CHARACTERISTICS OF COBALT CHROMIUM ALLOY SURFACES FINISHED USING MAGNETIC ABRASIVE FINISHING

By

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To my family
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<td>COEFFICIENT OF FRICITION</td>
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<td>DLC</td>
<td>DIAMOND-LIKE CARBON</td>
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<td>HDPE</td>
<td>HIGH DENSITY POLYETHYLENE</td>
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<td>LVDT</td>
<td>LINEAR VARIABLE DIFFERENTIAL TRANSFORMER</td>
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<td>UHMWPE</td>
<td>ULTRA HIGH MOLECULAR WEIGHT POLYETHYLENE</td>
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Characteristics of Cobalt Chromium Alloy Surfaces Finished Using Magnetic Abrasive Finishing

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Freeform surfaces, including the femoral components of knee prosthetics, present a significant challenge in manufacturing. The finishing process is often performed manually, which leads to surface finish variations. In the case of knee prosthetics, this can be a factor leading to accelerated wear of the polyethylene tibial component. The wear resistance of polyethylene components might be influenced by not only the roughness but also the lay of femoral component surfaces. This study applies Magnetic Abrasive Finishing (MAF) for nanometer-scale finishing of cobalt chromium alloys, which are commonly used in knee prosthetics and other freeform components. First, using flat disks as workpieces, this paper shows the dominant parameters for controlling the lay in MAF and demonstrates the feasibility of MAF to alter the lay while controlling the surface roughness. The manually finished disk surfaces (with roughness around 3 nm \( Sa \)), consisting of random cutting marks, were compared to MAF-produced surfaces (with roughness between 2-3 nm \( Sa \)) with various lays. Tests using deionized water droplets show that the lay influences the wetting properties even if the surface roughness changes by no more than a nanometer.
Surfaces with unidirectional cutting marks exhibit the least wettability, and increasing the cross-hatch angle in the MAF-produced surfaces increases the wettability. Surfaces consisting of short, intermittent cutting marks were the most wettable by deionized water. Coefficient of friction tests in deionized water show a decrease in coefficient of friction for MAF-processed surfaces. The MAF process is extended to finish femoral knee components. The previously mentioned surface lays were reproduced on the freeform condyle surfaces of the femoral knee components. The as-received surface consisted of several protuberances (with roughness of 8.4/2.3 nm Sa at 10X/40X), which were removed after the MAF process (to a roughness of 5.5/2.7 nm Sa at 10X/40X). It was verified that the MAF process does not alter the form accuracy of the freeform surface, suggesting that this process can be used to control the surface lay and surface roughness of freeform surfaces.
CHAPTER 1
INTRODUCTION

1.1 Freeform Finishing

Surface finishing is often a critical step in the manufacturing process. Finishing can be performed for a variety of reasons such as to remove burrs, reduce friction, improve adhesive properties, increase electrical conductivity, or simply to improve the aesthetic properties of a part. A wide range of techniques have been established to accomplish these tasks such as sand blasting, shot peening, honing, grinding, buffing, electropolishing, and magnetic field assisted finishing. The specific approach necessary depends on the geometry of the part in question and the surface finish required. Freeform surfaces in particular, present a great deal of difficulty in the manufacturing process. For example, the geometry of artificial knee joint surfaces is produced by grinding, and a finishing process is required following grinding to reduce the surface roughness to less than 5 nm $Sa$ without disturbing the form accuracy. The surface finishing of freeform surfaces is often performed manually in practice, increasing quality variation and production costs. To improve the current situation, freeform finishing in practical use (e.g., in optical-related industries) has been reportedly automated using two technologies using flexible tools: magnetorheological (MR) fluid polishing [1-4] and bonnet polishing [5, 6]. The former process uses MR polishing fluid as a polishing tool. The rheological properties (e.g., viscosity) can be controlled by a magnetic field. The behavior of the fluid suspended in a magnetic field enables it to form a tool to polish while conforming to a freeform surface. The latter process uses a reinforced rubber tool attached to a seven-axis CNC machine tool. Physical contact of the tool against a freeform surface causes the tool to deform and conform to the workpiece. Both of these...
flexible tools have been applied to the surface finishing of the femoral components of knee prosthetics [7-9].

Magnetic Abrasive Finishing (MAF) has also been used to finish complex components. Shinmura et al. [10] manipulated a composite magnetic abrasive particle (made by sintering aluminum oxide to iron powder) in a magnetic field to finish cylindrical components. Fox et al. [11 fox] studied the effects of slurry type, lubricant, flux density, and rotational speed and vibration on the finishing of rollers. Jain et al. [12] improved the rate of material removal by using a pulsed magnetic field to stir the magnetic abrasive slurry and introduce new cutting edges to the workpiece surface. Yamaguchi et al. [13] used MAF to polish internal surfaces of tubes and verified that the “process belongs to the category of pressure-copying processes” by demonstrating that “longer wavelength components of the roughness profile” remained after finishing. Jayswal et al. [14] developed a numerical technique to simulate the material removal mechanism during MAF and predict the changes in surface roughness. Mori et al. [15] described the energy requirements for forming the magnetic abrasive brush and developed a mathematical model of the forces necessary to achieve finishing. Singh et al. [16] performed a parametric study to identify the parameters responsible for influencing surface quality. Using voltage, working gap, rotational speed of the magnet, and abrasive size as the parameters, they found that voltage and working gap were the most significant parameters responsible for imparting the largest change in surface roughness.
Although these and other laboratory-level technologies are ever progressing, to further improve the surface quality by orders of magnitude, a significant advance is highly desired.

1.2 Wear Mechanisms of Knee Prostheses

As seen in Figure 1-1, knee prostheses consist of multiple parts: a freeform shaped femoral component that attaches to the femur, a tibial tray that attaches to the tibia, a tibial insert (the main load bearing element) that is housed on top of the tibial tray, and occasionally a patellar component (not shown) [17]. Currently, the most common materials used in knee prostheses are a CoCr femoral component that articulates against an ultra-high molecular weight polyethylene (UHMWPE) tibial component. Over 600,000 knee joint replacement surgeries are performed in the United States every year [18]. The reason for performing a knee joint replacement varies, but is commonly attributed to pain associated with diseases such as osteoarthritis and rheumatoid arthritis, and of course physical trauma most commonly associated with automobile accidents. With improvements in engineered materials and prosthetic longevity, knee joint replacement is becoming more and more common, with experts estimating that in 10 years there could be as many as 3.2 million knee replacement surgeries per year [19]. Younger and more active patients are receiving knee prostheses resulting in a higher demand for longer lasting components. Currently, there are over 35,000 knee bearing failures each year in the US, requiring revision surgery to correct for these failures [20]. Wear typically occurs in the UHMWPE component and can be attributed to numerous factors. Surface topography, third-body debris, and prostheses geometry and load affect the wear rate of the UHMWPE component. Additionally, the surface roughness of the UHMWPE component and its material
property may change depending on the manufacturing and sterilization methods, which may cause further wear.

Surface topography, specifically the surface roughness of the femoral and tibial components, has a large influence on UHMWPE wear [21]. With the metallic femoral component being made of a much harder material, greater care is taken in order for its surface to have a very low surface roughness. The last step in the manufacturing of the metallic femoral component consists of a polishing process whereby skilled laborers perform buffing by hand on the bearing surface of the femoral knees in order to achieve a surface roughness of less than 5 nm Sa. The UHMWPE component, on the other hand, is made using either a machining or compression molding process. Typically their surface roughness is 10 to 100 times greater than the femoral component [22]. The effective counterface surface roughness has shown to increase during simulated, in vitro, articulation. Research has shown that as the counterface roughness increases, the wear factor also increases.

Another form of abrasive wear is observed when third-body debris is generated and trapped between the articulating surfaces. Sources of third-body debris can consist of bone, bone cement, and UHMWPE particles. Third-body debris has been shown to be the leading cause of polyethylene wear and premature failure in vivo [23]. This can be validated by observing embedded particles beneath the surface of UHMWPE components. Third-body debris causes scratches on the articulating surfaces of the prostheses, increasing its surface roughness and thereby increasing wear rates by a factor of as much as 30 to 70, depending on the relative scratch direction [24]. One way to limit abrasive wear due to the effects of third-body debris is by applying a hard
coating such as TiN and diamond-like carbon (DLC) to the articulating surface of the femoral component [25]. Alternatively, limiting the production of third-body debris associated with bone cement may be achieved by using new cementless fixation techniques. This technique is achieved by encouraging bone growth at the interface between the bone and prosthetic via a specialized surface topography on the proximal surface of the prosthetic [26]. Recovery time for cementless fixation is considerably longer, and yet these prostheses still suffer from wear and part loosening analogous to the cementation method [26].

Part loosening, resulting from osteolysis, is a serious complication that is an indirect result from third-body debris, specifically UHMWPE debris. UHMWPE wear particles within a critical size range of 0.1-1 µm have been shown to activate macrophages in the tissues around the replacement joints [27]. Bone resorption then occurs, leading to prosthetic micromotion, which increases wear and encourages additional prosthetic loosening.

Another kind of wear mechanism associated with knee prostheses is delamination wear. Delamination occurs when the loads on the UHMWPE inserts reach high enough values that the contact stresses exceed the compressive yield stress of UHMWPE [28]. The resulting worn surface flakes off as flat fragments of debris, which then contribute to other wear mechanisms such as abrasion in the form of third-body debris. In order to reduce this type of wear, much work has gone into the design of the prostheses, via FEA studies, in order to increase congruency between components and thereby reduce contact stresses. The evolution of knee prostheses’ geometry is a testament to this fact, having become more freeform and complex shaped. Research
has shown that increasing congruency between femoral and tibial components helps reduce wear [28].

The surface roughness of UHMWPE inserts (either machined from extruded stock or compression molded) can also have an effect on its wear rate. Bankston et al. performed a study comparing results from 54 patients from each of two groups: those who had molded polyethylene and those with machined polyethylene acetabular cups [29]. Both groups had approximately the same average weight (161 pounds), age (66 years old), and follow-up time (6.7 years). The paper concluded that rates of polyethylene wear for compression molded inserts were 0.05 mm per year whereas those for machined polyethylene were 0.11 mm per year. Both followed a linear wear rate. Although this study focused on hip arthroplasty, since the material and manufacturing technique is the same as used for tibial inserts in knee arthroplasty, we can draw the same conclusion. It suggests that compression molded polyethylene inserts are preferred over machined inserts. However, the much lower production costs associated with machined inserts has led to its continued use.

The final step in the manufacturing process of knee prostheses is the sterilization of the components in preparation for implantation. Sterilization of the polyethylene component is achieved by gamma irradiation, typically of 25 kGy. Irradiation is known to cause crosslinking within the polymer resulting in chain scission and the generation of long-lived free radicals [30]. This can have an effect in the long term mechanical properties of the material and therefore its wear rate. Specifically, there is concern that gamma irradiation causes oxidative degradation which affects the density and modulus of the material [30]. A study performed by Fisher et al. tested three groups of UHMWPE
materials: unirradiated material, irradiated material (aged 2 months), and irradiated material (aged for 5 years) [30]. Results showed a statistically significant increase in wear rate for materials irradiated and aged for 5 years. The current method used to mitigate these problems is to irradiate the components in an inert gas, thereby reducing the ageing effects and oxidation, which may lead to improved wear characteristics.

Consequently, wear of artificial knee joints is composed of a complex series of mechanisms. A variety of these mechanisms, however, can be attributed to surface irregularities of the femoral component that causes wear of the UHMWPE tibial component during articulation and create debris. This is often cited as the primary cause of tissue inflammation and osteolysis, leading to a wide range of medical issues including eventual failure [27, 31].

