers. The
machine has three independent servo-controlled motions corresponding to the pin rotary motion, the plate with the disks rotary motion, and a normal load on the six pins [26].

Pin-on-disk testing has been criticized because it does not reproduce accurately the kinematic contact conditions seen by implant components. Kinematic contact of the UHMWPE bearings used in knee and hip implants includes gliding, rolling, and sliding. Cornwall et al. [27] defined gliding as the UHMWPE bearing sliding over a stationary Co-Cr insert, rolling is defined as rotating contact of the Co-Cr insert over a stationary UHMWPE bearing, and sliding as the Co-Cr insert sliding over a stationary UHMWPE bearing. Figure 3.3 shows test results reported by Cornwall et al. [27] while testing crosslinked Chirulen® sliding and gliding across polished Co-Cr disks or rolling with a Co-Cr roller. As can be seen from the figure, worst-case wear occurs during rolling and gliding. Pin-on-disk testing is usually a combination of gliding as the disk slides under the pin and sliding as the pin rotates around an axis over the disk, but rolling motion cannot be tested.

Despite this issue, numerous pin-on-disk studies have generated test results quantifying wear versus a specific wear parameter, especially multi-directional sliding paths.

Turell et al. [28] completed repetitive pin-on-disk testing of conventional UHMWPE rods sliding along identical, 20mm long tracks, but with paths that varied

Figure 3.3: Comparison of UHMWPE wear from sliding, gliding, and rolling. Sliding has been broken down into A, standard sliding with a flat-surfaced pin and B, sliding with a rounded pin, referenced from [27]
from a straight line, to rectangles of different aspect ratios, to a square. Examples of these paths are shown in Figure 3.4. Results from this testing indicated that for identical loading and sliding path distances, the highest volumetric wear occurred with a 3mm x 7mm rectangular path [28]. Korduba et al. [29] repeated this testing for both conventional and crosslinked UHMWPE. The wear results from Korduba correlate well with Turell’s, although the Korduba study found peak wear for conventional UHMWPE occurred with the 2 mm x 8 mm rectangular path. Mazzucco and Spector [15] focused on the effect of contact area and stress on volumetric wear, discovering for the same 10 mm x 10 mm path and identical loading conditions, variations in lubrication replenishment protocol significantly affected wear.

Dressler et al. [22] used two types of crosslinked UHMWPE, GVF with a lower crosslinked value and XLX with a higher value, and completed pin-on-disk testing with pins following various sized square paths under constant load. Dressler’s study reported varying wear rates after an abrupt 90° sliding path change with the wear reducing nonlinearly for the first 5 mm of sliding after the turn. Wear rates for squares with sides larger than 5 mm plateaued for both types of materials tested, indicating a constant wear rate for sliding a set distance after the abrupt angular change. Dressler et al. [22] theorized that after the abrupt angular change in sliding, the wear rate rapidly transitions from a maximum value to a minimum value approaching a unidirectional sliding wear rate level. Figure 3.5 compares wear rates from this study normalized to path length, number of turns, and cumulative sliding distance. Wear rate normalized by cumulative sliding distance decreases for both materials as sliding distance increases, supporting the theory of an elevated wear zone directly after a turn in sliding path.

Comparing the results from these published pin-on-disk tests is important, but difficult because each study used different test parameters, test materials, test methods, and published tests results in different units: volumetric loss (mm$^3$), weight loss (mg), wear rate (mg/MCycle), or wear factor (mm$^3$/Nm). Differences in numerous factors effecting UHMWPE wear produce large variations in wear data generated. Despite these
issues, Figures 3.6 and 3.7 compare several of these studies by estimating wear rate in mg/MCycles for each study and grouping like cross-shear paths. Different conventional

**Figure 3.5**: Wear normalized by (a) number of cycles, (b) number of turns, and (c) total sliding distance, referenced from [22]

**Figure 3.6**: Literature review comparing cross-shear path and wear for studies using conventional UHMWPE in pin-on-disk testing
materials have been grouped together and are shown in Figure 3.6. As can be seen in the figure, even when cross-shear path is identical, as with the 10 mm x 10 mm testing, just varying cleaning procedures as done by Mazzucco et al. [15] yields wear rates that varied from 4.5 mg/million-cycles to 14.8 mg/million-cycles. Figure 3.7 shows different levels of crosslinking can produce significantly different wear rates, and also compares the wear rate obtained by Cornwall et al. [27] for rolling and gliding against the cross-shear paths tested by Dressler et al. [22].

![Figure 3.7](image)

**Figure 3.7:** Literature review comparing cross-shear path and wear for studies using crosslinked UHMWPE

In addition to abrupt angular path changes, the effect of circular and elliptical paths on wear has been tested. Saikko et al. [30] tested crosslinked UHMWPE pins sliding along elliptical and circular paths with aspect ratios that varied from 1 to 388. Track length varied for each path, but the results showed maximum wear occurred at aspect ratios below 5.5 as the path became more circular. Kang et al. [31] tested both conventional and crosslinked UHMWPE pins oscillating along a sinusoidal path and varying the angle of pin rotation from 0° to 55°. These results show increased volumetric loss for greater angular rotation. Galvin et al. [32] studied the wear of crosslinked and conventional UHMWPE pins rotating around their centers as a plate translated. One test had a stroke length of 28 mm for a translation angle of ±30° and a second test had a stroke length of 10 mm for rotation of ±10°. This testing showed that for a smooth
counterface, wear rates increased for conventional materials as rotation angle increased but for higher cross-linked material, exposed to levels 100 kGy (10 MRad) and higher, the reverse was true.

Ge et al. [33] completed testing comparing wear from linear sliding (sliding distance 24 mm) with that of an oval (sliding distance 36.4 mm), a figure eight or double ellipse (sliding distance 56.1 mm), and a triple ellipse (sliding distance 78.8 mm). Testing was done with a Si3N4 4mm ball reciprocating in one direction under load against a UHMWPE disk reciprocating in a direction 90˚ from the ball. Paths were generated by altering the frequency of the ball. Although not comparable to pin-on-disk testing, the results are of note. The oval sliding path produced the highest wear rate, almost six times that of unidirectional sliding while the double and triple-elliptical paths had similar wear rates that were approximately half that produced by the oval sliding, indicating that the gentler angle changes experienced in the oval sliding produced the worst-case wear.

Despite the extensive published data described above, to the author’s knowledge, little data exists on the relationship between wear and variations of the cross-shear angle. In 2001, Wang [23] proposed a unified theory of wear in which he predicted the UHMWPE wear factor would increase almost linearly as the maximum cross-shear angle increased to 90˚, as shown in Figure 3.8. Hamilton et al. [34] assumed a uniform circular counterface motion produced worst-case wear and Petrella et al. [35], in agreement with the unified theory of wear, proposed a worst-case cross shear of 90˚. This thesis completed pin-on-disk testing to gain a better understanding on the effects of sliding path angular change on wear rates.

![Figure 3.8: Wang et al. prediction of UHMWPE wear versus cross-shear angle, referenced from [23]](image-url)
3.3 Experimental Methods

Testing was completed as a collaborative effort between Colorado School of Mines and the Biomechanics Laboratory at the University of Nebraska Medical Center (UNMC). Each pin-on-disk test was comprised of three pins machined from ram extruded rods of conventional GUR 1050 UHMWPE and three pins from gamma irradiated GUR 1050 (95.7 kGy). GUR 1050 was chosen both because of its use in prosthetic implant bearings and because it is a common material used in other pin-on-disk testing. The raw material was generously donated by Orthoplastics Limited of Lancashire England. Individual pins were machined to Ø9.525mm x 20mm (.375 in x .787 in) to fit existing Ortho-POD™ pin adaptors. Material data sheets are reproduced in Appendix A and summarized in Table 3.1.

Table 3.1: Material characteristics of UHMWPE used in angle testing

<table>
<thead>
<tr>
<th>Orthoplastics PUR – 1050 Medical Grade UHMWPE</th>
<th>Gamma Crosslinked PUR – 1050 Medical Grade UHMWPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>o Material certified according to ASTM F648 – 10 a</td>
<td>o Batch: ORTHO 172</td>
</tr>
<tr>
<td>o Meets requirements of ISO 5834/2 – 2006</td>
<td>o Base Batch 1875M</td>
</tr>
<tr>
<td>o ISO Classification Type: 2</td>
<td>o Polymer GUR: 1050</td>
</tr>
<tr>
<td>o Batch No. 1913M</td>
<td>o Properties before Irradiation:</td>
</tr>
<tr>
<td>o Ticona Powder</td>
<td>o Density: 934 kg/m³</td>
</tr>
<tr>
<td>o Material annealed in accordance with Orthoplastics Quality procedures</td>
<td>o Ash: 38 mg/kg</td>
</tr>
<tr>
<td>o Density: 931 kg/m³</td>
<td>o Properties after Irradiation/Crosslinking</td>
</tr>
<tr>
<td>o Ash: 41 mg/kg</td>
<td>o Irradiation Dosage: 95.75 kGy</td>
</tr>
</tbody>
</table>

Pins articulated against six Co-Cr disks, each mirror polished to a surface finish of Ra less than 15 nm. Disk surface finish was measured using an Ambios Technology Xi-100 profilometer interfacing with Image Studio V1.1.3 software. This system allows the user to obtain both surface magnification snapshots and surface roughness measurements, as shown in Figure 3.9. Measurements were made at a minimum of 7 locations across the disk to determine an average surface roughness.
During testing, the articulating surfaces of the components were immersed in a diluted filter-sterilized bovine serum with 20 g/L protein concentration, the protein content found in healthy human synovial fluid [4]. The lubricating solution was kept at a temperature of $37^\circ \pm 2$ C because “research has shown that the Young’s modulus of UHMWPE decreases by almost 50% between room temperature ($24^\circ$ C) and body temperature ($37^\circ$ C) and that the wear rate is different between the two temperatures” [27]. The lubrication was supplemented with 20 mM (7.45 g/l) ethylenediaminetetraacetic acid (EDTA) to reduce calcification and protein precipitation, and 0.2% sodium azide (2 g/l) was added to retard bacterial growth.

