IMPROVING TOOL LIFE OF TUNGSTEN CARBIDE TOOLS FOR TITANIUM ALLOY MACHINING WITH MAGNETIC ABRASIVE FINISHING

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2016
To my parents
ACKNOWLEDGMENTS

I would like to thank my parents and brothers for their continued and unwavering support during my pursuit of higher education and beneficial life experiences. I would also like to thank Dr. Hitomi Yamaguchi Greenslet for the opportunity to explore advanced manufacturing and for her guidance and support during my short time in the NTML. I would like to thank my committee member Dr. Nagaraj Keshavamurthy Arakere for his participation in my thesis defense. Furthermore, I would like to thank Dr. Radu Pavel for his guidance during this project. I would also like to thank Dr. Arthur Graziano and Mike Tan for their guidance during my introduction to the NTML. This work is supported by TechSolve Inc.
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<td>Built-up edge</td>
</tr>
<tr>
<td>CBN</td>
<td>Cubic boron nitride</td>
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<tr>
<td>CNC</td>
<td>Computer numeric controlled</td>
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<tr>
<td>HDPE</td>
<td>High density polyethylene</td>
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<td>MAF</td>
<td>Magnetic abrasive Finishing</td>
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<tr>
<td>PHD</td>
<td>Plastohydrodynamic lubrication</td>
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<td>SWLI</td>
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<td>WC</td>
<td>Tungsten carbide</td>
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Abstract of Thesis Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Master of Science

IMPROVING TOOL LIFE OF TUNGSTEN CARBIDE TOOLS FOR TITANIUM ALLOY MACHINING WITH MAGNETIC ABRASIVE FINISHING

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Chair: Hitomi Yamaguchi Greenslet
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Magnetic abrasive finishing (MAF) has been shown to improve tool life of uncoated carbide tools used while turning Ti-6Al-4V titanium alloy by finishing the flank, nose, and rake of the tool. This discovery could lead to reduced cost of machining by reducing tool purchasing overhead and requiring less time for tool changing during machining. However, the time required to finish each insert was too high to make the current technology fiscally viable to bring to industry. The objective of this project is to increase the efficiency of the MAF process applied to uncoated carbide inserts by reducing the total time required to finish an insert as well as prove that the project is scalable to industry standards while conserving the process’s benefits to tool life.

In order to increase the efficiency of the MAF process, it has been shown that using a mixed particle brush can increase finishing forces therefore reducing finishing time. It has also been shown that MAF applied only to the rake can provide the previously observed benefits to tool life while drastically reducing finishing time. The finishing time applied to the rake was then reduced to 2.2 min by testing the impacts of finishing time on tool life during cutting of titanium alloys. Scalability of the project was
proven by testing simultaneous finishing of multiple inserts with improvements to tool life present.
CHAPTER 1
INTRODUCTION

Using WC-Co Tools to Machine Ti-6Al-4V Titanium Alloy

Titanium alloys, especially Ti-6Al-4V, are commonly used for aerospace applications due to its relatively high specific strength, resistance to fracture and corrosion, and conservation of material properties at elevated heat. However, these benefits are paired with manufacturing challenges such as low thermal conductivity and low modulus of elasticity that define titanium alloys as “difficult-to-machine” materials. When using carbide tools to machine titanium alloy, tool wear is usually dominated by flank and crater wear. Abrasion between the tool and workpiece surface has been identified as a major cause of flank wear, while chemical diffusion at high temperature and adhesion propagate crater wear [1-4].

Tungsten carbide (WC) is a compound composed of grains bound together with cobalt and is commonly used for creating machining tools. Due to the high hardness and stiffness of WC, the compound is rarely traditionally machined by milling or turning. Instead it is usually formed at dimensions similar to the intended final geometry and either ground with diamond or cubic boron nitride (CBN) or machined with electro-discharge machining. For the purpose of machining titanium, carbide tools with fine grain (between 0.8 and 1.5 µm diameter) and 3-6 wt% Cobalt (Co) binder are suggested for semi-finishing applications. Ultra-fine (<0.7 µm diameter) grain tools with roughly 10 wt% Co binder are recommended for rough cuts or machining that is commonly interrupted or stopped [2].