1.3 Desired Functions for Knee Prosthetic Surfaces

It is known that surface roughness has a significant correlation with contact angle (a measure of surface wettability) [32-34]; this trend has been exploited to improve component performance in various fields, such as in the bio-medical, chemical, electrical, and mechanical fields [35-38]. In addition to surface roughness, surface lay (repetitive impressions created on the surface of a part) is considered to be a critical factor affecting the fluid film condition between solid bodies and the coefficient of sliding friction for precision finished surfaces [39]. In a study on the honing of engine cylinder liners, cross-hatch angles and groove patterns on the liner surfaces were shown to play important roles in the sliding friction of components and thus engine performance [40].

Tribological studies of UHMWPE and stainless steel couplings have found that the wear factor (normalized wear volume with respect to load and sliding distance) increases exponentially with increasing surface roughness [31]. The wear rate may be
enhanced—and thus the longevity of prosthetics—by decreasing the surface roughness. Additionally, material wettability has also been shown to play a role in wear [41]. Research shows that contact between two solid surfaces that have a large difference in wettability leads to an increased fluid film thickness between the surfaces, which results in a reduced wear rate [41]. Specifically, research shows that in order to increase the fluid film thickness, the pin in pin-on-disk experiments must display hydrophilic properties while the disk must display hydrophobic properties [42]. Observing that the bearing surface on a knee prosthesis consists of a relatively flat UHMWPE tibial component and a convex femoral part, it was hypothesized that the wear rate in the prosthesis would decrease with the combination of a more hydrophilic femoral component and a less hydrophilic tibial component.

Although the focuses of these previous studies were on the submicron to micrometer scales, similar effects might be shown on the nanometer scale. In other words, controlling surface texture and the surface roughness on the nanometer scale might show potential for increasing the hydrophilicity of femoral components, thereby improving the wear resistance of tibial components in knee prosthetics.

MAF has been shown to finish freeform surfaces and other complex geometries because of its characteristics including flexible magnetic particle chains that form along the lines of magnetic force and conform to the workpiece surface [43-45]. The material removal mechanism of MAF is attributed to micro-cutting of the surface, and the motion of the magnetic particle tools results in characteristic surface textures [12, 13, 46].

1.4 Objectives

This study proposes the application of MAF to finish freeform surfaces (e.g., femoral knee components). The finishing equipment is specifically designed and built for
this study, and both flat cobalt chromium (CoCr) disks and femoral knee components are used as workpieces. In addition to finishing the surfaces, this project aims to develop a method to modify the surface lay and wettability in order to decrease wear of the finished part. The surface lay is varied through different abrasive types, size, and dynamic motion controlled by the ferrous particles in the presence of a magnetic field. The dominant parameters for controlling the lay with MAF are determined and the feasibility of MAF to alter the lay while controlling the surface roughness is demonstrated. Using different surface lays produced by MAF, the effects of lay on the contact angle with deionized water (i.e., the wettability), and the coefficient of friction are studied.

Figure 1-1 Knee prosthetic (Photograph courtesy of Exactech) [17]
CHAPTER 2
MAGNETIC ABRASIVE FINISHING

2.1 Processing Principle of Cobalt Chromium Disk

In Magnetic Abrasive Finishing (MAF), a magnetic field is used to maneuver a flexible “magnetic brush” (composed of ferromagnetic particles and abrasive particles suspended along the lines of magnetic flux) over the surface to be finished. The relative motion between the brush and the surface can be obtained either by rotating the brush, moving the workpiece, or both. The brush typically consists either of a composite of magnetic abrasive particles, where the ferromagnetic and abrasive particles (e.g., silicon carbide, aluminum oxide, cubic boron nitride, or diamond) are sintered together; or separate abrasive and ferromagnetic particles which are homogeneously mixed. For the latter case, a lubricant is often used to aid in holding the abrasive particles in suspension within the flexible brush.

The advantage of using MAF to finish freeform surfaces is that the characteristic flexible magnetic brush applies a constant pressure to the surface, resulting in consistent material removal despite the surface geometry. The surface is finished, but longer wavelength components of the surface roughness remain [13]. This ensures that the part geometry is maintained after polishing. For certain components with freeform surfaces whose geometry is critical to its performance, this is often a necessity.

A schematic of the MAF principle for finishing freeform surfaces is shown in Figure 2-1. In this MAF process, material is removed by abrasive slurry pushed by magnetic particles in the presence of a magnetic field. The CoCr alloy workpiece is nonmagnetic, so the workpiece is mounted on a magnetic workpiece holder to generate the magnetic circuit needed to form magnetic particle chains between the north (N) and
south (S) poles normal to the target surface. The magnetic force $F$ acting on the particle is given by

$$F = V \chi H \cdot \nabla H$$

(2-1)

where $V$ is the volume of the magnetic particle, $\chi$ is the magnetic susceptibility, and $H$ and $\nabla H$ are the intensity and gradient of the magnetic field at the finishing area, respectively [10].

The abrasive slurry is introduced between the target surface and magnetic particles, and only the abrasives pushed by the magnetic particles (with the force shown by Eq. (2-1)) perform the finishing action. When the pole tip rotates, the mixture of magnetic particles and abrasive slurry rotates with the pole tip, generating relative motion between the abrasive slurry and target surface. The feed motion of the workpiece extends the finishing area to cover the entire surface of the freeform component.

If the workpiece is fed linearly in the vertical direction, the pole-tip rotation and the workpiece feed combine to drive the abrasive along the path shown in Figure 2-2. The cutting velocity $v$ and inclination angle $\Theta$ at any point P is calculated using the following equations:

$$v = \sqrt{(-r \omega \sin \omega t)^2 + (r \omega \cos \omega t + v_i)^2}$$

(2-2)

$$\Theta = \tan^{-1}(-r \omega \sin \omega t / (r \omega \cos \omega t + v_i))$$

(2-3)

where $v_i$ is the workpiece feed velocity, $r$ is the distance from the pole-tip center to the particle, $\omega$ is the angular velocity, and $t$ is the finishing time.
The magnetic particles are suspended along the lines of magnetic force, and the particles suspended at the edge of the pole tip \((r = R)\) show the highest cutting velocity. The cutting velocity \(v\) is maximum \((v_{\text{max}})\) at position A (as shown in Figure 2-2) and calculated as

\[
v_{\text{max}} = v_f + R\omega
\]  

(2-4)

In a strong magnetic field, the magnetic particles form stiff chains. The particle chains and abrasive slurry rotate with the pole tip and show continuous relative motion against the target surface to create a surface finished with long cutting marks [13]. By modifying the workpiece feed \(v_f\) and angular velocity \(\omega\), the instantaneous cutting velocity \(v\) and inclination angle \(\theta\) are altered, resulting in different lays on the finished surface.

If the magnetic force is reduced, the stiffness of the magnetic brush is reduced, resulting in an increase in flexibility of the particle chains. If the stiffness is sufficiently reduced, the friction between the particles and the target surface exceeds the magnetic force binding the particles to one another, resulting in particles being released from the brush. Thus, the magnetic particles do not rotate with the pole tip; instead they may relocate (change position) within the particle chains and release the abrasive slurry. In turn, the finished surface is an accumulation of short, intermittent cutting marks.

In the internal finishing of nonmagnetic tubes, a similar trend has been observed when using slurry with iron particles several micrometers in diameter [46]. When the magnetic force is even weaker, the magnetic particles are spun off and no finishing occurs.
2.2 Limitation of Existing Magnetic Abrasive

Figure 2-3 shows a scanning electron microscopy (SEM) photograph of a composite magnetic abrasive. It is composed of alumina particles (less than 10 µm in diameter) sintered onto iron particles (overall mean diameter 80 µm). This is currently the only commercially available magnetic abrasive. The process for manufacturing composite magnetic abrasives was briefly outlined by Shinmura et al. [10]. Pure iron powder and aluminum oxide (Al₂O₃) are mixed at a weight ratio of 4:1 and sintered under high temperature/pressure conditions (1600K/5MPa) in an inert gas atmosphere. Following sintering, the compound is crushed mechanically and sifted in order to filter the compound to the appropriate particle size.

Since particle size is one of the key parameters responsible for surface quality in MAF, it is desirable to have access to a wide range of sizes. To achieve nanometer scale surface roughness, a smaller abrasive size is typically necessary. The only current means of achieving this is by using a homogeneous mixture of ferromagnetic particles and abrasive particles (often called a “mixed-type magnetic abrasive”). As previously mentioned, a lubricant is often used to keep the abrasive in suspension and maintain the mixture homogeneous. In practical use, however, the finishing motion (often rotational), causes the mixture to separate. Centrifugal force causes the nonmagnetic abrasive particles to be pushed out of the magnetic brush and away from the finishing area. Once outside the finishing area, the abrasive dries and seizes to function as intended. This limitation makes it desirable to develop a new, smaller, composite magnetic abrasive designed to be used for finishing nanometer scale surfaces.
2.3 Development of Nano-Scale Magnetic Abrasive

The development of a smaller (nano-scale) magnetic abrasive particle was investigated. The goal was to synthesize a nano-scale sized magnetic abrasive particle by modifying current synthesis methods in the literature. In particular, two synthesis routes were investigated: solution precipitation and solvothermal reactions. The equipment used for these routes are shown in Figure 2-4.

The solution precipitation reaction setup, shown in Figure 2-4(A), allows for a chemical reaction to take place in an inert atmosphere that can be refluxed for a large amount of time. The contents of the reaction are placed in the triple-neck round bottom flask and heated via the heating mantle. A thermocouple is inserted via a neck of the round bottom flask and monitors the temperature. The inert gas, typically nitrogen or argon, is supplied from the top of the condenser, via Schlenk line (not shown), and preserves an inert atmosphere inside the round bottom flask. Water is constantly pumped through the outside of the condenser in order to ensure that any vapors produced from heating the mixture is returned to liquid phase. This process allows for a reaction to be maintained for substantial time at elevated temperatures.

Another synthesis method explored was solvothermal synthesis, as shown in Figure 2-4(B). If the solvent used in this process is water, the process is termed hydrothermal synthesis. The reactants are placed in a Polytetrafluoroethylene (PTFE) sample holder and filled partially with a given solvent. This insert is placed in the pressure vessel and sealed accordingly. This is then placed in an autoclave, and the temperature is modified according to the specific reaction requirements. The increased temperature and pressure initiates the chemical reaction.
Initial research focused on replicating previous published results, namely the synthesis of nano-sized magnetic particles of various shapes. The first method investigated followed a process by Woo et al. [47], where spherical nanoparticles of 5-10 nm diameter were synthesized via the thermal decomposition of Fe(CO)$_5$ as seen in Eq. 2-5

$$\text{Fe(CO)}_5 \xrightarrow{\Delta 295 \degree C (2h)} \text{FeO} \quad \text{OE/OA/air} \quad \Delta 80 \degree C (18h) \quad \Delta 295 \degree C (2h) \quad \text{Fe}_2\text{O}_3$$

where Fe(CO)$_5$, OE, OA, and Fe$_2$O$_3$ stand for iron pentacarbonyl, octyl ether, oleic acid, and iron oxide, respectively.

Specifically, the nanoparticles were synthesized by injecting 0.4 mL (3.04 mmol) of iron pentacarbonyl, into a mixture containing 20 mL of octyl ether and 1.92 mL of oleic acid at 100 °C and under argon flow. The mixture was heated slowly up to 295 °C and refluxed for 2 hr. Allowing it to cool to 80 °C, aerating for 18 hr, and then refluxing for an additional 2 hr (at 295 °C) completed the decomposition into iron oxide. The solution was washed with ethanol and separated by centrifugation.