During testing, a single cycle consisted of 40 mm linear articulation, rotation at a set angle (10°, 40°, 70°, and 90°), articulation for another 40 mm, and rotation back into the initial position. During unidirectional sliding, a constant vertical load of 400 N (5.6 MPa) was applied but during rotation, the load was reduced to 50 N (~0.7 MPa). Each cycle required 2 seconds to complete and consisted of two translations and two rotations. Testing was completed using an Ortho-POD™ Wear Testing Machine (AMTI, Waterton, MA), therefore due to machine size limitation, the 40 mm unidirectional sliding distance was broken into three reciprocating unidirectional legs of 13.3 mm.

An exacting cleaning and drying protocol was used every 250,000 cycles when pins were removed from testing to be weighted. This protocol has been developed by the

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**Figure 3.9**: (a) Magnification of pin surface showing machine marks (b) Surface roughness analysis
University of Nebraska Medical Center Biomechanics Laboratory to account for the porosity of UHMWPE that tends to absorb the lubricating fluid. This fluid absorption can lead to measurement error if the drying, cleaning, and weighting procedures are not extremely consistent. The drying and weighting protocol is summarized in Table 3.2. During all steps of this protocol, the user wore powder-free gloves to reduce contamination and sample absorption of skin oils. Because there is no absolute definition of ‘dry’, weight loss due to wear is often blurred due to weight gain from fluid absorption [4], therefore six soak pins, three conventional and three crosslinked, were used to compensate for fluid absorption during testing.

Table 3.2: Cleaning and weighting protocol used during testing

<table>
<thead>
<tr>
<th>Cleaning Step</th>
<th>Protocol Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Rinse</td>
<td>Rinse pins with deionized water to remove all serum particles</td>
</tr>
<tr>
<td>Ultrasonic Cleaning</td>
<td>10 minutes cleaning in deionized water using a Prosonic Digital Heated Ultrasonic Cleaner with tank temperature set at 35°C</td>
</tr>
<tr>
<td>2nd Rinse</td>
<td>Pins rinsed using deionized water</td>
</tr>
<tr>
<td>2nd Ultrasonic Cleaning</td>
<td>10 minutes cleaning in deionized water mixed with liquid ultrasonic cleaning detergent (80 ml Contrad from Decon Labs, Inc.)</td>
</tr>
<tr>
<td>3rd Rinse</td>
<td>Pins rinsed using deionized water</td>
</tr>
<tr>
<td>3rd Ultrasonic Cleaning</td>
<td>10 minutes cleaning in deionized water</td>
</tr>
<tr>
<td>Initial Drying</td>
<td>Dry off with a jet of nitrogen or suitable dry gas</td>
</tr>
<tr>
<td>4th Ultrasonic Cleaning</td>
<td>5 minutes cleaning in 95% methyl alcohol</td>
</tr>
<tr>
<td>2nd Drying</td>
<td>Dry off with a jet of nitrogen or suitable dry gas</td>
</tr>
<tr>
<td>Final Drying</td>
<td>Vacuum dry for 60 minutes</td>
</tr>
</tbody>
</table>

After cleaning and drying, pins were left for 1 hour to acclimate before gravimetric weighting. Pins were weighed using a Genius Sartorius Precision weighting balance located on a bearing-balanced nano-lab table. Before each weighing, the balance was calibrated using a 2 g calibration weight. Custom software made a minimum of 110 weights to determine stability (average of first 100 weights was within 0.005 mg of average of last 10 measurements) before recording final pin weight. After each
weighting, pin weight was adjusted by the average weight gain from like material soak pins. Appendix B details the test plan and measurement methods used during testing. Appendix C shows all raw measurement data taken during pin-on-disk testing.

3.4 Experimental Results

Wear data presented in Figure 3.10 was calculated by averaging gravimetric weight loss during each test cycle for three conventional material pins and three crosslinked material pins after adjusting for average soak pin weight gain. In Figures 3.11 and 3.12, a best fit linear regression analysis was used to calculate wear rate equations and $R^2$ factors. As Figure 3.11 indicates, and an ANOVA one-way analysis of variance confirmed statistically, the wear of the 40, 70, and 90 degree angle testing for conventional UHMWPE yielded no statistical difference, indicating equally elevated wear for cross-shear paths 40$\degree$ and greater. Crosslinked UHMWPE results were less conclusive, as shown in Figure 3.12, due to increased scatter in the data. Trends from the crosslinked material wear were similar to those of conventional UHMWPE but did not reach statistical significance due to high standard deviations in relation to the low measured wear rates. An interesting outcome from both conventional and crosslinked wear data was the indication that wear rates were highest for the 70$\degree$ testing. This trend was not statistically supportable, but interesting to note. Future testing to determine if wear
maximizes around a 70 degree angle change and then reduces as the angle increases to 90° might improve understanding of the UHMWPE wear process.

**Figure 3.11**: Wear of conventional UHMWPE pins, with weight gain corrected for passive soak control pins, for different angular siding paths

**Figure 3.12**: Wear of Crosslinked UHMWPE Pins, with weight gain corrected for passive soak control pins, for different angular siding paths
3.5 Discussion

Testing did not support the hypothesis of maximum wear after a 90° path change, and instead, indicated elevated wear occurs after turns as small as 40°. These results must now be considered with regard to current wear theories and empirically derived wear models. In 1996 Wang hypothesized that in unidirectional sliding, UHMWPE strings reorient along the direction of sliding and resistance to wear is determined by the longitudinal strength of the polymer strings [3]. Wang theorized that multi-dimensional sliding produces stresses at an angle to the polymer string orientation, inducing a failure between polymer strings dependent on the strength of the van der Waal bond between the fibers, which is much weaker than the covalent bonds between individual polymer monomers. Figure 3.13, as theorized by Wang [3], shows graphically how stress applied at an angle, \( \alpha \), to the string orientation produces different failure modes depending on the angle of attack. In this figure, failure stress reduces exponentially as \( \alpha \) approaches 90°, thus, if the stress remains constant during a sliding path, failure rate will increase as sliding path angular changes approach 90°. From the figure it can be seen that the exponential drop of failure stress begins to level off around the 40° off-axis angle. During pin-on-disk angular testing, all test parameters except cross-shear angle were kept constant. This being the case, the results from this study support Wang’s failure mechanism predictions for a leveling off of wear after 40°.

Petrella et al. [35] introduced a cross-shear metric to quantify wear during cross-shear sliding. Petrella and colleagues theorized that an incremental weight factor, \( m \), could be introduced into wear modeling to account for increased wear due to cross-shear path changes. This new wear model followed finite element methodology by breaking
the wear surface into discretized wear surfaces with locations described by $j = 1, 2, ..., N$
and time increments as the wear surface slides along a path defined by $i = 1, 2, ..., n$.
Equation 3.1 shows the definition for this model’s incremental weight factor, $m$.

$$m_{ij} = \sum_{s=1}^{mem} \left(1/mem \right) \left| \sin(\theta_{ij} - \theta_{i-s,j}) \right| \quad (i > mem) \quad (3.1)$$

As defined in [23], the incremental weight factor, $m_{ij}$, is calculated using the angular change in sliding path, $\theta_{ij} - \theta_{i-s,j}$ and a factor, mem, which represents the number of sliding increments occurring during elevated wear after an abrupt angular path change. Dressler et al. [22] defines this distance to be 5 mm and mem breaks this distance into finite increments. Wear is calculated using a modified Archard’s law. Equation 3.2 is the modified Archard’s law equations for wear depth (mm), $H_j$ at a discrete location on the surface, and Equation 3.3 calculates wear volume (mm$^3$), $W$.

$$H_j = k_0 \sum_{i=1}^{n} p_{ij} \Delta_{ij} + k^* \sum_{i=1}^{n} p_{ij} \Delta_{ij} m_{ij} \quad (3.2)$$

$$W = k_0 \sum_{j=1}^{n} \sum_{i=1}^{n} p_{ij} A_j \Delta_{ij} A_j + k^* \sum_{j=1}^{n} \sum_{i=1}^{n} p_{ij} A_j \Delta_{ij} m_{ij} A_j \quad (3.3)$$

In these equations, $k_0$ (mm$^3$/N-mm) is an experimentally measured apparent wear factor for unidirectional sliding, $k^*$ (mm$^3$/N-mm) is an experimentally measured apparent wear factor for cross-shear sliding, $p_{ij}$ is incremental contact pressure (MPa), $\Delta_{ij}$ (mm) is the scalar magnitude of an incremental slip vector, and $A_j$ is an element of surface area (mm$^2$).