While machining titanium alloys, there are two major causes of tool wear propagation: chemical diffusion and adhesion. Chemical diffusion of W and Co into
titanium at temperatures above 800 °C, commonly exceeded while machining titanium, W and Co will penetrate up to 20 µm within a Ti-6Al-4V when the materials are held together at elevated temperature. This loss of material leads to a decline of hardness at the point of contact along the WC-Co tool [5]. The loss of hardness may accelerate tool wear rates during machining.

Adhesion of the chip to the tool’s rake can also greatly increase tool wear of carbide inserts. Due to the compound nature of WC-Co tools, as the built up material of the chip adheres to the surface of the tool and subsequently gets removed due to cutting stress, large chunks of WC particles may also be removed from the tool’s surface [2]. This increases the stresses experienced at the rake surface and, combined with the reduced hardness caused by chemical diffusion, will quickly lead to the degradation of the cutting edge due to chipping or fracture.

**Current Methods Used to Extend Tool Life**

Tool wear is commonly increased due to cutting speed, thermal effects on the tool’s geometry or material properties, and friction or adhesion. Reducing the cutting speed can extend tool life at the cost of production rate, which usually leads to much higher production costs than replacing spent tools used in higher speed machining. Low cutting speeds can also increase the built up edge (BUE) of workpiece material that adheres to the rake’s face [6-8].

Coolant or cutting fluids can be applied to the cutting tool in process to fight negative thermal effects on tool life. The fluids can be misted, sprayed, flooded, or jetted towards the tool or cutting surface. Recently, cryogenic technologies have applied liquid nitrogen at high pressure along a tool’s surfaces to super cool the cutting edge. Not only does this cool the tool, but also assists in removing the chip from the surface by acting
as a hydraulic wedge. These technologies have been shown to improve tool life while being applied both internally through the cutting tool and externally along the cutting edge [9-11].

Cutting fluids not only reduce heat in the system, but also extend tool life by providing lubrication between the tool and the workpiece and preventing BUE from forming along the rake of the tool [13-14]. Tailoring the surface of cutting tools in an effort to improve lubrication life and the tribological situation at the tool-chip interface can also improve tool life. These changes to surface geometry encourage plastohydrodynamic (PHD) lubrication to occur. PHD lubrication occurs when a lubricant is trapped within a surface while under great pressure, causing the opposing surface to plastically deform while reducing actual surface contact area between the bodies of the tool and workpiece [15].

It has been shown that laser texturing of carbide tool surfaces can reduce the friction experienced by the tools during machining. Using femtosecond lasers, surface textures including circular pools and lines have been machined into carbide tool surfaces in order to improve the lubricant life during machining. The textures vary from 5-200 µm in diameter or width, and can also be used to create raised textures similar to knurled surfaces at the micrometer scale. It has been shown that the tribological improvements caused by laser texturing can be directionally dependent on the features with respect to chip sliding direction. These changes can lead to reduced contact area between the tool and chip, reduced forces during machining, and reduced coefficients of friction [16-21].
Magnetic abrasive finishing has also shown an improvement to tool life via surface texturing with micro- and nano-scale surface features. By applying diamond abrasive mixed with ferrous particles caught in a magnetic field to the flank, nose, and rake of uncoated carbide cutting tools, tool life has been shown to nearly double while machining titanium alloys [22-23].

**Objectives**

Previous studies have shown that tool life of WC-Co tools can be greatly improved while machining Ti-6Al-4V via surface processing of the rake, flank, and nose of the tool by MAF. However, the processing time currently required by MAF to improve tool life is currently too high to be a fiscally viable addition to carbide tool manufacturing. The objective of this project is to refine the MAF process in an effort to reduce the processing time of carbide inserts while preserving the beneficial effect on tool life previously displayed.

To ensure efficient machining characteristics during MAF processing, a study on finishing forces is conducted to quantify the effects of particle brush composition on normal and tangential forces during finishing. These studies are further investigated by observing the effects of particle brush composition on carbide tool surfaces during repeated finishing trials.