Figure 2-5 shows transmission electron microscopy (TEM) photographs at three different magnifications of the products of the reaction. The TEM results show monodisperse, spherical particles of approximately 6-7 nm in diameter (Fe$_2$O$_3$ dots). X-ray diffraction (XRD) was performed in order to confirm its composition. Figure 2-6 shows the XRD pattern of the nanoparticles (in red) and γ-Fe$_2$O$_3$-maghemite (in green). There is good agreement between the synthesized product and Fe$_2$O$_3$; therefore we conclude that the synthesis was successful.
The second type of magnetic particles that were synthesized produced nano-sized rods of 25 nm mean diameter and 400 nm in length. A low temperature hydrothermal synthesis process described by Tang et al. [48] was followed. The synthesis is outlined in Eq. 2-6.

\[
\begin{align*}
\text{FeSO}_4\cdot7\text{H}_2\text{O} + \text{NaO}_2\text{CCH}_3 & \xrightarrow{\Delta 100 \degree \text{C} \atop 8\text{h}} \text{FeOOH}_{(\text{ppt})} + \text{Na}_2\text{SO}_4_{(\text{aq})} \\
\text{FeOOH} & \xrightarrow{\Delta 250 \degree \text{C} \atop \text{Air, } 2\text{h}} \text{Fe}_2\text{O}_3
\end{align*}
\] (2-6)

Distilled water (20 mL) was mixed vigorously with a mixture of FeSO$_4$·7H$_2$O (0.5 mmol of iron sulfate heptahydrate) and anhydrous NaO$_2$CCH$_3$ (1 mmol of sodium acetate). The solution was then placed in the PTFE sample holder shown in Figure 2-4(B) such that it filled about 80% of the volume. An autoclave was used to heat the solution at 100 °C for 8 hr. After cooling to room temperature naturally, the product was centrifuged and washed with distilled water and ethanol, and dried at 40 °C under a vacuum for 4 hr. This produces FeOOH nano-rods as shown in Figure 2-7(A). Considerable agglomeration is witnessed in this TEM photograph. An additional step of heating the as-obtained FeOOH in air at 250 °C for 2 hours results in iron oxide (Fe$_2$O$_3$-hematite) rods with slightly less agglomeration. This is shown in Figure 2-7(B). X-ray diffraction was also performed on the products of this reaction and the results are shown in Figure 2-8. It confirms that the products are Fe$_2$O$_3$-hematite.

Once the synthesis of Fe$_2$O$_3$ dots and rods were successful, attempts were made to bond abrasives to the Fe$_2$O$_3$ during synthesis in order to create a “hybrid nano-crystal” that could be used as a magnetic abrasive. Two commercially available abrasives were considered: aluminum oxide and diamond.
Previous research [49] has shown the viability of synthesizing a core/shell hybrid nano-crystal by forming a silicon dioxide coating over the Fe$_2$O$_3$ dots synthesized from Eq. 2-5. Casavola et al. [50] has shown a surfactant-directed approach to synthesize hybrid nano-crystals composing of titanium dioxide (TiO$_2$) rods with cobalt (Co) spheres where the TiO$_2$ rods act as nucleation sites for the Co spheres. These approaches motivated the attempt to synthesize a hybrid nano-crystal with Fe$_2$O$_3$ and Al$_2$O$_3$. The procedure, a modification of [50], was as follows:

Three mmol of Fe(CO)$_5$ and 3.1 mL of oleic acid was injected into a sonicated mixture of 2/3 mmol Octanoic acid, 1 mmol oleylamine, 5/3 mmol Al$_2$O$_3$ (shown in Figure 2-9(A)) and 5 mL of octadecene. The above solution was refluxed in argon for 30 min as it slowly heated to 250 °C. The result was centrifuged, washed with methanol and dispersed in hexanes.

The resulting product is shown in Figure 2-9(B) and Figure 2-9(C). A coating of what is believed to be γ-Fe$_2$O$_3$ has formed around small clumps of Al$_2$O$_3$. As a magnetic abrasive, it would be ideal to have the opposite relationship: have iron oxide serve as the core, and the alumina serve as the shell.

XRD was also performed of this product. Figure 2-10 shows the Al$_2$O$_3$ content in the product and Figure 2-11 shows the iron content. The presence of Al$_2$O$_3$ was confirmed, but suggests that the Fe$_2$O$_3$ did not form as well as in the case of Eq. 2-5. Increasing temperature and time of reaction will hopefully help to form more solid iron oxide particles on the alumina. A different synthesis route, however, would be required to swap the core/shell components.
The other abrasive used to synthesize a hybrid nano-crystal was polycrystalline diamond (0-0.05 μm) suspended in water. The process described by Tang et al. [48] was again followed from Eq. 2-6 with one modification – 3mL of diamond solution and 7mL of deionized water was added to the iron sulfate and sodium acetate mixture.

The particles are washed in deionized water and dispersed in ethanol. The resulting product is shown in Figure 2-12. The Fe₂O₃ rods are approximately 150 nm in length and 25 nm in diameter. Figure 2-12(A) shows a low magnification TEM that demonstrates considerable agglomeration of the hybrid nano-crystals with a few isolated particles. Figure 2-12(B) shows another TEM photograph in a different area of the grid where isolated particles were present. Small polygonal particles seem to have attached themselves to the longer slender rods. Although no diamond content was detected using XRD analysis, Figure 2-13 confirms the presence of Fe₂O₃ (hematite) content present in the product (most likely the rod shaped particles). Additional characterization is required to further analyze this compound.

To test whether or not the synthesized particles could potentially be used as a magnetic abrasive in MAF, a neodymium magnet (Fe-Nd-B) measuring 0.5 × 0.5 × 1 in. was placed on the lateral surface of the cylindrical glass container (Ø1 × 2 in.) housing the sample. The Fe₂O₃ dots and rods synthesized by following literature [47, 48] showed slight magnetism as they could be manipulated by the magnet. The hybrid nano-crystal samples however showed no reaction to the magnet. Leaving the magnet overnight next to the sample to test for separation of magnetic particles from the hexane suspension resulted in no discernible difference; therefore, no additional tests were conducted. It is concluded that the hybrid nano-crystals synthesized could not
immediately serve as magnetic abrasives in MAF. Suggested improvements for future research include using Fe$_3$O$_4$ (magnetite) as the base iron oxide in future synthesis since it is the most magnetic mineral in the iron oxide family, as well as increasing the temperature and time of synthesis for both hybrid nano-crystal reactions in order to allow more time for iron oxides to form and bond to the abrasives.

Figure 2-1 Schematic of processing principle

Figure 2-2 Schematic of resulting particle motion
Figure 2-3 SEM photographs of magnetic abrasive

Figure 2-4 Synthesis Equipment (A) Solution precipitation (B) Solvothermal synthesis (Photographs courtesy of Author)

Figure 2-5 TEM photographs of iron oxide (Fe$_2$O$_3$) dots at different magnifications
Figure 2-6 X-ray diffraction pattern of iron oxide dots

Figure 2-7 TEM photograph of nano-sized rods (A) FeOOH rods (B) Fe$_2$O$_3$ rods
Figure 2-8 X-ray diffraction pattern of iron oxide rods

Figure 2-9 TEM photographs of iron oxide (Fe$_2$O$_3$) and alumina (A) Al$_2$O$_3$ (B) Al$_2$O$_3$ and Fe$_2$O$_3$ (C) Al$_2$O$_3$ and Fe$_2$O$_3$
Figure 2-10 X-ray diffraction showing Alumina content in Fe$_2$O$_3$+Alumina reaction
Figure 2-11 X-ray diffraction pattern showing Iron content in Fe$_2$O$_3$+Alumina reaction

Figure 2-12 TEM photograph of diamond tipped Fe$_2$O$_3$ rods at different magnifications
Figure 2-13 X-ray diffraction pattern showing Iron content in Fe$_2$O$_3$+Diamond reaction
3.1 Design Concept

In order to realize the described principle from Chapter 2, an MAF machine was developed. In practice, there are two options for creating a magnetic field for use in MAF: a permanent magnet or an electromagnet. While a finishing machine made with permanent magnets is easier to design, an electromagnet allows for precise control of the magnetic field intensity via simply altering the supplied current. Accordingly, an electromagnet was chosen for the design of the finishing machine.

Figure 3-1 shows a schematic of the design of the finishing machine. The finishing machine is composed of an electromagnetic coil that is constrained between two aluminum supports. When current is supplied to the coil, a magnetic field is induced in the ferrous core that is fixed at the center of the coil. The ferrous core extends through the front aluminum support and is housed in a ferrous spindle via a bearing as shown in the section views provided in Figure 3-2. The bearing allows the spindle to rotate about the fixed core. An interchangeable ferrous pole tip is attached to the end of the spindle and assists in concentrating the magnetic field towards its tip. A magnetic flux density of at least 0.2 T at the end of the pole tip is desired in order to provide the necessary force to create a stiff particle chain. A timing pulley is fitted around the spindle and is connected via a timing belt, set in tension by a tensioner, to another timing pulley near the base of the finishing machine. A DC motor drives a coupled shaft that spins the timing pulley and therefore spins the spindle of the machine. This creates part of the relative motion necessary for MAF. Since it is not practical to move the electromagnetic coil, the finishing machine remains stationary. Workpiece feed will be
achieved by manipulating the workpiece in space via a six-axis robot. The robot allows for x, y, and z translation as well as rotation about each of those axes. This creates all motions necessary for finishing the workpieces.

3.2 Finishing Machine

The completed finishing setup is shown in Figure 3-3. It is composed of the previously described electromagnetic finishing machine, a six axis robot, and a DC power supply. The finishing machine is fixed to the table via C-clamps, and power is supplied to the coil of the finishing machine via the power supply. A fan keeps the coil cool during finishing trials with a supplied current to the coil of over 1.0 A. Figure 3-4 shows a photograph of the setup in more detail. The motor that drives the pulleys to rotate the pole tip is a 40 W single-phase brushless motor with a manual speed controller that can vary the rotational speed from 25-2000 min⁻¹.

The coil shown in Figure 3-5 was fabricated by winding 4230 turns of 18 AWG (Ø1.024 mm) insulated copper wire around a double-layered insulated core (Ø40 × 145 mm) made of 1144 carbon steel. The total resistance of the coil is 22.84 Ω and the exciting current can be varied up to 2.63 A. The spindle was made of 1144 carbon steel, the pole tip was machined out of 1018 carbon steel, and the bearing nut is made of 1215 steel (all ferrous materials). The ball bearing housed inside the spindle is made of 440C stainless steel and the timing pulleys are made of 2017 aluminum. The material selection, whether magnetic or non-magnetic, was essential in controlling the magnetic flux flow.

Figure 3-6 shows a photograph of the front of the finishing machine as well as the geometry of the pole tip. As previously mentioned, the pole tip is interchangeable,
allowing for different geometries to be used – just one of the ways that the magnetic field at the pole tip can be varied.

### 3.3 Workpiece Holders

In order to achieve finishing, relative motion between the workpiece and the magnetic brush on the pole tip is required. In addition to the pole tip rotation, translational motion of the workpiece is achieved by the six-axis robot. Since it is easier to clarify the fundamental finishing characteristics and the finishing mechanisms on a flat surface rather than a freeform one, a flat disk was used as a workpiece. The workpiece being finished is a 6.3 mm thick flat disk measuring 31.8 mm in diameter. Since the target application for this process is freeform components, specifically femoral knee components, the workpieces were made of CoCr alloy, the same material that is used for femoral knee components, and were polished to approximately 3 nm Sa, prior to the finishing experiments.

An end effector was designed and fabricated to hold the workpiece onto the robot. The workpiece holder needs to serve three functions: it has to properly secure the workpiece during finishing, maintain positional accuracy during remounting, and be magnetic. Positional accuracy after remounting is important because it is often desired to pause and measure the workpiece surface numerous times during a finishing trial. Positional accuracy allows for finishing of the same location after remounting. As shown in Figure 2-1, magnetic field lines flow from north to south poles. Since the CoCr alloy workpiece is non-magnetic, a magnetic workpiece holder is required to create an opposite pole that draws the magnetic field lines through the workpiece. Without a magnetic holder, the magnetic field lines would curve away from the pole tip, thereby
reducing the magnetic flux density at the workpiece surface. Based on these requirements, the following design was implemented.