Figure 3.14 shows results produced from the angular wear testing plotted against the cross-shear wear metric derived by Petrella et al. [35] and Wang’s prediction of wear versus angular change (approximated from Figure 3.8). Both curves were normalized to the 90° test wear results in order to generate comparable prediction curves. Test results do not validate Wang’s prediction of maximum wear after a 90° cross-shear angle. The Petrella wear curve more closely tracks the measured wear, but the prediction of worst case wear occurring after a 90° turn did not match test results. Instead, test results indicate wear rate may follow an S-like curve with worst case wear starting to occur after as little as a 40° angular path turn.
Figure 3.15 compares wear results from different published pin-on-disk angle studies with the current test results and with the Wang and Petrella predictions. A 4th order polynomial curve was fit to the study results for comparison purposes. As can be noted in the figure, for a 90° angular change, significant variations in wear rates occur.
Limitations of the results from this study include small sample size (3 pins per material per test) and only four angular tests completed. The material tested GUR 1050 is a common material used in implant bearings, but only conventional and a single highly crosslinked version of the material were tested. Additional testing on lower crosslinked materials would help verify wear trends observed. The crosslinked material used had an irradiation dose of 95.8 kGy and wear rates for this material were significantly lower than conventional material, a trend documented in other crosslinked material pin-on-disk testing [29,31,32]. This low wear rate introduced measurement complications since

![Figure 3.15: Comparison of literature published pin-on-disk angle testing of conventional UHMWPE to measured data](image)

- Mazzucco et al. (2003) Group 3A
- Mazzucco et al. (2003) Group 3B
- Turell et al. (2003) unidirectional path
- Turell et al. (2003) 5 mm x 5 mm sq
- Korduba et al. (2010) unidirectional
- Korduba et al. (2010) 5 mm x 5 mm sq
- Ernsberger et al. (2007) 10 mm x 10 mm sq - 69 N Load
- Ernsberger et al. (2007) 10 mm x 10 mm sq 208 N Load
- Kang et al. (2008) 55 Deg
- Kang et al. (2008) 45 Deg
- Kang et al. (2008) 20 deg
- Galvin et al. (2006) 30 deg
- Galvin et al. (2006) 10 deg
weight loss due to wear was in the same order of magnitude as weight gain seen in the soak pins, producing results with significant standard deviations. Because of these limitations, a more comprehensive test with additional angles and material samples is needed to determine more specific trends of wear rate versus angular path change.

The surface of the CoCr was polished and measured to an Ra below 15 um at the start of each test but scratches developed non-uniformly during the test life. Published studies [2,9,36] have determined that counterface roughness is an important factor affecting UHMWPE wear. Although all tests produced some scratching, as shown in Figure 3.16, the non-uniformity of the scratching introduce an uncontrolled error in the results produced.

The AMTI OrthoPOD™ pin-on-disk tester has become a standard for the type of testing done in this study, but its limitations must be understood. The linear path lengths generated by the machine are slightly curvilinear and extended lengths are comprised of multiple small distances of reciprocating motions. In this study, the 40 mm linear path traveled between rotations was comprised of three reciprocating 13.3 mm paths, each with an arc height of 0.42 mm. During this arced motion, the orientation of the pin remained parallel to the sliding direction but sliding velocity varied due to the reciprocating nature of the path. It was felt the variations of velocity did not affect wear rates [7], but the gentle curvature of the path slightly increased cross-shear.

It has been demonstrated that scratches on the CoCr surface of an implant can increase UHMWPE wear [2,9-11]. Paul et al. [37] completed experimental testing and a
finite element analysis of UHMWPE wear compared to the angle of scratches on the counterface surface. As with the wear predictions for pin-on-disk sliding, it was hypothesized that worst-case wear would occur with scratches oriented 90 degrees to the direction of sliding. Interestingly, Paul et al. found in conventional UHMWPE (CPE 4150 HP), “a scratch oriented at 15° with respect to the sliding direction produced the greatest wear” and for crosslinked UHMWPE (HXPE, DePuy Marathon®), 5° produced the greatest wear [37]. In both this scratch test and the angle testing completed by this thesis, the mechanism of wear is not clearly understood, but because both tests produced results that do not agree with present wear theories, these tests bring into question the accuracy of present theories and emphasize the importance of understanding wear at a molecular level.

Understanding wear in medical grade UHMWPE is critical to improving the life of bearings in knee, hip, shoulder and other implants. The discovery that cross-shear motion plays an important role in increased wear was a significant enhancement of the understanding of UHMWPE bearing wear [1,3,8]. Unfortunately, experimental studies take significant time and money, providing valuable insight at a high price. Each of the tests in this study required 23.2 days of machine run time and took over a month per test.

The results from this testing provide new insights and questions in the understanding cross-shear wear. Most importantly, the results from the angular test indicating elevated cross-shear wear occurs after a 40° or higher turn should be incorporated into computational methods to improve wear predictions.

### Conclusion

In conclusion, this study indicates increased UHMWPE wear occurs after an abrupt angular change in sliding path of 40° and higher for conventional UHMWPE. A similar trend was seen in highly crosslinked UHMWPE. The underlying mechanism causing this wear is unknown and further morphological studies are needed to adequately explain these results. Additionally, future research should be completed to determine if maximum wear occurs after a 70° turn.
3.7 Acknowledgements

The author would like to thank Kevin Swierczek, Joel Weisenburger, David Lusk, and Alex Pieper from the University of Nebraska Medical Center Biomechanics Laboratory for all their help with the pin-on-disk testing and Neil Hubbard and Orthoplastics Ltd. for the donation of all UHMWPE materials used in this study.

3.8 References Cited


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CHAPTER 4
COMPUTATIONAL ANALYSIS AND SIMULATION
OF WEAR IN UHMWPE

4.1 Introduction

Archard et al. [1] developed one of the first wear theories for a deformable and non-deformable material sliding against each other. Wang et al. [2-4] and Turell et al. [5] were pioneers in the study of cross-shear wear and developed a unified theory of wear. Lee et al. [6] later improved on this unified theory with a theoretical model of orientation softening. As cross-shear rose as a major UHMWPE wear concern, several empirically derived wear models were developed [7-11]. Petrella et al. [7] developed a novel cross-shear metric, Hamilton et al. [8] introduced a formulaic method to predict the severity of crossing motions during cross-shear sliding paths, Abdelgaied et al. [9] introduced a new wear law to predict artificial knee joint wear, Willing et al. [10] developed a holistic numerical model to predict wear due to strain hardening and creep, and Strickland et al. [11] proposed an adaptable computational-numerical framework for theoretical models. In the following paragraphs, these models will be briefly described and compared.

In 1953 Archard et al. [1] wrote a groundbreaking article theorizing and quantifying wear mechanisms between two flat, contacting surfaces, one of which had a non-deformable, hard surface while the other had a softer, deformable surface. Archard and Hirst theorized that these surfaces, when pressed against each other by a load, made contact at the tips of the higher asperities on each surface and as one surface slid against the other, the softer material’s asperities plastically deformed. At high loads or repetitive contact, the deformed asperities ruptured, producing micron and sub-micron wear particles.

Archard’s law may be written either in wear depth, $H_j$ as shown in Equation 3.2, or in wear volume, $W$, as shown in Equation 3.3. Archard’s law was used to predict wear in orthopedic implants for many years, but improved analysis of clinical implant failures yielded wear factors of the order of $10^6$ mm$^3$/N m while repetitive, unidirectional sliding yielded wear factors two orders of magnitude lower, in the order of $10^8$ mm$^3$/N m [12-14]. Newer computational models incorporated cross-shear, creep, and other factors to improve wear predictions.
In 2001 Wang [2] introduced a unified theory of wear for UHMWPE that incorporated both unidirectional and cross-shear wear. Earlier publications [3,4] had shown that unidirectional sliding produced molecular reorientation in the direction of motion and it was theorized that this reorientation produced anisotropic behavior. Wang [2] theorized molecular reorientation in the direction of sliding put tensile-like loads on the molecular chains, producing stretching of the molecular chains and strain hardening, but in the transverse direction, orientation softening is produced. This orientation softening caused inter-fibril rupture during off-axis loads, or loads normal to the primary direction of sliding.

Turell et al. [5] expanded on the unified theory of wear by completing pin-on-disk testing where ram-extruded GUR 1050 pins were exposed to identical test conditions with only the sliding path varying. The wear factor, \( k \), was defined per Equation 4.1 with \( V \) as the volumetric wear rate, \( P \) the load, \( B \) the principle (longer) sliding direction (mm), and \( A \) the secondary (shorter) sliding direction (mm). The path geometry “theoretically quantifies the effect of cross-path motion on the wear of UHMWPE” [5] and is represented by the fraction \( A/(A+B) \), as shown in Equation 4.1.

\[
k = \frac{V}{P+(2A+2B)} \propto \frac{A}{(A+B)} \quad (4.1)
\]

Wang’s unified theory [2] predicted the maximum wear factor would occur when \( A=B \), but testing indicated wear factor peaked at \( A/(A+B) = 0.3 \) [5]. Korduba et al. [15] repeated similar rectangular testing and found maximum wear occurred at \( A/(A+B) = 0.4 \).