Figure 3-7 demonstrates the two-part workpiece holder initially used for finishing the flat disk workpiece. The bottom piece, which mounts to the robot arm, is made of 6061 aluminum alloy – this distances the magnetic field from the robot electronics, preventing any potential interference. The top piece is made from 1018 carbon steel. A v-groove provides support for the workpiece and a set screw holds the workpiece in place.

Due to the lack of a rotational reference frame, consistent workpiece repositioning between finishing trials was unachievable with this design. Additionally, the v-groove and set screw, being magnetic, attracted the magnetic abrasive slurry away from the finishing area.

Two modifications were made to account for these challenges. First, an 8 mm flat was machined on the side of the workpieces, allowing for a rotational reference plane. Additionally, a new magnetic holder was designed and fabricated. Figure 3-8 shows the redesigned workpiece holder that is currently in use. The aluminum base remains the same, but the top magnetic workpiece holder is faced flat and aluminum supports were added to hold the workpiece in place. A stainless steel set screw is still used to hold the workpiece in place. The aluminum supports and set screw prevent translational motion of the workpiece, and the newly machined flat on the workpiece prevents its rotational motion. Additionally, since the supports are non-magnetic, the magnetic abrasive slurry is kept within the target area during finishing.
3.4 Magnetic Flux Density

The pole tip-workpiece clearance and the current supplied to the coil affect the magnetic field, which is the dominant parameter of the finishing force. It is important to know the magnetic field at the finishing area; therefore, the effects of the pole tip-workpiece clearance and current on the magnetic flux density at the finishing area are measured. Additionally, since the exact surface design specifications of knee components are proprietary, it was important to ensure that a finishing program with small variations in the pole tip-workpiece clearance would impart a negligible change in finishing force. Since the finishing force is directly related to the magnetic field intensity, once the workpiece holder was fabricated, the magnetic flux density was measured around the pole tip. Figure 3-9 shows the setup used to measure the magnetic flux density at a given distance from the center of the pole tip. A Hall sensor was used as the probe to measure the magnetic flux density. An aluminum holder clamps the probe to a 3-axis stage that positions the sensor such that it is at the center of the pole tip. This is demonstrated in Figure 3-10, along with the geometric values of the probe.

Figure 3-11 shows the magnetic flux density as a function of current and pole tip-workpiece clearance. An increase to the supplied current of the finishing machine results in an increase in the induced magnetic field. Measurements are taken at a pole tip-workpiece clearance of 1, 2, and 3 mm for every 0.2 A increase in current. Additionally, the probe is calibrated before every measurement. The results in Figure 3-11 show mostly a linear relationship between supplied current and measured magnetic flux density. The difference in the magnetic flux density at 1 and 3 mm clearance is increased as the current increases. The difference is almost negligible for an operating current of less than 1 A, and reaches a maximum difference of 19.1 mT at maximum
operating conditions. These small changes in the magnetic field for such large changes in working distance suggest that the distance between pole tip and workpiece during finishing can be flexible and yet the finishing force shall remain fairly constant. As previously stated, this is important for finishing complex freeform workpieces whose actual surface geometry is unknown and maintaining an exact distance from the surface is not possible.

The power supply supplying current to the coil of the finishing machine operates at a constant voltage designated by the user. During operation, the temperature of the coils is increased, decreasing the magnetic field intensity. Therefore, it is desirable to understand how the current and temperature change as a function of operating time. Figure 3-12 plots the change in temperature and the change in current as a function of time for a supplied voltage of 55.5 V (highest value possible). At this voltage, the starting current is 2.5 A and the starting temperature is approximately 24 °C. After 40 min, the current dropped to 2.10 A and the temperature increased to 50 °C. The temperature at the outer surface of the coil was measured using an infrared thermometer, whereas the value of the current was provided by the power supply. Generally, the temperature increases towards the center of the coil, therefore it was decided to limit the finishing experiments to a maximum outer coil temperature of 40 °C. By repeating the experiment for an initial current set to 1.0 A, it was found that the resulting change in current was negligible. This suggests that as the current increases, the temperature gradient increases. The results from Figure 3-12 are therefore used to determine a maximum finishing time of 15 min.
Figure 3-1 Schematic of the finishing machine

Figure 3-2 Section view of finishing machine design (A) Section side view (B) Detail view
Figure 3-3 External view of finishing setup (Photograph courtesy of Author)
Figure 3-4 Photograph of finishing machine (Photograph courtesy of Author)

Figure 3-5 Fabrication of electromagnet (Photograph courtesy of Author)
Figure 3-6 Photograph of finishing machine and pole tip geometry (A) Front view of finishing machine (B) Pole tip geometry (Photograph courtesy of Author)

Figure 3-7 Workpiece holder for flat disk (Photograph courtesy of Author)
Figure 3-8 Redesigned workpiece holder for flat disk (Photograph courtesy of Author)

Figure 3-9 Magnetic field density measurement setup (Photograph courtesy of Author)
Figure 3-10 Hall sensor positioned concentrically with pole tip (Photograph courtesy of Author)

Figure 3-11 Magnetic flux density as a function of current and pole tip-workpiece clearance
Figure 3-12 Changes in temperature and current with time
CHAPTER 4
SURFACE CHARACTERIZATION METHODS

4.1 Surface Roughness Characterization

To characterize the changes in surface roughness and lay with finishing time, the surfaces of the workpieces were analyzed using an optical surface profilometer. Specifically, a scanning white light interferometer (SWLI) was used to profile the surface and generate surface roughness data and three-dimensional images of the measured surfaces. The profilometer has a lateral resolution of 275.7 nm and a vertical resolution of 0.1 nm.

Figure 4-1 shows a representative image of the as-received surface of the flat workpiece used in this research. Multiple scratches of different length are seen in random directions. Deep scratches and pits are also visible. This texture is characteristic of a buffed surface where the workpiece is pressed against a buffing wheel treated with abrasives. Due to an inevitable range of abrasive size, the occasional large abrasive will therefore dig deeper into the workpiece, removing more material than intended and creating a deeper scratch. Human error during buffing may also lead to surface defects. Although the surface roughness value varies, the as-received roughness was typically around 3 nm Sa.

The surface was evaluated at five locations termed L1, L2, L3, L4, and L5 as shown in Figure 4-2. A 125 µm × 125 µm target area at each location was filtered using a Gaussian spline band pass filter with low and high cutoff wavelengths of 25 µm and 0.828 µm, respectively. The high cutoff wavelength is intended to remove noise and is derived from the resolution of the objective used. The low cutoff wavelength was chosen
based on the specifications for assessing surface textures as detailed in ISO 4287 and ISO 4288.

Five different surface roughness parameters are used to characterize the surfaces in this research: $Ra$, $Rz$, $Sa$, $S_z$, and $S_{sk}$. $Ra$ corresponds to the arithmetic mean deviation of the assessed line profile, $Rz$ corresponds to the maximum height deviation of the profile (also known as peak-to-valley), $Sa$ corresponds to the arithmetic mean deviation of the assessed area, $S_z$ corresponds to the maximum height deviation of the assessed area, and $S_{sk}$ corresponds to the skewness of the three dimensional surface texture.

In order to evaluate the 2-dimensional surface roughness parameters $Ra$ and $Rz$ from this target area, four 80 µm profile lines placed equidistant in the target area were measured. The surface roughness, $Ra$ or $Rz$, of the entire workpiece is therefore an average of 20 measurements. This was done to ensure that the results were representative of the overall surface. The 3-dimensional surface roughness values $Sa$, $S_z$, and $S_{sk}$ on the other hand, corresponds to an area surface roughness or skewness and thus only one value is recorded per location evaluated. Since five locations were evaluated, a total of five measurements make up the average $Sa$, $S_z$, and $S_{sk}$ of a given workpiece.

4.2 Coefficient of Friction Characterization

One of the goals of this study is to use MAF to improve the tribological properties of the surface in order to improve wear. A key parameter of wear between components is its coefficient of friction. The coefficient of friction of eight CoCr workpieces against High Density Polyethylene (HDPE) was measured before and after finishing with the use of a reciprocating tribometer. A schematic of the principle is shown in Figure 4-3.
The workpiece (CoCr) is fixed to a one-axis stage that allows for reciprocating motion while a load cell presses the sample (HDPE) down onto the workpiece at a constant force. The load cell measures forces in the normal and frictional (tangential) directions during reciprocation. The coefficient of friction between the two samples is calculated as the ratio between the frictional and normal forces.

Figure 4-4 shows a photograph of the tribometer used for measuring the coefficient of friction between cobalt chromium alloy disk and a spherical high density polyethylene (HDPE) sample. Since UHMWPE was unattainable, HDPE was used because its material properties are similar to UHMWPE. UHMWPE’s density and tensile strength are commonly reported as 927-944 kg/m$^3$ and 21 MPa, respectively; whereas those of HDPE are 940-965 kg/m$^3$ and 20-32 MPa, respectively [51, 52]. The HDPE sample is mounted directly underneath the load cell (not visible) and replaced after each test. A linear variable differential transformer (LVDT) is fixed to the one-axis stage in order to measure workpiece position, speed, and total displacement. The workpiece is placed in a holder, shown in Figure 4-5. It was designed to be submerged in deionized water during measurement to act as a lubricant. A constant velocity is required to properly measure the coefficient of friction. Due to the workpiece’s small size, measurements were taken along the polishing direction (up/down with respect to the SWLI figures shown in Chapter 5) since it provides the largest translational distance for achieving constant velocity.

Parameters used for the testing were chosen based on physiological values for loads and speeds of a knee joint. Hertzian contact pressure calculations were used to determine a normal load of 38-40 N in order to simulate typical joint pressures. A speed
of 30.48 mm/s (1.2 in/s) was chosen to prevent splashing of the lubricant. A stroke of 20 mm was used to transverse the finished region of the workpieces. The HDPE sample was used under these conditions for 10 m to allow time for the coefficient of friction values to reach steady state. The data is sampled at 1000 s\(^{-1}\). After one complete cycle (40 mm), an average coefficient of friction is calculated and recorded along with its standard deviation. This is repeated for the duration of the experiment. Coefficient of friction values achieved a steady value after approximately 3-4 m. The average coefficient of friction in this steady state region was recorded as the workpiece coefficient of friction.

### 4.3 Wettability Characterization

A Rame-Hart contact angle goniometer was used to measure the wettability of the workpieces. The experimental setup is shown in Figure 4-6(A). A CCD camera is oriented toward the sample while a light source provides diffuse background lighting. A computer controlled micro-syringe forces liquid (deionized water) through a micro-pipette onto the surface of the sample. The camera records an image of the droplet and sends the image to the computer for post processing. Post processing software such as “Image J” or “Photoshop” is then used to measure the angle at the triple point (solid, liquid, and gas interface). This angle is termed the contact angle and is what defines a sample’s wettability. Generally, contact angles less than 45° are identified as very hydrophilic and contact angles larger than 90° are considered very hydrophobic [42].

Different types of contact angles can be measured: ascending, descending, static, or dynamic contact angles. For the purposes of measuring wettability, only an ascending or a static contact angle is necessary. A static contact angle refers to the contact angle measured immediately after dispensing a precise amount of fluid,
whereas the ascending contact angle is measured during continuous addition of fluid to a droplet. The maximum angle before the droplet spreads across the surface of the workpiece is the ascending angle. In this research, the static contact angle is used due to its ease of use, repeatability, and reduction of user bias.

The workpieces in this study were cleaned with acetone and rinsed with ethanol prior to measurement. Two microliters of deionized water was deposited and the droplet shape was recorded and analyzed. As shown in Figure 4-6(B), the droplet is hemispherical, allowing for measurement of the contact angle using the spherical-cap model. The static contact angle $\theta$ is given as a function of the droplet height $h$ and diameter of contact area $d$:

$$\theta = 2 \cdot \tan^{-1} \left( \frac{2h}{d} \right)$$  

(4-1)

The contact-angle tests were conducted at each location (L1–L5 in Figure 4-2) for all workpieces. The average of five contact angles measured at each location in the workpiece feed direction are shown as representatives.

Figure 4-1 Image of as-received surface by optical profilometer
Figure 4-2 Workpiece geometry and measurement areas

Figure 4-3 Schematic of principle to measure coefficient of friction
Figure 4-4 Photograph of tribometer setup (Photograph courtesy of Author)

Figure 4-5 Workpiece holder for coefficient of friction measurement (Photograph courtesy of Author)
Figure 4-6 Goniometer setup and contact angle measuring method (A) Experimental setup (B) Spherical-cap model (Photograph courtesy of Author)
CHAPTER 5
SURFACE MODIFICATION AND CHARACTERIZATION

5.1 Control of Surface Lay

As previously stated, the goal of this research is to use MAF to finish freeform surfaces, with femoral knee components serving as a target application. This research aims to modify the surface texture while controlling the surface roughness in order to improve its tribological properties. Therefore, the goal of the finishing tests is to create various surface lays and investigate the relationship between lay, surface roughness, wettability and coefficient of friction. Current literature has shown that wear of prosthetic implants increases logarithmically with surface roughness, therefore, maintaining a low surface roughness is essential [31].

This chapter discusses the results from finishing the flat disk workpieces described in section 4.1. The finishing motion consists of feeding the workpiece vertically from the center of the workpiece while the finishing machine’s pole tip rotates. This up and down motion is repeated for the duration of the polishing trial. Since the workpieces being finished have already been buffed to a surface roughness of approximately 3 nm Sa, in order to further reduce the surface roughness, a mixed-type magnetic abrasive slurry is used in order to take advantage of the smallest commercially available abrasive particles.

The experimental protocol for a finishing trial involves:

1. Weigh a designated amount of iron powder and diamond (abrasive) powder onto a plastic petri dish

2. Mix in lubricant to create a uniform mixture (components are mixed by rotating a magnet underneath the petri dish)

3. Apply mixed slurry to the pole tip and run the selected finishing program
4. Resupply the pole tip with fresh magnetic abrasive slurry every 15 minutes

5. Clean workpiece by rinsing off excess slurry with deionized water and wiping with ethanol soaked cotton wipes

5.1.1 Key Parameters for Controlling Particle Motion

Various trials were initially performed using a heuristic approach in order to determine the appropriate values of experimental parameters. Parameters that were varied include iron particle size, weight ratios of iron particle to abrasive particle, supplied current, and finishing time. The trends observed during these initial experiments were used to develop processing parameters for the finishing trials presented in this document.

Since one of the goals of this study was to find the relationship between surface lay and wettability, the challenge was to set conditions that altered the lay with minimal changes to the roughness $Sa$. In order to create different surface lays, it is necessary to control the magnetic abrasive particle motion as described in section 2.1. This was done by changing the relative motion between the particles and the workpiece surface through controlling the stiffness of the magnetic abrasive brush.

Figure 5-1 demonstrates the concept of the magnetic particle brush in MAF: a chain of magnetic particles is formed along a line of magnetic force. The force of this magnetic brush can be influenced by both the intensity of the magnetic field and the volume of the magnetic particles forming the brush. Increasing the magnetic field intensity or increasing the magnetic particle size will increase the brush’s stiffness. This increased stiffness causes the abrasives to plow deep into the workpiece surface and be dragged for a long distance. This results in long, deep scratch marks on the finished surface. The surface lay is determined by the relative motion between the abrasives and
the workpiece. This can be manipulated by altering the rotational speed and feed rate during finishing, causing different scratch directions. The equations describing particle motion for a stiff particle chain was described in section 2.1. The resulting surface pattern is a combination of these parameters.

On the other hand, if the magnetic particle brush is flexible, then the abrasives create shallower and shorter cutting marks. The weaker force holding the brush together means that abrasive particles release from the chain (due to friction against the surface) more easily, resulting in short intermittent cutting marks on the finished surface.

Table 5-1 lists four finishing conditions used to generate four kinds of surface lays. Iron particles with two different size distributions, 0-45 µm and 45-150 µm, were used. The workpiece feed rates were 1, 10, and 50 mm/s. The rates of pole tip revolution were 100, 150, and 500 min⁻¹.

Figure 5-2 shows the particle paths in Conditions 1, 2, and 3. The value of \( \theta \) at position B (as shown in Figure 2-2) in Conditions 1, 2, and 3 was calculated using the following equation

\[
\theta = \tan^{-1}(-R\omega/v_f)
\]

(5-1)

to be 50.9°, 80.8°, and 89.8°, respectively. Two-phase finishing was applied in Condition 4, which was designed to produce short, intermittent cutting marks. The first phase produced the desired lay but with a slightly increased roughness. The second phase reduced the roughness, \( Sa \), without disturbing the surface lay.
5.1.2 Surface Fabrication

Finishing experiments for all four conditions were performed twice, resulting in eight finished workpieces. The terminology for finished workpieces is: “Xy” where X denotes the finishing condition used (1, 2, 3, or 4) and y denotes the first or second act of the finishing (either a, or b).

Figure 5-3 shows changes in the surface roughness, Ra, for workpiece 1a at each of the five measured locations (L1-L5) discussed in Figure 4-2. Unless otherwise stated, error bars designate one standard deviation in each direction. Figure 5-4, Figure 5-5, and Figure 5-6 show the average surface roughness (Ra, Sa, and Rz respectively) calculated from locations L1-L5 for each workpiece. Figure 5-7, Figure 5-8, and Figure 5-9 summarize the relationship between average surface roughness, Sa, Sz, and skewness Ssk and the finishing condition used.

Conditions 1-3 show improvement in the surface roughness after MAF. Condition 4a shows an increase to the surface roughness, followed by a reduction in surface roughness after Condition 4b, albeit the surface roughness did not return to its original value. Overall, Figure 5-7 suggests that the conditions used in this study more uniformly finished the target surface with minimal influences in the roughness, Sa. Figure 5-8 suggests that the peak to valley surface roughness Sz, is reduced for conditions 1-3 and has minimal change for condition 4. The skewness of the surface, shown in Figure 5-9, approaches zero for conditions 1-3; suggesting a more uniform surface texture after MAF. The skewness in condition 4 is marginally decreased.

In order to state with certainty whether or not the surface roughness has been modified via MAF, statistical analysis must be conducted. For the purposes of analyzing workpieces before and after MAF, a paired t-test was performed for the data obtained in
this chapter (the pairs consist of the surface roughness at each location before and after finishing). One of the assumptions necessary to perform a t-test is that the data must be obtained from a normal distribution. Figure 5-10 shows a histogram of the surface roughness for an as-received buffed surface and an MAF-processed surface. Each graph represents the spread of the surface roughness for the entire area analyzed. The green bars represent the data set, while a Gaussian curve, in red, is fit to the data. Both Figure 5-10(A) and Figure 5-10(B) show that the surface roughness of the as-received surface and the MAF-processed surface follows an approximate normal distribution. Additionally, since the location of measurement was pre-determined, we can assume a random sampling and therefore avoid selection bias.

A null hypothesis was formed that stated that the mean surface roughness before and after MAF is the same. An alpha value of 0.05 was used to test this hypothesis. The surface roughness parameter, \( Sa \), was evaluated since it provides the most unbiased data due to surface lay. The resulting p-values for a two-tailed, paired, two sample t-test for the data shown in Figure 5-5 is given in Table 5-2. Only workpieces 1a and 3b show a p-value of less than 0.05. This suggests that other than workpieces 1a and 3b, the difference in surface roughness, \( Sa \), before and after MAF are not statistically significant.

Figure 5-11 shows optical images of the finished surfaces at the center of the finished region. These images demonstrate the effects of the finishing conditions on the surface lay. In Conditions 1-3, irregular, multidirectional scratches and indentations on the as-received surfaces (Figure 4-1) have been removed by MAF. The lays resulted from long cutting marks that were generated by the abrasives pushed by the large
magnetic particles. The cross-hatch angle $\phi$ shown in Figure 5-11(A) and Figure 5-11(B) was measured for Conditions 1-3. Five locations on the optical images of the finished surfaces (shown in Figure 5-11) were chosen for the angle measurements. Using ten optical images of each condition, the angles from fifty locations were measured, and the averages of the fifty values were reported as the cross-hatch angle for each condition in Table 5-3. The angle $\phi$ is also calculated as $\phi = 2(90^\circ - \Theta)$, where $\Theta$ is the inclination angle in Equation 5-1. The calculated values are also shown in Table 5-3.

The cross-hatch angles in Conditions 1, 2, and 3 were calculated as 78.2°, 18.5°, and 0.4°. The measured angles are 77.9°, 20.7°, and 0°, respectively. The slower workpiece feed rate resulted in a smaller cross-hatch angle. It is also noted that the calculated and measured values agreed well, demonstrating that the suspended magnetic particles accurately follow the pole tip rotational motion. The major differences between Conditions 1-3 are the relationships between the workpiece feed rate and pole-tip rotational speed. In other words, the relationship between linear and rotational motion was varied. The ratios $R\omega/v_i$ are 1.23, 6.15, 307.3 in Conditions 1, 2, and 3, respectively, and the increased ratio produces a decreased cross-hatch angle.

Condition 4a produced a finished surface consisting of short, intermittent cutting marks using small magnetic particles. The small magnetic particles resulted in a smaller finishing force due to the reduced magnetic force acting on the abrasive particles. The small magnetic force acting on the magnetic particles causes difficulties in overcoming the finishing friction against the workpiece and encourages relocation of the magnetic particles within the particle chains. This facilitates the production of shallow marks with low material removal resulting in the continued presence of some deep scratches.
observed on the as-received surface. The finishing action in Condition 4b was performed in a weaker magnetic field, due to a lower exciting current and lower volume of magnetic particles, and with reduced pole tip revolution. These changes cause the removal of the asperity peaks while maintaining the lay.

Accordingly, the finishing experiments demonstrated that MAF can alter the surface lay while controlling the nanometer-scale surface roughness. The magnetic force (controlled by particle size and exciting current) influences the particle motion within the particle chains and alters the contact between the magnetic particles and target surface, which determine the length and depth of the cutting marks. With chains made of stiffly linked magnetic particles, the surface lay is the result of the cycloidal motion of the particles, which is the result of the rotational motion of the pole tip and the linear motion of the workpiece.

5.2 Surface Lay at Edges

The final manufactured part for the target application (femoral components) would need to be finished over its entire surface, which is greater than the current pole tip diameter; therefore, it was desired to examine the effects of finishing near the edges of the finished region. Figure 5-12 demonstrates the additional areas of study at locations L6, L7, L8, and L9. Two types of surface textures were studied: surfaces showing long directional cutting marks and short intermittent cutting marks. The finishing conditions used to produce these surfaces, termed A and B, are given in Table 5-4. Conditions A and B are similar to Conditions 3 and 4 from section 5.1, respectively, with the only modification being to the workpiece feed. Similar to Condition 4 from section 5.1, Condition B is composed of two phases, the first phase, B1, produced the
desired lay and the second phase, B2, reduced the surface roughness without disturbing the surface lay.

The surface roughness, $Ra$, was measured at each location for a representative workpiece finished with Condition A and Condition B; the results are shown in Figure 5-13 and Figure 5-14. For Condition A, the results show a decrease in the average surface roughness at locations L7, L8, and L9. However, only location L9 showed any statistically significant change in surface roughness (p-value of 0.0004) according to a t-test performed as outlined in section 5.1.2. For Condition B, locations L7 and L8 showed the same trend as was observed at locations L1-L5, however locations L6 and L9 display only slight changes to its surface roughness. A t-test performed on surface roughness data for these locations yield no statistically significant change to surface roughness for locations L6 and L9. Locations L7 and L8, however, yield a p-value of 0.008 and 0.011 respectively; suggesting that the surface roughness was significantly different after MAF. Analyzing the resulting surface texture will yield a better explanation for these surface roughness changes.