In 2011, Lee, Korduba, and Wang [6] improved on the unified theory of wear altering an important assumption. In the initial model, it was assumed that sliding along the principle side (longer) of the rectangle (B) produced molecular reorientation and sliding along the secondary (shorter) side (A) produced shearing of the molecules and wear particles. In this new model, it was hypothesized that sliding along each leg of the rectangular produces both molecular realignment and wear in proportions dependent on the \( A/B \) ratio. In this new model, the wear factor, \( k \) (mm\(^3\)/Nm) is a function of load, \( P \) (N), friction, \( \mu \), and a cross-shear wear factor of energy exerted orthogonal to molecular orientation (mg/J), \( \varepsilon \), as shown in Equation 4.2.

\[
k = 2 * P * \mu * \varepsilon \quad (4.2)
\]
Petrella et al. [7] developed a novel cross-shear metric to predict UHMWPE wear based on existing understanding of cross-shear wear due to molecular reorientation and published tribological test data. In his model, Petrella hypothesized that a material’s wear coefficient, $k$, can be broken down into a material property for wear due to unidirectional sliding, defined as $k_o$, and a second material property for wear due to worst case cross-shear, defined as $k^*$. These material properties were theorized to be measurable for any UHMWPE material, regardless of cross-shear wear path.

Once these material properties were determined, Petrella et al. [7] hypothesized that wear for any path can be predicted by calculating a cross-shear intensity factor, $x^*$, that is dependent only on sliding kinematics. Equation 4.3 shows the calculation for the overall wear coefficient, $k$, which includes the effect of unidirectional wear, $k_o$, cross-shear wear, $k^*$, and sliding path kinematics, $x^*$.

$$k = k_o + k^* x^* \tag{4.3}$$

The cross-shear intensity factor, $x^*$, described above, is predicted by calculating an incremental weight factor, $m$, as described in Chapter 3, and repeated below for clarity in Equation 4.4. This material memory factor accounts for increased wear seen after an abrupt directional change in sliding.

$$m_{ij} = \sum_{s=1}^{mem} \left(1/\text{mem}\right) | \sin(\theta_{ij} - \theta_{i-1,s,j}) | \quad (i > \text{mem}) \tag{4.4}$$

In this equation, mem represents the number of sliding increments corresponding to the elevated wear distance after an abrupt change in sliding direction. This distance was hypothesized to be 5 mm by Dressler et al [16]. Once the incremental weight factor, $m_{ij}$, has been calculated, the cross-shear intensity factor, $x_j^*$, can be determined, as shown in Equation 4.5. In the calculation of cross-shear intensity factor, $\sigma_j$ is sliding intensity for an arbitrary motion path and $\sigma_j^0$ is the maximum sliding intensity corresponding to $m = 1$, the sliding path that produces the worst-case wear due to cross-shear. To calculate the sliding intensities, Petrella et al. [7] uses Archard’s law [1] and the previously calculated incremental weight factor, $m_{ij}$, as shown in Equations 4.6 and 4.7.

$$x_j^* = \sigma_j / \sigma_j^0 \tag{4.5}$$

$$\sigma_j = \sum_{i=1}^{n} p_{ij} \Delta_i m_{ij} \tag{4.6}$$

$$\sigma_j^0 = \sum_{i=1}^{n} p_{ij} \Delta_i \tag{4.7}$$
Following Archard’s law, \( p_{ij} \) is the incremental contact pressure, and \( \Delta_{ij} \) is the scalar magnitude of an incremental slip vector. As before, discretized wear surface locations are described by \( j = 1, 2, \ldots, N \) and time increments as the wear surface slides along a path are defined by \( i = 1, 2, \ldots, n \).

Hamilton et al. [8] introduced a statistical formulation for quantifying and visualizing the intensity of crossing motions experienced during cross-shear wear. In his model, he introduced a tribological intensity factor, \( \tau \), as defined by Equation 4.8. In this equation, \( p \) is the contact pressure and it is multiplied by the slip vector, \( d \).

\[
\tau = p |d| \tag{4.8}
\]

In order for Hamilton et al. [8] to define principle sliding direction, a second quantity, \( \bar{\theta} \), is defined as the dominant orientation of the tribological intensity. This factor, defined in Equation 4.9, follows finite element methodology by discretizing time, as indicated by the \( i \) indices. Therefore, \( \theta_i \) represents the instantaneous crossing orientation relative to a fixed medial-lateral axis corresponding to \( \tau_i \), the tribological intensity factor at that same instant in time [8]. In this equation, \( \theta_i \), is restricted between 0 and \( \pi \).

\[
\bar{\theta} = \frac{\sum_{i=1}^{n} \tau_i \theta_i}{\sum_{i=1}^{n} \tau_i} \tag{4.9}
\]

Similar to Petrella, Hamilton defines a ‘normalized crossing intensity factor, \( \sigma * \), defined by Equation 4.10. This equation is identical to Petrella’s cross-shear intensity factor, but Hamilton’s definition of crossing intensity, \( \sigma \), shown in Equation 4.11 weights each \( \tau_i \) value by how much its associated slip direction deviates from the dominant orientation direction [8].

\[
\sigma * = \frac{\sigma}{\sigma_0} \tag{4.10}
\]

\[
\sigma = \sqrt{\frac{\sum_{i=1}^{n} (\tau_i \Delta \theta_i)^2}{n}} \tag{4.11}
\]

Using this methodology, Hamilton produced a series of bidirectional intensity maps for many types of sliding paths. Figure 4.1 shows an example of one such map.

Although similar in several ways to Petrella’s cross-shear metric, Hamilton’s formulation has one significant drawback. For all paths, a dominant crossing orientation, \( \bar{\theta} \), must be specified, which can be difficult to do with normal joint kinematics.
Abdelgaied et al. [9] introduced a wear predictor that is unique because it does not adopt Archard’s wear law. Instead, citing results from wear versus load testing, Abdelgaied introduces a wear coefficient based on the idea that wear volume is proportional to contact area and sliding distance. This non-dimensional wear coefficient, $C$, shown in Equation 4.12 has $W$ defined as the wear volume, $A$ the contact area, and $S$ the sliding distance. As is clear by examining this equation, this new wear factor is independent of contact pressure.

$$C = \frac{W}{AS}$$  \hspace{1cm} (4.12)

Using empirical data generated by Kang et al. [17] and the unified theory of wear and frictional work developed by Wang [2], Abdelgaied et al. [9] generated a best fit wear coefficient as a function of cross-shear ratio (CS) [9]. Shown in Equation 4.13, Abdelgaied’s cross-shear ratio, $CS$, is composed of the frictional work component perpendicular to the principal molecular orientation direction, $E_{cross-shear}$, divided by the total frictional work, $E_{total}$ [9].

$$CS = \frac{E_{cross-shear}}{E_{total}}$$  \hspace{1cm} (4.13)

Abdelgaid’s computational wear predictor is unique in that it moves away from Archard’s law, but the definition of his cross-shear ratio, $CS$, is not significantly different than Petrella’s cross-shear intensity factor, $x^*$. Both factors attempt to quantify the effect of UHMWPE cross-shear by producing a ratio between the wear over a specific path compared to wear over a worst-case path. Abdelgaid raises valid questions about the effectiveness of continuing to apply Archard’s law in UHMWPE. Although initial testing appears promising, further study on the effect of wear versus load is needed to validate Abdelgaid’s assumptions.

---

Figure 4.1: Bidirectional intensity maps with corresponding counterface motion and normalized crossing intensity, as developed by Hamilton [8]
The cross-shear metric derived by Petrella et al. [7] is based on Archard’s law but the key factors of his metric, the unidirectional wear factor, $k_0$, cross-shear wear factor, $k^*$, sliding path kinematics, $x^*$, and $m$, the number of sliding increments corresponding to the sliding distance of elevated wear after cross-shear, are properties that could be defined independent of Archard’s law. If future work indicates the need, as Abdeglaid predicts, of a wear factor that is independent of load, the cross-shear model could be easily updated.

4.2 Determination of Cross-shear Metric Parameters

The cross-shear metric developed by Petrella et al. [7] was used to predict wear rates of existing published pin-on-disk wear studies and the wear of the cross-shear angle testing described in Chapter 3. In order to use the model, the value of three critical parameters needed to be determined: the distance after an abrupt turn that experiences elevated wear, the material dependent wear factor for unidirectional sliding, $k_0$, and the material dependent factor for worst-case cross shear sliding, $k^*$.

The model uses the material memory weighting factor, $m$, to account for elevated wear after an abrupt sliding path turn. As discussed in Chapter 3, Dressler et al. [16] tested irradiated GUR1020 pins sliding against polished CrCo disks with square articulation paths and found “the wear rate immediately following the change in direction is high, but with continued linear sliding the wear rate appears to drop to near zero” with 5 mm being the transition distance [16].

Although the 5 mm predicted by Dressler et al. [16] is within the hypothesized range of 3-8 mm, an understanding for the sensitivity of the cross-shear metric to this parameter is needed. Figure 4.2 shows wear volume predicted for the 90° angle test described in Chapter 3 when the

![Figure 4.2: Wear volume for 90 degree angle test with elevated wear distance varied from 3 mm to 8 mm](image)
elevated wear distance was varied from 3 mm to 8 mm. As can be seen from the figure, wear volume increases linearly from 7.32 mm$^3$/Mcycles to 17.32 mm$^3$/MCycles over this 5 mm variation in distance, producing a large uncertainty. Therefore, although 5 mm was used for the computational analysis, further testing to corroborate this distance is needed, including testing to determine if this distance is material dependent.