Figure 5-15 shows generated three-dimensional images of the surface of a workpiece finished with Condition A at locations L6-L9 measured by an optical profilometer. Since the process parameters for Condition A promotes a stiff particle chain, the surface lay in regions finished directly underneath the pole tip will consist of directional scratches that follow the particle motion described in Figure 2-2. As such, the lay at the inner edge of the pole tip (L7 and L8) consist of angled directional scratches (shown in Figure 5-15(B) and Figure 5-15(C)). As the distance from the center of the pole tip increases beyond the pole tip radius, the abrasive slurry no longer follows the
typical particle motion previously described. Abrasive slurry separates from the magnetic particles and accumulates around the edges of the slurry due to centrifugal force. Additionally, the rotational speed of this mixture is significantly reduced due to the lower concentration of magnetic particles. Locations L6 and L9 correspond approximately to the area finished by this part of the magnetic abrasive mixture. This agglomeration of abrasives causes large pits to be formed on the surface as seen in Figure 5-15(A). The lower rotational speed also causes less directional material removal as seen by the non-directional surface textures of location L6 and L9 in Figure 5-13(A) and Figure 5-13(D), respectively.

Figure 5-16 shows generated three-dimensional images of the surface of a workpiece finished with Condition B at locations L6-L9 measured by an optical profilometer. The surface pattern in the center of the workpiece (Locations L1-L5) is very similar to Figure 5-16(B) and Figure 5-16(C), which illustrate the surface at locations L7 and L8. Due to the low magnetic force in Condition B, the magnetic particle brush is much more flexible, resulting in increased particle relocation during finishing. This particle motion is very similar to the particle motion at greater distances from the center of the pole tip. As a result, the lay is consistent throughout the surface. As the distance from the center increases further (L6 and L9), the surface is only marginally changed from its original as-received condition.

These edge effects can be undesirable if a particular lay is required throughout the entire surface for optimal workpiece efficiency. A few different methods exist to mitigate these effects: the first is to increase the pole tip radius. If the pole tip radius is larger than the area being finished, then the abrasives at the edge do not perform any
finishing and do not contribute to the resulting surface texture, thereby preventing pitting as seen in Condition A location L6. Additionally, resupplying the machine with fresh abrasive slurry during the finishing trial more frequently will help prevent separation between abrasive and magnetic particles.

5.3 Ultra-Precision Surface Modification

The surface roughness of the femoral component has a direct effect on the wear of the polyethylene insert. Improving upon the current surface roughness was desired. To this effect, a set of finishing conditions were developed whose goal was to significantly reduce the surface roughness. After a rigorous heuristic approach was followed, the optimal finishing condition, termed Condition C, was developed and is described in Table 5-5. Condition C is composed of two phases, whose only difference is the feed direction. After the first phase, termed C1, is complete, a fresh batch of abrasive slurry is used in phase two, termed C2, in order to complete the finishing. The surface lay after C1 finishing consists of long, horizontal directional cutting marks. In an attempt to remove these ridges, the second phase was performed at a 90° to the ridges in an attempt to create a crosshatch surface with lower surface roughness.

Two workpieces were finished with finishing Condition C; they are designated as workpieces 5a and 5b. Figure 5-17 presents the change in surface roughness, $S_a$, for both workpieces before and after finishing. The roughness parameter, $S_a$, was chosen because it is unbiased towards directionality. The result shows an average surface roughness of 1.7 nm and 1.8 nm, representing the lowest surface roughness recorded for any workpiece in this research. These values were consistent throughout the finished area.
To test if these results are statistically significant, a single-tailed, paired, two-sample t-test was conducted. The null hypothesis was that the mean surface roughness, $S_a$, in the as-received workpieces is equal to the mean surface roughness after MAF. The alternative hypothesis is that the surface roughness of the as-received workpieces is larger than after MAF-processing. Both workpieces yield a p-value of less than 0.05 (0.004 and 0.029 for workpieces 5a and 5b, respectively) suggesting that the surface roughness for the MAF-processed workpieces is in fact lower than that of the as-received workpieces.

Figure 5-18 shows SWLI generated three-dimensional images of the surface of a workpiece finished with Condition C at locations L1-L4 and Figure 5-19 shows the surface finished at location L3. Since the last finishing phase was oriented perpendicular to the finished region shown in Figure 5-12, locations L1 and L5 are the furthest away from where the pole tip last finished, locations L2 and L4 are near the edge of where the pole tip finished, and location 3 is located directly underneath both pole tip finished regions. The resulting surface lay at L1 and L5 is characteristic of long directional cutting marks at a slight angle, similar to Condition 2 in section 5.1 shown in Figure 5-11(B). The surface lay at L2 and L4 consist of non-directional peaks (the desired result) and location L3 is characteristic of long directional cutting marks as seen in Figure 5-11(C), but rotated by 90°. It is believed that by reducing the finishing force in the second phase of finishing, the lay would be consistent throughout the different measured locations.
5.4 Effect of Surface Lay on Wettability

5.4.1 Effect of Surface Roughness on Contact Angle

The contact angles were measured five times both parallel and normal to the workpiece feed direction. It has been reported that the droplet tends to spread along grooves on sub-micrometer scale surfaces, reducing the contact angle [53]. In other words, the contact angle measurements could be influenced by the directionality of the lay. However, the effect of cutting mark direction on the droplet spreading was negligible under the conditions in this research.

Although previous research has shown a correlation between surface roughness and contact angle, these studies were performed over large scales; for example (0.1 to 10 µm) [32-34]. In this research, we explore the correlation of surface roughness to contact angle at the nanometer scale for cobalt chromium workpieces. Figure 5-20 shows the recorded contact angle as a function of surface roughness.

Although there might appear to be a slight increase in contact angle with increasing surface roughness, most workpieces with surface roughness between 2-4 nm, vary in contact angle between 90° and 100°. The coefficient of determination, $R^2$, was calculated to be 0.12, 0.13, and 0.14 for a logarithmic, exponential, and linear relationship, respectively. Therefore, there does not appear to be any significant correlation between surface roughness and contact angle at the nanometer scale.

5.4.2 Effect of Cross-Hatch Angle on Contact Angle

Figure 5-21 shows the contact angles (before and after MAF) for each finishing condition from section 5.1. Figure 5-22 shows the relationship between the contact angle and cross-hatch angle for Conditions 1-3 from section 5.1. The as-received surface, consisting of random multidirectional cutting marks, had an average contact
angle between 96° and 97°. After finishing, the contact angles of the MAF-processed surfaces (93°-97°) were smaller or nearly equal to those of the as-received surfaces. As shown in Figure 5-23(B)-(D), the differences in surface roughness profiles between the x- and y-directions are reduced with increasing cross-hatch angle. When the deionized water droplet is placed on the workpiece surface for the contact angle measurement, the droplet tends to spread into the valleys of the surface asperities. The surface produced using Condition 1, which has a large cross-hatch angle, encouraged the water droplet to flow outward in a radial fashion. In contrast, the surface from Condition 3 consists of unidirectional cutting marks. The unidirectional lay could better constrain the spread of the water droplet in a direction perpendicular to the cutting marks (i.e., the y-direction), resulting in smaller changes in the droplet shape. As a result, the contact angles decreased with increasing cross-hatch angle. Condition 4 produced short, intermittent cutting marks. As shown in Figure 5-23(E), the roughness profiles in the x- and y-directions are similar, although the peak-to-peak distances are slightly different. This might have facilitated the spread of the droplet in a radial fashion, resulting in the smallest contact angle recorded. Considering that the workpieces have similar surface roughness Sa, these results show that wettability (i.e., contact angle) is a function of surface lay. Specifically, the results show that the contact angle decreases with decreasing directionality of the cutting marks.

5.5 Coefficient of Friction

The coefficient of friction (COF) of workpieces from section 5.1 was measured before and after MAF. Measurements were taken along the polishing direction (up/down with respect to the images shown in Figure 5-11. Each finishing condition was applied to
two workpieces, for a total of eight finished workpieces. The results are shown in Figure 5-24.

The COF tests show that finishing Condition 2 causes a reduction in COF in both cases. Conditions 1 and 4 cause a decrease in COF in one case, and no change in the other. Condition 3 is inconclusive, with an increase in one case and a decrease in the other. The irregularities of the COF results could be due to the fact that as measurement time increases, the HDPE wear progresses and the contact area increases. Additionally, a layer of the HDPE tip may get deposited on the workpiece and affect the results as time progresses.

The COF was also plotted as a function of cross-hatch angle in Figure 5-25. The COF does not seem to be significantly influenced by cross-hatch angle. It remains to be seen if the COF would change significantly for a cross-hatch angle of 180°.

Figure 5-26 plots the COF as a function of surface roughness. When all finishing conditions are considered collectively, a single-tailed, paired, two sample t-test comparing the as-received surface to the MAF-processed surface reveals that the COF of the MAF-processed surfaces is in fact statistically significantly smaller than the as-received surfaces (p-value of 0.042).
Figure 5-1 Schematic of magnetic particle brush (A) Flexible chain (B) Stiff chain

Table 5-1 Finishing conditions

<table>
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<th>3</th>
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Figure 5-2 Schematic of cutting marks for finishing conditions 1, 2, and 3 (A) Condition 1 (B) Condition 2 (C) Condition 3
Figure 5-3 Surface roughness $Ra$ at locations 1-5 for workpiece 1a

Figure 5-4 Average surface roughness $Ra$ from locations 1-5 for workpieces 1a-4b
Figure 5-5 Average surface roughness $S_a$ from locations 1-5 for workpieces 1a-4b

Figure 5-6 Average surface roughness $R_z$ from locations 1-5 for workpieces 1a-4b
Figure 5-7 Relationship between average surface roughness $Sa$ and finishing condition

Figure 5-8 Relationship between average surface roughness $S_z$ and finishing condition
Figure 5-9 Relationship between average skewness $S_{sk}$ and finishing condition
Figure 5-10 Surface roughness histograms of workpieces before and after finishing (A) Histogram of as-received surface (B) Histogram of MAF-processed surface

Table 5-2 Results of paired, two sample t-test

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Figure 5-11 Images of MAF-finished surfaces captured by an optical profilometer

Table 5-3 Cross hatch angle

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<th>Measured cross hatch angle</th>
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Table 5-4 Finishing Conditions

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Figure 5-14 Surface roughness $Ra$ at locations 6-9 of condition B
Figure 5-15 Three-dimensional image of surface finished with condition A (A) Location 6 (B) Location 7 (C) Location 8 (D) Location 9
Figure 5-16 Three-dimensional image of surface finished with condition B (A) Location 6 (B) Location 7 (C) Location 8 (D) Location 9

Table 5-5 Finishing condition

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<td>Iron particle amount, mg</td>
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<tr>
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</tr>
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</table>
Figure 5-17 Average surface roughness $S_a$ from locations 1-5 finished with condition C
Figure 5-18 Three-dimensional image of surface finished with condition C (A) Location 1 (B) Location 5 (C) Location 2 (D) Location 4

Figure 5-19 Three-dimensional image of surface finished with condition C at location 3
Figure 5-20 Contact angle as a function of surface roughness $S_a$

Figure 5-21 Contact angle as a function of finishing condition
Figure 5-22 Change in contact angle with cross-hatch angle
Figure 5-23 Surface roughness profiles in x and y directions
Figure 5-24 Coefficient of friction for workpieces 1a-4b

Figure 5-25 Change in coefficient of friction with cross-hatch angle
Figure 5-26 Change in coefficient of friction with surface roughness
6.1 Finishing Machine Modification

Figure 6-1 shows a femoral knee component. The two main articulating surfaces are the femoral condyles located on the distal surface shown in Figure 6-1(A). The proximal surface shown in Figure 6-1(B) is not finished. Although the entire distal surface of a commercial component is finished, for simplicity, the finishing experiments in this research focus on the femoral condyles. The previously described finishing setup was designed for use with a flat workpiece. In order to extend the MAF process to finish the freeform surface of femoral knee components, modifications to the finishing setup are required. A different workpiece holder would need to be designed and built in order to secure the workpiece (the femoral knee component) during finishing. The tapped holes on the proximal side of the femoral component are exploited to achieve this goal. Additionally, a reliable and consistent measuring apparatus would need to be designed in order to measure the workpiece surface roughness before and after finishing experiments. In this chapter, for brevity, the term "knee" is commonly used in place of "femoral knee component."