In the cross-shear model, the material memory weighting factor, $m$, drops linearly over the elevated wear distance, as shown in Figure 4.3. In this figure, the elevated wear distance is assumed 5 mm and a 90˚ abrupt turn is assumed. For a turn less than 90˚, the weighting factor has a sinusoidal drop such that the initial value after the turn is less than one.

Although there is significant agreement that this elevated wear distance exists [7,16, 18], there is little understanding on how wear varies over this distance. Petrella et al. [7] assumes a linear decrease in wear while Strickland et al. [11] assumes an exponential decrease. The author was unable to find published literature that supported either assumption, so an experimental comparison was completed. Altering the model developed by Petrella et al. [7] using the equations shown in Table 4.1 allowed the weighting factor, $m$, to vary with a moderate exponential decay or a rapid exponential decay over the elevated wear distance, as shown in Figure 4.4.

| Table 4.1: Equations used to generate material memory weight factor, $m$ |
|-------------------------|-------------------------|
| **Original Model**      | **Exponential Model**   |
| $m_{ij} = \sum_{z=1}^{mem} \left(1/\text{mem} \right) |\sin(\theta_{ij} - \theta_{i-s_j})|$ | $m_{ij} = \sum_{z=1}^{mem} (k_1 * e^{-k_2s}) |\sin(\theta_{ij} - \theta_{i-s_j})|$ |
| Rapid Exponential Decay | Rapid Exponential Decay |
| $k_1=1.718$, $k_2=1$   | $k_1=0.3094$, $k_2=0.25$ |
Two wear factors, the material dependent wear factor for unidirectional sliding, $k_0$, and the material dependent factor for worst-case cross shear sliding, $k^*$, must be determined in order to use the cross-shear metric. To determine these factors, a literature search was conducted, as shown in Tables 4.2 through 4.4. These wear factors are considered material dependent, but it was hypothesized that the values for conventional UHMWPE were close enough to be lumped into a single value, despite the material. For the analysis done on conventional UHMWPE, a unidirectional wear factor, $k_0 = 1 \times 10^{-11}$ mm$^3$/N*mm was used and a cross-shear wear factor, $k^* = 5 \times 10^{-9}$ mm$^3$/N*mm.

**Table 4.2: Wear factor for unidirectional sliding of conventional UHMWPE**

<table>
<thead>
<tr>
<th>Study</th>
<th>Unidirectional Wear Factor</th>
<th>Experimental Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kang et al. (2008)</td>
<td>$1 \times 10^{-7}$ mm$^3$/Nm</td>
<td>Conventional UHMWPE sliding against polished CoCr</td>
</tr>
<tr>
<td>Kang et al. (2008)</td>
<td>$0.2 \times 10^{-7}$ mm$^3$/N</td>
<td>GUR 1050 UHMPE (10 MRad irradiation) sliding against polished CoCr</td>
</tr>
<tr>
<td>Wang et al. (1996)</td>
<td>$2.4 \times 10^{-9}$ mm$^3$/N</td>
<td>Conventional UHMWPE</td>
</tr>
<tr>
<td>Turell et al. (2005)</td>
<td>$5.06 \times 10^{-8}$ mm$^3$/N</td>
<td>Conventional GUR 1050</td>
</tr>
</tbody>
</table>
Table 4.3: Wear factor for cross-shear sliding of conventional UHMWPE

<table>
<thead>
<tr>
<th>Study</th>
<th>Cross-shear Wear Factor (m³/N m)</th>
<th>Experimental Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kang et al. (2008) [19]</td>
<td>6.8*10⁻⁷ mm³/Nm</td>
<td>Conventional UHMWPE sliding 38 mm while rotating ±55°</td>
</tr>
<tr>
<td>Galvin et al. (2009) [21]</td>
<td>1.8*10⁻⁶ mm³/Nm</td>
<td>Conventional GUR 1050 pins sliding against polished Cobalt Chrome rotating ± 55°</td>
</tr>
<tr>
<td>Korduba et al. (2011) [15]</td>
<td>1.9*10⁻⁶ mm³/Nm</td>
<td>Conventional GUR 1020 pins sliding 2 mm x 8 mm rectangle</td>
</tr>
<tr>
<td>Galvin et al. (2006) [18]</td>
<td>4.8*10⁻⁷ mm³/Nm</td>
<td>GUR 1050 pins (medium crosslink with 5MRad and highly crosslinked with 10 MRad) sliding against polished stainless steel</td>
</tr>
<tr>
<td>Turell et al. (2005) [20]</td>
<td>4<em>10⁻⁶ mm³/Nm (Rough Counterface) 2.5</em>10⁻⁶ mm³/Nm (Smooth Counterface)</td>
<td>GUR1050 pins articulating across CoCr – rectangular (3 mm x 7 mm) wear path</td>
</tr>
</tbody>
</table>

This methodology was repeated for crosslinked material, but worst-case cross-shear wear factor, \( k^* \), appeared to vary based on degree of crosslinking. This is not surprising since, as shown in Table 2.2, individual material properties of UHMWPE are altered by the degree of crosslinking. Therefore, the worst-case cross-shear wear factor was broken into two numbers, one for lower degrees of crosslinking exposed to irradiation below 50 kGy, and one for higher degrees of crosslinking exposed to irradiation above 50 kGy. Estimates for both these values were based on the literature review wear factors shown in Table 4.4.

Estimating the unidirectional sliding wear factors for crosslinked UHMWPE was difficult because studies showed this value graphically, but usually it was so close to zero it was difficult to estimate. Table 4.5 shows the estimates of unidirectional wear factors from various studies used to determine the crosslinked unidirectional wear factor.

Therefore, for each of the analysis done on crosslinked UHMWPE, a unidirectional wear factor, \( k_0 = 1*10^{-12} \) mm³/N*mm was used, a cross-shear wear factor, \( k^* = 1.5*10^{-9} \) mm³/N*mm for low crosslinked materials was used, and a cross-shear wear factor, \( k^* = 2*10^{-10} \) mm³/N*mm for highly crosslinked materials was used.
Once these factors were determined, they were used to estimate wear, or wear factors, for several published pin-on-disk studies and for the pin-on-disk angle testing.

### Table 4.4: Wear factor for cross-shear sliding of crosslinked UHMWPE

<table>
<thead>
<tr>
<th>Study</th>
<th>Cross-shear Wear Factor (m^3/N m)</th>
<th>Experimental Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korduba et al. (2011)</td>
<td>0.1*10^{-6} mm^3/Nm</td>
<td>GUR 1020 irradiated to 30 kGy and annealed 3 times (HXPE) sliding 3 mm x 7 mm rectangle</td>
</tr>
<tr>
<td>Kang et al. (2008)</td>
<td>1.5*10^{-7} mm^3/Nm</td>
<td>GUR 1050 UHMPE (10 MRad irradiation) sliding against polished CoCr</td>
</tr>
<tr>
<td>Saikko, V. (2006)</td>
<td>2.7 *10^{-6} mm^3/Nm</td>
<td>Sulene-PE (GUR 1020, γ-sterilized pins sliding against polished CoCr under varying loads</td>
</tr>
<tr>
<td>McGloughlin et al. (2004)</td>
<td>1.5*10^{-7} mm^3/Nm</td>
<td>Average wear factors from TKR and ball-on-flat wear tests used for modeling of knee simulations</td>
</tr>
<tr>
<td>Galvin et al. (2006)</td>
<td>5.3*10^{-7} mm^3/Nm (5 Mrad)</td>
<td>GUR 1050 pins (medium crosslink with 5MRad and highly crosslinked with 10 MRad) sliding against polished stainless steel</td>
</tr>
<tr>
<td></td>
<td>1.9*10^{-7} mm^3/Nm (10 Mrad)</td>
<td></td>
</tr>
<tr>
<td>Saikko et al. (2004)</td>
<td>1.86*10^{-6} mm^3/Nm</td>
<td>GUR 1020 pins (Sulene-PE) gamma-irradiated (25-40 kGy) sliding against polished CoCr in circular path (dia: 5 mm)</td>
</tr>
</tbody>
</table>

### Table 4.5: Wear factor for unidirectional sliding of crosslinked UHMWPE

<table>
<thead>
<tr>
<th>Study</th>
<th>Cross-shear Wear Factor (m^3/N m)</th>
<th>Experimental Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cornwall et al. (2001)</td>
<td>6.8*10^{-8} mm^3/Nm</td>
<td>Chirulen® (γ-irradiation at 25 kGy (2.5 Mrad) sliding unidirectionally over CoCr (Per ASME Standard)</td>
</tr>
<tr>
<td>Cornwall et al. (2001)</td>
<td>5.3*10^{-7} mm^3/Nm</td>
<td>Chirulen® (γ-irradiation at 25 kGy (2.5 Mrad) sliding unidirectionally over CoCr</td>
</tr>
<tr>
<td>Korduba et al. (2011)</td>
<td>5*10^{-8} mm^3/Nm</td>
<td>GUR 1020 irradiated to 30 kGy and annealed 3 times (HXPE) sliding unidirectionally</td>
</tr>
<tr>
<td>Saikko et al. (2004)</td>
<td>1*10^{-7} mm^3/Nm</td>
<td>GUR 1020 pins (Sulene-PE) gamma-irradiated (25-40 kGy) sliding against polished CoCr in with aspect ratio 388</td>
</tr>
</tbody>
</table>
discussed in Chapter 3.