6.1.1 Workpiece Holder

Similar to the design specifications mentioned in section 3.3, the workpiece holder needs to serve several functions: it has to properly secure the workpiece during finishing, maintain positional accuracy during remounting, and be magnetic. Additionally, it was desired to use the same workpiece holder on the measuring apparatus used for surface roughness measurements in order to minimize positioning
errors due to remounting between measurements during a finishing trial. Based on these requirements, the following design was implemented.

The newly designed end effector that serves as the workpiece holder is shown in Figure 6-2. The non-magnetic jig is the same part that is used in conjunction with the flat workpiece holder from Figure 3-8. A set of magnetic knee attachments are designed to attach via the tapped holes to the proximal side of the femoral component. These attachments serve as the end of the magnetic circuit that draws the magnetic field through the workpiece from the pole tip. The magnetic knee attachments are fixed to the magnetic jig and positioned against the reference plate, which allows for consistent positioning. This jig is mounted to the non-magnetic jig. A non-magnetic knee attachment connects both pieces of the magnetic knee attachments and serves an important role during surface roughness analysis that is discussed later. Figure 6-3 shows a photograph of the finishing setup with the workpiece holder in position.

6.1.2 Measurement Holder for Surface Roughness Analysis

In order to measure changes in the surface roughness and lay during finishing trials while ensuring that finishing resumed on the same location, reliable repositioning was required. A measurement holder was designed such that the workpiece did not have to be completely removed from the workpiece holder. Figure 6-4 shows the design of the measurement holder for surface roughness measurements. The magnetic knee attachments and the non-magnetic knee attachment remain fixed to the knee. A shaft that is cylindrical on one end and square on the other is inserted on either side of the non-magnetic knee attachment. This assembly is then mounted to the rest of the measurement holder which allows rotation via a measurement adjuster. The holes on the measurement adjuster are located on a 25.4 mm radius and spaced every 15°. This
setup allows for up to seven locations along the femoral condyle for measuring the surface roughness. A photograph of the completed assembly is shown in Figure 6-5. Figure 6-6 illustrates the locations being measured for the finishing trials in this chapter. Seven locations were measured before and after finishing. From the superior to inferior end on the knee, the locations are termed L1 through L7.

6.2 Magnetic Flux Density

6.2.1 Simulated Magnetic Field

Asymmetry of the magnetic attachments of the new workpiece holder and a varying workpiece thickness affect the magnetic flux density at the workpiece surface. Therefore, the magnetic flux density at the workpiece surface needed to be analyzed. Magnetic field simulation software was used to predict the magnetic flux densities of the previously described setup. By importing solid models of the finishing setup and inputting the necessary coil details (material, dimensions, number of turns, current, etc.) the magnetic field generated by the electromagnet can be predicted.

Since the position of the magnetic workpiece holder influences the magnetic field at the workpiece holder, there are an infinite number of solutions possible for the magnetic field. For simplicity, three setup configurations were chosen for analysis that corresponds to positions when the pole tip is directly above locations L1, L4, and L7. These orientations were chosen because in each orientation, a planar face of the magnetic workpiece holder is parallel to the circular plane of the pole tip. Figure 6-7 demonstrates these orientations as well as the mesh generated for solving the simulation.

The distance between the pole tip and the workpiece surface is 1 mm in each case. A shaded plot of the magnitude of the magnetic flux density for orientations L1,
L4, and L7 are shown in Figure 6-8, Figure 6-9, and Figure 6-10 respectively. These figures show the field on a cross section of the orientations. Note that the workpiece is thinnest at the L7 orientation and a drilled hole, for screws that attach to the workpiece, is present in the L1 and L7 configurations. Measurements of the magnetic flux density, centered 1mm from the center of the pole tip, were taken along the x and y directions. The resulting values are plotted in Figure 6-11. The black line labeled EM, represents the magnetic flux density without a workpiece holder present and clearly has the lowest value at approximately 0.14 T. Locations L1, L4 and L7 have average magnetic flux density values of 0.22 T, 0.23 T, and 0.26 T respectively. Magnetic flux density values in the x and y direction for orientations L1 and L4 were very similar with a variation of only about 0.007 T. Results for the L7 orientation however, yielded non-symmetric variations between x and y values, as well as overall higher values than at other orientations. This can be explained by noticing that in the orientation shown in Figure 6-10, the planar face of the magnetic attachment of the workpiece holder does not extend past the entire surface of the pole tip. Therefore, the edge of this plane creates an edge effect, increasing the magnetic flux density near the ends and attributing to the non-symmetric nature of the values in Figure 6-11. The overall higher values of magnetic flux density is due to the decreased distance between the magnetic attachments of the workpiece holder and the pole tip, which is a factor of the thickness of the workpiece at that location.

6.2.2 Measured Magnetic Field

To verify the simulation results from section 6.2.1, the magnetic flux density would have to be manually measured. Figure 6-12 shows a photograph of the setup used to measure the magnetic flux density. As previously described in section 3.4, a
Hall sensor was used as the probe to measure the magnetic flux density. The sensor is clamped in an aluminum holder that is fixed to three single axis micrometer stages, which allow for precise positioning. Since the presence of the workpiece would interfere with the exact positioning of the holder and sensor (the sensor is too thick to fit in the pole tip-workpiece clearance), the workpiece was excluded from the setup. The exclusion of the workpiece is suitable because its material is non-magnetic and does not influence the magnetic field.

The Hall sensor was located 1 mm away from the pole tip during measurements. This coincides with the location of the workpiece surface during finishing experiments. Three locations along one of the condyles were studied corresponding to measurement locations L1, L4, and L7. In order to measure the edge effects, at each location, measurements were taken along both x and y directions, where the x direction corresponds to the workpiece feed direction (direction of articulation) and the y direction is in the knee’s lateral direction.

Figure 6-12 shows the magnetic flux density as a function of supplied current 1 mm away from the center of the pole tip at locations L1, L4, and L7. Figure 6-14 displays the magnetic flux density as a function of distance from the center of the pole tip in both x and y directions for locations L1, L4, L7, and without the workpiece holder present (EM) at a supplied current of 2.0 A.

Figure 6-13 shows that location L4 on the workpiece displayed the lowest values of magnetic flux density. The thickness of the workpiece at location L4 is greater than at the other measured locations, therefore maximizing the distance between the pole tip and the magnetic knee attachments and decreasing the magnetic flux density.
Locations L1 and L7 have similar magnetic flux densities up to 1.0 A and then deviate slightly from one another.

Figure 6-14 shows that without the workpiece holder present, the magnetic flux density is fairly constant throughout the entire face of the pole tip at approximately 0.12 T. As predicted, the presence of the workpiece holder significantly increases the magnetic flux density, but varies based on location. As Figure 6-13 showed, location L4 displays the lowest values at approximately .18 T. This is followed by locations L1 and L7, who have average magnetic flux density values of 0.22 and 0.23 T, respectively. These results are in line with the predictions based on the magnetic field simulation.

The slightly higher values of magnetic flux density predicted by the simulation, is due to the fact that the manufactured coil was wound by hand, and does not form a perfect coil. Additionally, the model for the knee was derived by the author from pictures, rather than an actual solid model provided by the manufacturer, which may result in positioning error in the simulation results.

In all measurements involving the workpiece holder, the values for magnetic flux density in the x direction exceeded those in the y direction. This is most likely due to the fact that there is more magnetic material along the x direction than along the y direction. The main discrepancy between the simulated and measured results is in the shape of the magnetic flux density curves. The measured values show a convex shape for locations L1 and L7, but relatively flat or slightly concave for location L4 and without the workpiece holder; whereas simulated values are slightly concave for all locations. This is because in locations L1 and L7, a screw is used to secure the workpiece to the holder. This screw extends past the plane of the magnetic attachments – thereby
introducing magnetic material that is closer to the pole tip. Without these screws, the holes would most likely cause a dip in the magnetic flux densities as predicted in the simulated values.

These results show that magnetic workpiece holders can greater increase the magnetic flux density at a workpiece’s surface. The magnetic flux densities in the pole tip region in the x and y directions are fairly constant. The greatest variation in magnetic flux density arises from locations where there is a large increase in the workpiece thickness, causing a greater distance between the pole tip and the magnetic attachments of the holder. If necessary, this can be overcome by altering the programming motion to decrease the pole tip to workpiece clearance, as the workpiece thickness increases.

6.3 Knee Prosthetic Finishing

Initial as-received measurements of the femoral knee components revealed a different surface texture than the flat workpieces. Figure 6-15 shows surface images taken at 10X magnification at location L2 of three separate knees. Visible in each workpiece are several protuberances of approximately 100 µm scattered across the surface. Preliminary experimental results showed that using the finishing conditions established in Chapter 5 was not sufficient to remove the undesired surface features present in the workpieces. These surface features would first have to be removed via a more aggressive finishing trial prior to recreating the surface lays described in Chapter 5.

Table 6-1 lists the finishing conditions developed to finish the freeform knee surface. The first three finishing trials, termed P1, P2, and P3, are designed to remove the previously described surface irregularities. Condition P1 employs a larger diamond
abrasive than previously used (0-1 µm) and larger iron particles (149-297 µm). The increase in iron particle size results in an increase in the finishing force. By combining this increased force with a large abrasive size, the resulting material removal is significantly increased. The resulting material removal and surface deformation undoubtedly increases the surface roughness. Condition P2 is identical to condition P1, but is composed of a smaller diamond abrasive (0-0.5 µm). The presence of the larger iron particles results in the same finishing force as P1, but the smaller diamond abrasives cause smaller cutting marks. This helps to reduce the surface roughness. Condition P3 is geared solely at reducing the surface roughness back to its original value. It employs smaller iron particles (44-149 µm) and increased pole tip revolution.

Following these three finishing trials, the final finishing trial, termed either Condition 1, 2, or 3, is designed to impart the desired texture on the surface of the knee. They are similar to Conditions 1, 2, and 3 from Table 5-1. All workpieces go through finishing P1, P2, and P3, but only one texture is imparted via either Condition 1, 2, or 3. Therefore, each workpiece goes through four finishing trials.

Three workpieces were selected for finishing. Each condition is applied to an individual knee’s condyle. The process is repeated on the other condyle. This results in two sets of finishing experiments for each condition. They are termed 1L, 1R, 2L, 2R, 3L, and 3R; where the number represents the final finishing condition employed and the letter corresponds to either the left or right condyle.

In order to track changes in both the surface roughness and the removal of surface irregularities, measurements were taken at both 40X and 10 X magnifications. The 40X magnification corresponds to an area of 125 µm × 125 µm as previously
described in Chapter 4 and used for surface roughness calculations in finishing experiments in Chapter 5. The 10X magnification corresponds to an area of 500 µm × 500 µm. For the target area of 500 µm × 500 µm, a Gaussian spline band pass filter with low and high cutoff wavelengths of 100 µm and 3.312 µm, respectively was used for surface roughness calculations.

Figure 6-16 demonstrates the progression of the surface throughout the finishing process ending with Condition 1 at both 10X and 40X magnifications. The trends are similar for both magnifications. After P1 finishing, the new directional texture causes a visible reduction in the heights of the irregularities, but other surface features such as the scratch in Figure 6-16(C) still persist. Further reductions in these features occur after P2 finishing. After P3 finishing, the surface irregularities are almost completely removed as evidenced by Figure 6-16(g) and (h). The last finishing trial in the example shown in Figure 6-16, is responsible for creating a cross-hatch texture on the surface.