4.3 Application of Cross-shear Metric

Using the values determined for the cross-shear metric and applying a linear weighting factor, a moderately exponential decay weighting factor, and a rapid exponential decay weighting factor, wear for the angular testing described in Chapter 3 was calculated. A comparison of experimental results and analysis results for the

![Graph](image)

Figure 4.5: Comparing experimental results of angle testing of conventional material to predictions from the cross-shear model assuming an elevated wear distance of 5 mm, a unidirectional wear factor, $k_0 = 1 \times 10^{-11} \text{ mm}^3/\text{N*mm}$, and a cross-shear wear factor, $k^* = 5 \times 10^{-9} \text{ mm}^3/\text{N*mm}$. (a) Volumetric wear rate (b) Cross-shear intensity factor
conventional material is shown in Figure 4.5 (a). This comparison indicates that the linear weighting factor produces the most accurate wear results for the 90° and 70° turns, but for the 10° turn, the highly exponential weighting factor produces the best results. In Figure 4.5 (b) the cross-shear intensity factors, x*, are compared. It should be noted that the cross-shear intensity factors are very low due to the relatively long sliding distance of 40 mm on either side of an angular turn. The model correctly estimates decreasing cross-shear intensity and decreasing wear as the angular change drops from 90° to 10°.

A similar analysis was completed to compare testing done by Turell et al. [5] and Korduba et al. [15]. Turell et al. [5] completed pin-on-disk testing of conventional UHMWPE GUR 1050 sliding over paths that varied from square to rectangular to linear. Korduba et al. [15] repeated these experiments using both conventional and crosslinked UHMWPE GUR1020 and found wear peaked during the 2mm x 8 mm rectangular path where Turell et al. found that wear peaked during the 3 mm x 7 mm rectangular path [5].

Figure 4.6 compares the wear factor data provided in both of these studies with predictions from the cross-shear model. The figure shows that the moderate exponential

![Figure 4.6: Comparing experimental results from Turell et al. [5] and Korduba et al. [15] for conventional UHMWPE pin-on-disk testing to predictions from the cross-shear model assuming an elevated wear distance of 5 mm, a unidirectional wear factor, $k_0= 1*10^{-11}$ mm³/N*mm, and a cross-shear wear factor, $k^* = 5*10^{-9}$ mm³/N*mm](image-url)
weighting factor spanned the middle of the two studies but the cross-shear model was unable to capture the peak wear factor occurring during either the 2 mm x 8 mm or 3 mm by 7 mm sliding paths.

Although the wear factor was unable to capture these peaks, a closer look at the cross-shear factor yields a different picture. Turell et al. [5] defined cross-shear as the ratio of the secondary side length, A, over total sliding distance, A/(A+B), where Korduba et al. [15] defined cross-shear as the ratio A/B. Figure 4.7 compares these two cross-shear ratios with Petrella’s cross-shear intensity factor, x*. The cross-shear intensity factors for the linear weight factor plateaued at the 3 mm x 7 mm rectangle while the moderately exponential plateau at the 2 mm x 8 mm rectangle.

![Figure 4.7: Comparing cross-shear for rectangular and square paths completed by Turell et al. [5] and Korduba et al. [15] assuming an elevated wear distance of 5 mm, a unidirectional wear factor, $k_0 = 1 \times 10^{-11}$ mm$^3$/N*mm, and a cross-shear wear factor, $k^* = 5 \times 10^{-9}$ mm$^3$/N*mm](image)

In 2008, Kang et al. [19] completed experimental and computational cross-shear testing on conventional and crosslinked (10 MRad, 100 kGy) GUR1050 UHMWPE exposed to both translation and rotation. Unlike the testing described in Chapter 3, Kang et al. [19] tested pins loaded with 160 N (nominal contact pressure of 3.18 MPa) that both translated and rotated under load during the course of a cycle. This motion was modeled using the cross-shear metric and Figure 4.8 compares Kang et al. [19] test results for conventional UHMWPE with predictions by the cross-shear model. As can be seen from
the figure, the cross-shear model follows the curve profile from the experimental results, but underpredicts the volumetric wear rate at higher angles, with the linear weight factor producing the closest estimate to the experimental results.

Kang et al. [19] tested two ± 20˚ wear paths, one with a sliding path 20 mm long and the second slid 12 mm. In this study it was reported that “the mean wear factors were 4.7±0.37 x 10^-7 and 5.5±1.7 x 10^-7 mm3/Nm for kinematical combinations of (±20°, 20 mm) and (±20°, 12 mm) respectively, although computational analysis showed a consistent CS of 0.039” [19]. The higher wear factor for the 12 mm sliding distance reflects a higher cross shear, but the analysis model used Kang et al. was unable to predict this [19]. The linear cross-shear model, using an elevated wear distance of 5 mm, a unidirectional wear factor, \( k_0 = 1*10^{-11} \text{ mm}^3/\text{N*mm} \) and a cross-shear wear factor, \( k^* = 5*10^{-9} \text{ mm}^3/\text{N*mm} \), predicted cross-shear intensity factors of .0792 and 0.08519 for the ±20°, 20 mm and ±20°, 12 mm respectively, correctly predicting a worse cross-shear for the shorter sliding distance. The highly exponential weighting factor, using the same parameters as above, also predicted worse cross-shear for the shorter sliding distance, but the cross-shear factors predicted by this model were 0.0264 and 0.0427 for the ±20°, 20 mm and ±20°, 12 mm respectively, close to the estimates made by Kang et al. [19].
Using the wear factors estimated for crosslinked material, the cross-shear model was used to predict wear in the angle testing described in Chapter 3. Figure 4.9 compares experimental results from the crosslinked material angle testing to predictions by each of the cross-shear models. As can be seen by the figure, the moderate exponential weighting factor provides a fairly good estimate for all test results except the 70˚ testing, which is estimated best by the linear weighting factor model. Cross-shear intensity factors reported in Figure 4.5 (B) are identical for crosslinked material since pins of both materials followed identical cross-shear paths.

As discussed earlier, Dressler et al. [16] measured crosslinked UHMWPE wear following square paths that varied in side length from 1 mm to 100 mm. This study experimented on two types of GUR 1020 crosslinked material, GVFT™ gamma irradiated to 40 kGy and XLK™ irradiated to 50 kGy. Figure 4.10 compares Dressler’s experimental results with predictions from the cross-shear model, using both linear and exponential weighting factors, and an elevated wear distance of 5 mm. For both materials, a unidirectional wear factor, \( k_0 = 1 \times 10^{-12} \text{ mm}^3/\text{N*mm} \), and a cross-shear wear factor, \( k^* = 2 \times 10^{-10} \text{ mm}^3/\text{N*mm} \), was used, but because of the different irradiation doses, the GVFT™ used a cross-shear wear factor, \( k^* = 1.5 \times 10^{-9} \text{ mm}^3/\text{N*mm} \), but the higher irradiated XLK™ used a cross-shear wear factor, \( k^* = 2.0 \times 10^{-9} \text{ mm}^3/\text{N*mm} \).
Only the linear weighting factor model was used in order to simplify the comparison. As can be seen in Figure 4.9, the XLK™ follows the same curvature as the test results but under predicts the experimental results. The GVFTM prediction is very close to the 5 mm x 5 mm square and higher, but underestimates the smaller square paths.

Figure 4.10: Comparing experimental results from Dressler et al. [16] for crosslinked UHMWPE pin-on-disk square path testing to predictions from the cross-shear model assuming an elevated wear distance of 5 mm, a unidirectional wear factor, $k_0 = 1 \times 10^{-12}$ mm$^3$/N*mm, and a cross-shear wear factor for GVFTM, $k^* = 1.5 \times 10^{-9}$ mm$^3$/N*mm and 2.0x10$^{-10}$ mm$^3$/N*mm for XLK™

The comparisons described in this section were completed using the cross-shear matrix developed by Petrella et al. [7] implemented into several MatLab scripts. Appendix D shows examples of the MatLab scripts and Excel spreadsheet used to generate all wear rates, wear factors, and cross-shear intensity factors.

4.4 Finite Element Analysis Using Cross-shear Metric

In the model described above, the contact surface of the pin is considered a single wear surface with a constant load, yielding a wear rate for the entire surface. This model does not account for the pressure distribution across the surface of the pin and any edge effects from the articulating motion. Therefore, a Finite Element (FE) analysis was completed for the pin-on-disk angle testing, described in Chapter 3, to determine the pressure distribution across the surface of the pin as it completes a single wear cycle.
This pressure distribution was input into the cross-shear model to determine its effect on wear.

The Finite Element analysis used commercial software, Abaqus V6.10-1, and non-commercial subroutines, Python scripts interacting with Abaqus input decks and a friction model written in Fortran. The non-commercial software was developed by Jeff Armstrong [26] as part of his Colorado School of Mines master’s thesis. Figure 4.11 shows a flow diagram of the Finite Element analysis process and Appendix E shows

![Finite Element analysis process diagram](image_url)
examples of all files. As can be seen in the flow diagram, the pin and disk geometry and meshing were created using Abaqus/CAE, the finite element analysis was completed using Abaqus/Explicit Analysis, and pressure results from the finite element analysis were post-processed using Abaqus/Viewer. Pressure results were output into an Excel file and used as input for the cross-shear model to calculate wear. A detailed technical description of the finite element analysis can be found in [26] and thus is not repeated. Instead, this thesis focuses only on the specific changes made to the analysis model to complete the pin-on-disk wear analysis.