Figure 6-17 shows optical images of the final finished surfaces for Conditions 1, 2, and 3. The lays in Figure 6-17(A), (B), and (C) corresponding to Condition 1, 2, and 3 are the same as those shown in Figure 5-11. Note that the feed direction has changed from the y direction for the flat workpieces from Chapter 5, to the x direction for the freeform workpieces, resulting in a 90° rotation of the surface lays. This was done because of the limits of the robot’s range of motion in the y direction for the required finishing motion of the freeform knee. The cross-hatch angle shown in Figure 6-17 was measured five times at each location for each condyle, resulting in 70 measured angles for each finishing condition. The average cross-hatch angle for each finishing condition is given in Table 6-2 along with the associated standard deviation. The measured
angles match well with the calculated values that were derived in section 5.1 and similar conclusions can be drawn. Namely, as the workpiece feedrate is decreased, a smaller cross-hatch angle is produced. The agreement between measured and calculated angles demonstrates that the magnetic particles follow the pole tip rotational motion even when conforming to a freeform surface such as a femoral knee component. Thus, this demonstrates the ability of MAF to control of the surface lay not only on flat surfaces, but on freeform surfaces as well.

Wettability tests were not able to be conducted on the knee workpieces due to their freeform surface. However, Figure 6-18 shows the surface profile in the x and y directions are similar to those from Figure 5-23. Accordingly, the differences in surface roughness profiles between the x- and y-directions are reduced with increasing cross-hatch angle. This suggests that the wettability results from Chapter 5, also apply to the freeform surfaces of the knee.

Since the directionality of the surface can have a large impact on 2D surface roughness parameters, 3D surface roughness parameters are used. The parameters Sa, Sz, and Ssk are used to track the surface roughness during finishing and correspond to the arithmetic average, peak to valley, and skewness, respectively. The surface roughness was analyzed at each location at both 10X and 40X magnifications. Figure 6-19 shows the surface roughness Sa at 40X magnification for workpiece 2R (right condyle finished with condition 2) as a function of location. These locations are averaged together to yield the average surface roughness Sa for workpiece 2R. Following this example, Figure 6-20 lists the average surface roughness Sa for all workpieces both before and after MAF finishing at 10X and 40X magnifications. Figure
6-21 and Figure 6-22 list the surface roughness $S_z$ and $S_{sk}$, respectively. Figure 6-23 provides a summary of the surface roughness $S_a$ as a function of finishing condition by averaging the result from both condyles for each finished workpiece. The trends for $S_a$ show a substantial decrease in surface roughness at 10X and a slight increase in surface roughness at 40X. The peak to valley, $S_z$, is drastically reduced at 10X and only slightly reduced at 40X. Although the variation in the skewness is quite large, any changes if any after MAF show a decrease in skewness. This is as expected since the various protuberances on the surface were removed after MAF.

In order to test if the surface roughness changes were statistically significant, a two-tailed, paired, two sample t-test was conducted on each workpiece for both $S_a$ and $S_z$ surface roughness parameters. Table 6-3 lists the resulting p-values for this statistical analysis. The results confirm our previous statements that the surface roughness was statistically significantly altered at 10X magnification. The p-values for $S_z$ at 40X reveal that the change in surface roughness was not significant. Mixed results were obtained for $S_a$ at 40X.

### 6.4 Form Accuracy

As described in section 1.2, the geometry of femoral knee components is an important characteristic to its performance. Numerous attempts were made to measure the curvature of the knee before and after finishing. Due to the freeform nature of the surface, even the smallest deviation in positioning causes a large difference in curvature. Measurements taken without finishing showed that the current measurement holder from Figure 6-5 was not sufficiently accurate for form accuracy measurements. Instead, the flat samples from Chapter 5 (see Figure 3-8) were used. Comparisons between finishing trials are used to check the variation in geometry and in material
removal. In order for the geometry to be unaltered by the MAF process, the material removal must be constant throughout the finished region. A large profile line is analyzed, using the previously described SWLI, across the entire workpiece, encompassing both the finished and unfinished region of the workpiece. Figure 6-24 shows the dimensions of the flat workpiece along with the approximate finished region and the profile line.

The original surface profile of the workpiece is U-shaped due to previous finishing trials. Finishing condition 3 from Table 5-1 was used as the finishing condition to test the form accuracy of the workpiece. Figure 6-25 shows the complete profile before and after finishing for the entire surface profile. Due to the extremely small amount of material removal, both profile lines appear to be coincident. The left and right edges of the profile correspond to the unfinished region. Figure 6-26 zooms into the flat, unfinished region on the left of the workpiece and demonstrates the coincident lines and the beginning of their separation as it enters the finished region. Figure 6-27 is focused on the finished region and demonstrates the similarity of the surface geometry in both profile lines. The difference between the height values of these two surface profiles yields the material removal and is plotted in Figure 6-28. The result is a very constant material removal in the finished region of approximately 0.37 µm. A constant material removal suggests that the MAF process removes material evenly throughout the surface and can be used to finish freeform surfaces without affecting the form accuracy.
Figure 6-1 Femoral component of knee prosthetic (A) Distal surface (B) Proximal surface (Photographs courtesy of Author)
Figure 6-2 Exploded view of workpiece holder design

Figure 6-3 Knee finishing setup (Photograph courtesy of Author)
Figure 6-4 Design of measurement holder for surface roughness measurements
Figure 6-5 Photograph of knee holder for surface roughness measurements (Photograph courtesy of Author)

Figure 6-6 Measurement locations (Photograph courtesy of Author)
Figure 6-7 Mesh and configurations of analysis
Figure 6-8 Shaded plot for L1 configuration

Figure 6-9 Shaded plot for L4 configuration
Figure 6-10 Shaded plot for L7 configuration

Figure 6-11 Simulated values of magnetic flux density
Figure 6-12 Magnetic flux density measurement setup (Photograph courtesy of Author)

Figure 6-13 Magnetic flux density 1mm from center of pole tip
Figure 6-14 Magnetic flux density as a function of radial position at different orientations

Figure 6-15 Images of as-received surfaces captured by an optical profilometer (A) Workpiece 1R at L2 (B) Workpiece 2L at L2 (C) Workpiece 3R at L2
<table>
<thead>
<tr>
<th>Condition</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>Condition 1</th>
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Figure 6-16 SWLI 3D images of surface at location L2 finished with condition 1R
Figure 6-17 Images of MAF-finished surfaces captured by an optical profilometer

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<th>Finishing condition</th>
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<tbody>
<tr>
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<td>78.2°</td>
<td>78.1° (±11.8°)</td>
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<tr>
<td>Condition 2</td>
<td>18.5°</td>
<td>20.3° (±9.4°)</td>
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<tr>
<td>Condition 3</td>
<td>0.4°</td>
<td>5.7° (±7.6°)</td>
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Figure 6-18 Surface roughness profiles in x and y directions
Figure 6-19 Surface roughness $Sa$ at 40X as a function of location for Condition 2

Figure 6-20 Average surface roughness $Sa$ for all freeform workpieces at 10X and 40X
Figure 6-21 Average surface roughness $S_z$ for all freeform workpieces at 10X and 40X

Figure 6-22 Average skewness $S_{sk}$ for all freeform workpieces at 10X and 40X
Figure 6-23 Average surface roughness $Sa$ as a function of finishing condition

Table 6-3 P-value results on $Sa$ and $Sz$ for paired t-test for all workpieces

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<tr>
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<th>Sa 40x</th>
<th>Sz 10X</th>
<th>Sz 40X</th>
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<td>0.01</td>
<td>0.02</td>
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<tr>
<td>1R</td>
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<tr>
<td>2L</td>
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</tr>
<tr>
<td>2R</td>
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<td>3R</td>
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<td>0.02</td>
<td>0.08</td>
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Figure 6-24 Workpiece showing finished area and profile line

Figure 6-25 Complete stitched surface profile
Figure 6.26 Surface profile at unfinished area

Figure 6.27 Surface profile at finished area

Figure 6.28 Material removal as a function of distance
A product’s performance is often directly related to its surface finish. With advancements in manufacturing leading to increasing part complexity, including freeform surfaces, surface finishing continues to be an important, but difficult process to achieve effectively and economically. The current challenges facing knee prosthetics, specifically factors affecting wear of the UHMWPE component, were presented. Additionally, several studies suggest that along with surface roughness, material wettability plays an important role in wear. MAF was therefore proposed as a method to finish CoCr alloy workpieces, specifically the freeform surface on femoral knee components.

The findings from this research can be summarized as follows:

1. An MAF processing principle was proposed to finish the freeform surface of femoral knee components. A finishing machine, composed of an electromagnetic coil and a six-axis robot arm, was built to realize this principle.

2. Finishing experiments on flat workpieces demonstrated the feasibility of MAF to alter surface lay while controlling the nanometer-scale surface roughness by changing the length, depth, and direction of cutting marks. This is achieved by controlling the magnetic force acting on the particles (using parameters such as particle size and magnetic field intensity) and the particle motion.

3. MAF finishing significantly reduced the surface roughness on flat workpieces.

4. Using four different surface lays (short intermittent cutting marks and long directional cutting marks at 0°, 20.7°, and 77.9°) produced by MAF, it was shown that the contact angle (i.e., wettability) is a function of surface lay on the nanometer-scale surface. Surfaces with unidirectional cutting marks exhibit the least wettability, and increasing the cross-hatch angle in the MAF-produced surfaces increases the wettability. Surfaces consisting of short, intermittent cutting marks with less directionality are the most wettable by deionized water.

5. MAF-processed surfaces show a decrease in coefficient of friction for flat workpieces due to their reduced surface roughness.
6. The MAF process was successfully extended from flat finishing to freeform finishing of femoral knee components. Specified lays consisting of long directional cutting marks at 78.1°, 20.3°, and 5.7° were imparted on the surface of the condyles without altering its surface roughness. Additionally, the process does not alter the form accuracy of the components.

7. The synthesis of a hybrid nano-particle for use as a magnetic abrasive was studied. Several novel concepts were investigated, but ultimately yielded inadequate for use in MAF.

### 7.2 Future Work

Future work that should be considered includes extending the finishing to the entire distal surface of the femoral knee component and reducing the finishing time. Throughout this research, it was noticed that the consistency of the magnetic abrasive slurry changed significantly as a function of time. Figure 7-1 shows the initial slurry composition as it passes over the knee condyle. The slurry is homogenous and leaves a small layer of slurry on the surface of the workpiece. Figure 7-2 shows the same finishing trial after 4 minutes of finishing. The composition of the slurry has been significantly altered. A white ring has formed around the edge of the pole tip and the surface of the workpiece appears dry and dull. Figure 7-3 shows a close up of the slurry on the pole tip. As the pole tip rotates, the abrasives are pushed outside of the finishing region and begin to accumulate near the pole tip edge. Additionally, it is believed that as the lubricant dries, the particles agglomerate and the finishing efficiency is significantly reduced. By reintroducing additional lubricant, as seen in Figure 7-4, the slurry remixes and its composition returns to that of Figure 7-1. Future research efforts should focus on studying this behavior and modifying the finishing trials to allow for in-process mixing and lubrication. This should significantly reduce the overall finishing time.
Figure 7-1 Initial slurry composition (Photograph courtesy of Author)

Figure 7-2 Slurry after 4 minutes of finishing (Photograph courtesy of Author)
Figure 7-3 Brush at conclusion of 15 min finishing trial (Photograph courtesy of Author)

Figure 7-4 Slurry after application of 0.1 mL of lubricant (Photograph courtesy of Author)
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Arthur Graziano was born in São Paulo, Brazil to Thereza and Renato Graziano. He moved to the United States at an early age and was educated in Orlando, FL. Arthur obtained his Bachelor of Science in Mechanical Engineering from the Georgia Institute of Technology in 2008. He then attained his Master of Science in Mechanical Engineering under the guidance of Dr. Tony L. Schmitz at the University of Florida. In 2010 Arthur pursued a doctorate degree under the guidance of Dr. Hitomi Yamaguchi Greenslet with Dr. Schmitz co-advising. Once graduating, Arthur plans to continue his career as a researcher in private industry and eventually undertake his passion of teaching.