The finite element analysis broke the articulation cycle into 100 steps and the contact surface of the pin was meshed such that 209 nodes contacted the rigid surface of the disk. Figure 4.12 shows the pin and disk mesh used in this finite element analysis.

Initially the analysis used displacement and load outputs from the Ortho-POD™ sensors as input for the finite element analysis. Identical to testing described in Chapter 3, the initial analysis reciprocated the pin over the disk 13.3 mm for three legs, rotated the pin the angle defined by the test, and then repeated the 13.3 mm reciprocation three more times. Loading during these motions was also obtained from the Ortho-POD™ sensors with load dropping to 50 N during rotation and rising again to 400 N during translation. Unfortunately, the initial analysis encountered a bug in the Abaqus/CAE software during pin rotation that caused the diameter of the pin to constrict during the rotational motion, as shown in Figure 4.13. Therefore, the motion

![Figure 4.12: Pin and disk mesh used in Finite Element analysis. Graphic shows contact normal force during sliding](image)
was altered to a linearized L-shape motion that followed the pin-on-disk test strategy of three 13.3 mm translational legs, but rotation was replaced with an angular turn.

Conventional UHMWPE material properties were altered per the material data sheets, found in Appendix A, and plastic stress/strain curves were generated from testing of ram-extruded UHMWPE GUR 1050, as reported by Bergström et al. [27]. Table 4.6 shows the material parameters used in the analysis and the cross-shear wear coefficients used for the conventional UHMWPE testing.

![Figure 4.13: Abaqus error causing pin to constrict during rotational motion](image)

**Table 4.6: Analysis and material parameters used in the Finite Element analysis**

<table>
<thead>
<tr>
<th>Wear Model Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>0.931</td>
<td>Mg/mm³</td>
<td>Data Sheet Per Vendor</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>850</td>
<td>MPa</td>
<td>[27]</td>
</tr>
<tr>
<td>Poisson Ratio</td>
<td>0.46</td>
<td></td>
<td>[27]</td>
</tr>
<tr>
<td>Plastic Stress/Strain</td>
<td></td>
<td></td>
<td>[27]</td>
</tr>
<tr>
<td></td>
<td>14.3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23.4</td>
<td>.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25.4</td>
<td>.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51.0</td>
<td>.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>102.2</td>
<td>1.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>164.0</td>
<td>1.38</td>
<td></td>
</tr>
<tr>
<td></td>
<td>580.0</td>
<td>1.68</td>
<td></td>
</tr>
<tr>
<td>Friction Coefficient</td>
<td>.04</td>
<td>1</td>
<td>Default</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Viscosity</td>
<td>.05</td>
<td>1.0</td>
<td>[26]</td>
</tr>
<tr>
<td>Damping</td>
<td>Alpha</td>
<td>50</td>
<td>1/s</td>
</tr>
<tr>
<td>Fixed Mass Scaling</td>
<td>Dt</td>
<td>1*10⁻⁸</td>
<td>[26]</td>
</tr>
<tr>
<td>Cross-shear wear coefficient, $k^*$</td>
<td>5*10⁻⁹</td>
<td>mm³/Nmm</td>
<td>Table 4.3</td>
</tr>
<tr>
<td>Unidirectional wear coefficient, $k_0$</td>
<td>1*10⁻¹¹</td>
<td>mm³/Nmm</td>
<td>Table 4.2</td>
</tr>
<tr>
<td>Cycles</td>
<td>250,000</td>
<td></td>
<td>[26]</td>
</tr>
<tr>
<td>Mem (80 mm/100 cycles)</td>
<td>6</td>
<td>(4.8 mm) [16]</td>
<td></td>
</tr>
</tbody>
</table>
As shown in Figure 4.14, the finite element analysis produced pressure distributions across the contact surface of the pin that reflected the articulation motion and edge effects. Pressure distributions for one wear cycle for each test configuration were downloaded into excel spreadsheets, as shown in Appendix F, and used as input into the cross-shear model.

![Figure 4.14: Pressure distribution of translating pin for 90° path (a) moving to the right, (b) moving forward after the L turn](image)

The result of the FE analysis was compared against wear rates from the empirical testing and wear rates from the simplified MatLab analysis, as shown in Figure 4.15.

![Figure 4.15: Comparison of pin-on-disk test results, linear weighting factor cross-shear model, and finite element model](image)
This comparison shows that the finite element analysis successfully followed the wear rate trends as the angle reduced, but the finite element analysis under predicts wear compared to the simplified linear cross-shear model. This result is surprising, but can be justified by the cross-shear model's strong correlation between wear and load. The finite element pressure distributions depend on the cyclic loading of the pin, which drops to 50 N while the pin spins and rises to 400 N as the pin translates. The Ortho-POD™ could not instantaneously change loading, so each load change occurs with a time delay, as shown in Figure 4.16. This delay means the first 13.3 mm sliding distance occurs as the load is still rising from 300 N to 400 N and thus the finite element model experienced less loading during this initial sliding distance. In the simplified cross-shear model, the pressure is assumed a constant 5.61 MPa throughout the entire cycle.

Figure 4.16: Pressure distribution of each node on contact surface of pin through a single motion cycle
4.5 Discussion

Computational analysis provides a low-cost, quick turn-around method to predict UHMWPE wear of implant bearings. The cross-shear metric developed by Petrella et al. [1], like many wear models in development, is a wear algorithm based on empirical test results. The model assumes the cross-shear wear coefficient, $k^*$, and the unidirectional wear coefficient, $k_0$, are material properties that are independent of sliding path. Table 4.7 shows the wear coefficients for both conventional and crosslinked UHMWPE used in all analysis completed in this thesis.

<table>
<thead>
<tr>
<th>Wear Coefficient Description</th>
<th>Material</th>
<th>Wear Coefficient Value (mm$^3$/N*mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional wear coefficient, $k_0$</td>
<td>Conventional UHMWPE</td>
<td>$1 \times 10^{-11}$ mm$^3$/N*mm</td>
</tr>
<tr>
<td>Cross-shear wear coefficient, $k^*$</td>
<td>Conventional UHMWPE</td>
<td>$5 \times 10^{-9}$ mm$^3$/N*mm</td>
</tr>
<tr>
<td>Unidirectional wear coefficient, $k_0$</td>
<td>Crosslinked UHMWPE</td>
<td>$1 \times 10^{-12}$ mm$^3$/N*mm</td>
</tr>
<tr>
<td>Cross-shear wear coefficient, $k^*$</td>
<td>Crosslinked UHMWPE, below 50 kGy irradiation</td>
<td>$1.5 \times 10^{-9}$ mm$^3$/N*mm</td>
</tr>
<tr>
<td>Cross-shear wear coefficient, $k^*$</td>
<td>Crosslinked UHMWPE, above 50 kGy irradiation</td>
<td>$2 \times 10^{-10}$ mm$^3$/N*mm</td>
</tr>
</tbody>
</table>

The results from the comparisons described support the hypothesis that the unidirectional wear coefficient, $k_0$, and the cross-shear wear coefficient, $k^*$, are material properties, independent of cross-shear path. In the analysis done in this thesis, the wear coefficients and elevated wear distance were kept constant in all analysis and the cross-shear model produced reasonable predictions of UHMWPE wear for different studies with different cross-shear paths. The cross-shear intensity factors in the studies analyzed varied from 0 to 0.55, as shown in Figure 4.17, indicating the cross-shear metric is valid for many types of cross-shear paths. The comparisons also indicate that using an elevated wear distance of 5 mm, as determined by Dressler [16], is reasonable, but there is no conclusive evidence that the wear weighting factor reduces linearly or exponentially.

Additional experimental testing is needed to further evaluate elevated wear, both to determine how elevated wear changes (linearly, exponentially, etc.) as it moves further
from the turn and to more precisely determine the distance experiencing elevated wear. Ideally, pin-on-disk testing should be completed for squares that increase in side length from 3 mm to 8 mm with a 1 mm side increment increase per test. Other recommended future work includes increasing the number of comparisons of published studies to validate other cross-shear paths, especially for crosslinked materials. Crosslinking significantly alters the morphology and material characteristics of UHMWPE and it is believed wear coefficients for crosslinked materials may need to be broken down into more precise crosslink ranges. Most importantly, the cross-shear metric needs to be evaluated against empirical test results of actual implants, not just pin-on-disk testing.

Limitations of the computational analysis include the limited number of published studies analyzed and the necessity of estimating wear rates and wear factors published in some studies from graphics [5,15,19]. The cross-shear model was unable to predict the wear peaks observed by Turell et al. [5] and Korduba et al. [15] during their rectangle testing, indicating these tests encountered parameters contributing to wear not included in the cross-shear model. Pin-on-disk testing in Chapter 3 indicated elevated wear after

Figure 4.17: Comparison of cross-shear intensity factor, $x^*$, calculated using the linear cross-shear model, for the cross-shear paths used in the analysis.
angle turns of 40° and higher, but the present cross-shear model still assumes a 90° turn produces worst-case wear. Finally, the cross-shear model calculates wear using an Archard’s law model. Several published studies [9,22,28,29] question the validity of assuming UHMWPE wear is proportional to load and thus question the validity of using Archard’s law.

For future work, it is recommended the cross-shear model be updated to include elevated wear for 40° and larger cross-shear angles. Additional cross-shear modeling should be completed on a larger number of published studies, including wear testing of actual implants. Further testing should be completed to improve understanding of the relationship between load and UHMWPE wear and from this testing, a determination should be made if Archard’s law should be used to calculate wear, or if another model, like that proposed by Abdelgaied et al. [9] should be used. Finally, the finite element algorithm used should be updated to improve user interaction and provide a single input file that sets all parameters and runs the analysis.

4.6 Conclusion

In conclusion, a computational analysis was done using the cross-shear metric developed by Petrella et al. [7]. Using the wear coefficients specified in Table 4.6 and assuming an elevated wear distance of 5 mm [16], the cross-shear model made reasonable predictions of cross-shear wear for the pin-on-disk studies presented.

4.7 Acknowledgements

The author would like to thank Jeff Armstrong for all his patience and work during the application of the Finite Element Analysis.

4.8 References Cited


5.1 Summary

The excellent mechanical and biocompatible properties of ultra-high molecular weight polyethylene (UHMWPE) have made it the bearing material of choice for knee, hip, elbow, shoulder, and spinal implants [1]. Unfortunately, even with its excellent mechanical properties, analysis of failed orthopedic implants shows wear from UHMWPE bearing surfaces produces micro- and nano-particles that can cause tissue osteolysis, inflammatory bone loss, and aseptic loosening; conditions which can lead to pain during joint articulation and eventually the failure of the implant [1,2]. Implant failure requires revision surgery, often a complex surgery involving additional modifications to the bones surrounding the joint [3]. Therefore, understanding and reducing wear of UHMWPE bearings in implants is critical to reducing implant failure and improving product life.

Early research trying to understand and predict UHMWPE wear initially focused on repetitive, unidirectional wear testing and Archard’s Law [4]. Archard’s Law hypothesized that UHMWPE wear was proportional to contact pressure and sliding distance. Unfortunately, unidirectional wear testing produced wear factors of the order of $10^{-8}$ mm$^3$/N m compared to clinically observed wear factors of the order of $10^{-6}$ mm$^3$/N m [1,5,6]. This difference led to the discovery that cross-shear, or multidirectional sliding, as seen in normal joint kinematics, produced significant wear. Newer studies introduced repetitive, multidirectional sliding and were able to produce UHMWPE wear factors in the same order of magnitude as observed in failed orthopedic implants [7,8]. Improved understanding of UHMWPE wear has led to new analytical models that attempt to increase long-term performance of UHMWPE bearings through improved wear modeling and failure prediction.

Computational simulation is an attractive alternative to experimental testing of UHMWPE wear because of its low cost, versatility, and the speed it can yield results. Implant wear computational simulation studies, using both empirically derived metrics and finite element modeling techniques, have been completed on total knee, hip, and
shoulder arthroplasties [6,9,10]. More recently, iterative, adaptive remeshing analytical models have been developed to analyze wear by incorporating wear factors like cross shear and creep along with other UHMWPE material characteristics [10,11].

5.2 Conclusion

The purpose of this thesis was to use scanning electron microscopy, pin-on-disk testing, and computational methods to improve the understanding of cross-shear wear with the ultimate goal of validating a novel cross-shear model developed by Petrella et al. [10]. The following paragraphs describe the key methods and results from this thesis, the limitations of each area of research, and proposed future work.

Scanning Electron Microscopy (SEM) was used to study the micro-structural characteristics of the material and to visualize preferential reorientation of polyethylene chains and crystalline lamellae that occurs during unidirectional sliding. This thesis hypothesized that molecular realignment of polymer chains on the surface of UHMWPE bearings begin within the first 3-8 mm of sliding after an abrupt 90˚ angular sliding path change and that this movement is the reason for increased wear during cross-shear sliding. The thesis was unable to support this hypothesis due to limitations of the Field Emission Scanning Electron Microscopy (FESEM) used to visualize early molecular realignment. The non-conductive nature of UHMWPE and its reaction to the high energy electron beam used in FESEM scanning caused localized charging of the surface during high magnification and yielded scan errors. Overcoming this issue required sputter-coating of the surface with a conductive material. This thin coating “blanketed” extremely fine detail, yielding visualization of initial molecular realignment, if it exists, unattainable.

Pin-on-disk testing of conventional and irradiated medical grade GUR 1050 UHMWPE was completed on 10˚, 40˚, 70˚, and 90˚ cross-shear paths with pins exposed to identical sliding distances, loading, and contact conditions. It was hypothesized that worst-case cross-shear wear took place after an abrupt 90˚ angular sliding path turn, but results from testing indicate that elevated wear from cross-shear occurs at angles as low as 40˚ and did not increase significantly as this angle increased. Statistically, there was no difference in wear rates for the 40˚, 70˚, and 90˚ cross-shear paths. This indicates that
the cross-shear model will produce low estimates of wear for cross-shear paths with angular turns between 40-70 degrees.

Limitations of the pin-on-disk testing include small sample size (3 pins per material per angle test) and limited number of angular tests completed (four). The low wear rates of the crosslinked UHMWPE introduced measurement complications due to wear volume being in the same order of magnitude as weight gain seen in soak pins. Future pin-on-disk testing is recommended to determine if elevated wear due to cross-shear begins at angles less than 40° and further testing is needed to understand how this elevated wear increases from the wear rates measured at 10° to the elevated wear rates measured at 40°. Finally, additional testing of 60° and 80° angles is needed to determine if the elevated wear rate seen at 70° was statistically relevant and to determine if wear rates reach a maximum value around 70° turns.

The cross-shear model calculates UHMWPE wear using an overall wear coefficient, \( \bar{k} \), composed of a unidirectional wear coefficient, \( k_0 \), and a cross-shear wear coefficient, \( k^* \). The unidirectional wear coefficient and cross-shear wear coefficient are assumed to be material properties of UHMWPE, independent of cross-shear path. The model also assumes the elevated wear after cross-shear lasts only a set distance. The cross-shear model was implemented in a simplified MatLAB script and this script was used to validate the model by comparing published empirical wear rates with predictions from the model. During this comparison, the material properties shown in Table 5.1 were assumed, along with an elevated wear distance of 5 mm [8]. Results from this analysis show for conventional UHMWPE, the cross-shear model successfully predicts wear factors or wear rates of the same order of magnitude as those from empirical testing with a linear elevated weighting factor producing the overall best results. For crosslinked material, the cross-shear wear coefficient was broken into two coefficients, one for material with lower crosslinking and one for materials with higher crosslinking. Results from this analysis show reasonable agreement with empirical test data, but indicate the differences in the material properties of crosslinked UHMWPE may be great enough to warrant three or even four cross-shear wear coefficients for materials with different levels of crosslinking.
Table 5.1: Wear coefficients used in computational analysis

<table>
<thead>
<tr>
<th>Wear Coefficient Description</th>
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<td>$1 \times 10^{-11}$ mm$^3$/N*mm</td>
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<tr>
<td>Cross-shear wear coefficient, $k^*$</td>
<td>Conventional UHMWPE</td>
<td>$5 \times 10^{-9}$ mm$^3$/N*mm</td>
</tr>
<tr>
<td>Unidirectional wear coefficient, $k_0$</td>
<td>Crosslinked UHMWPE</td>
<td>$1 \times 10^{-12}$ mm$^3$/N*mm</td>
</tr>
<tr>
<td>Cross-shear wear coefficient, $k^*$</td>
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<tr>
<td>Cross-shear wear coefficient, $k^*$</td>
<td>Crosslinked UHMWPE, above 50 kGy irradiation</td>
<td>$2 \times 10^{-10}$ mm$^3$/N*mm</td>
</tr>
</tbody>
</table>

Limitations of this computational analysis include the limited number of studies used in the comparison (five) and the necessity to estimate wear rates published in some studies from graphical charts. Future work should include comparisons of additional studies, including computational analysis of implants. Another limitation of this analysis is the validity of calculating wear using an “Archard’s Law” like model. A number of published studies [11-14] have presented data questioning the validity of assuming wear is proportional to load. Future testing is needed to understand the relationship between UHMWPE wear and applied load and determine the validity of using Archard’s Law to calculate wear. Finally, pin-on-disk testing indicates elevated wear after angle turns as low as 40°. It is recommended to update the cross-shear model to increase the weighting factor, $m$, to reflect this new data.

In conclusion, this study focused on improving the understanding of cross-shear wear by validating a cross-shear wear model. In order to understand this wear, a detailed look at the changing morphology and molecular reorientation that occurs during wear was undertaken. In addition, empirical pin-on-disk studies were conducted to clarify the effect of sliding angle change on cross-shear wear. Finally, due to the high cost of experimental testing and clinical trials, computer modeling to predict UHMWPE wear was completed. The ultimate goal of this study was to validate a novel cross-shear metric developed by Petrella et al. [10] through the use of analytical and experimental methods to improve predictions of UHMWPE wear. This validation successfully shows the cross-shear model produces UHMWPE wear rates in the same order of magnitude produced by
empirical pin-on-disk testing, but additional testing is needed to validate if the model successfully predicts wear in implants.

5.3 References Cited