The effects of MAF processing of the flank, nose, and rake of carbide tools on tool life are explored in an effort to reduce finishing time. An exploration of reduced finishing times along the rake of the tools is conducted to observe their impact on tool life improvement. Tests for simultaneous polishing are also conducted to prove scalability of the project.
CHAPTER 2
MAGNETIC ABRASIVE FINISHING

Processing Principle

Magnetic Abrasive Finishing is a loose abrasive process that utilizes a magnetic field to create a brush from magnetic and abrasive particles with lubricant. The finishing force can be shown in Eq. (2-1) where $F$ is the force, $V$ is the volume of the magnetic particle, $\chi$ is the magnetic susceptibility of the material, and $H$ and $\nabla H$ are the magnetic field intensity and gradient, respectively. Quantifying the finishing force allows control of the MAF’s effect on the surface. Average diameter and concentration of abrasive grit, average diameter and amount of the magnetic particles, and the magnetic intensity and position of the magnetic pole tip are variables controlled during MAF. Relative motion between the particles and the workpiece is created by rotating the pole tip, moving the workpiece, or often both. MAF is used to polish difficult-to-machine materials and has been used to polish free-form surfaces such as prosthetics or dies [24-27].

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

(2-1)

Finishing Setup for Carbide Inserts

Figure 2-1 depicts MAF of the rake of a triangular, uncoated tungsten carbide cutting insert. The working gap between the workpiece and pole tip is 2 mm, creating a total distance between the tip and steel of 6.75 mm. The pole consists of three cylindrical neodymium permanent magnets (12.7 mm length, 25.4 mm diameter). The pole tip was mild steel and came to a final diameter of 6 mm. Polishing trials are conducted with the use of a Mikron UCP 600 computer numeric controlled (CNC) mill. This machine allows for a large range of motion in the Cartesian x, y, and z directions, as well as workpiece rotation about the y and z axes.
Two jigs were previously designed for protecting the edge of the cutting inserts while finishing. The first, pictured in Figure 2-1, allows HDPE (high density polyethylene) tape to lie even with the surface of the rake to prevent particles from passing around the cutting edge and changing the radius of the tool edge. The second was designed to allow the rake to lie along a titanium surface while finishing both the flank and nose of the workpiece, blocking the particles from attacking the edge altogether due to the mean diameter of the magnetic particles [22].

**Simultaneous Finishing of Multiple Inserts**

A major goal of the project is to move the discussed technology towards industry application. To be incorporated into large scale manufacturing of carbide inserts, it must be proven that MAF can efficiently finish multiple inserts simultaneously. Figure 2-2 shows the method used to polish multiple inserts while ensuring edge protection. This jig provides a scalable method of polishing multiple inserts, as many inserts can be added to the sequence. The effectiveness of this jig is discussed in Chapter 3.

**Effect of Particle Brush Composition on Finishing Forces**

Due to the high hardness and difficult-to-machine nature of WC, it is important that MAF effects the surface of the carbide inserts in a strong and efficient manner. Previously, a mixture of 40 wt% 25 mesh steel grit (707 µm mean diameter) and 60 wt% 100-325 mesh iron powder (44-149 µm diameter) was used to finish carbide tools resulting in a boost to tool life while shortening processing time. The mixture can be seen in Figure 2-3. This particular mixture resulted from tests exploring the static normal force caused by particle mixture as they were introduced to a magnetic field while resting atop a cantilever beam with a strain gage attached. Mixing ratios (by wt% iron powder) of 100, 80, 60, 50, 40, 20, and 0 wt% were tested using this device, with 60
wt% iron resulting in the largest normal force. It was assumed that the smaller and larger particles would help the particle brush become more rigid due to the increased particle packing density. The brush would then finish the surface more efficiently than a brush composed entirely of smaller iron powder and have more points of contact to attack the surface than a brush composed of larger steel grit, leading to a smoother surface in a lower finishing time.

To bring this discovery further, a study was initiated to measure the finishing forces of the mixed particle brush. The forces acting on brushes composed of non-mixed iron particles and steel grit were also measured in order to compare the results to the mixed particle brushes. Comparing these forces opens a dialog to weight the costs to the benefits for preparing mixed particle brushes. These studies were later progressed to finishing trials explore how each particle brush finishes the surface of the carbide inserts.

**Experimental Setup for Finishing Force Measurements**

A picture of the experimental setup used in this study is shown in Figure 2-4. In order to measure the normal and traverse forces during each trial, a Kistler 9257B multicomponent dynamometer will be utilized within the Mikron UCP 600 CNC mill. To recreate the finishing conditions used to polish the carbide cutting inserts by creating a similar working gap between the pole tip and steel backing, an aluminum plate with the same thickness as the inserts, 4.75 mm, was mounted to a steel plate. These plates were then mounted to the dynamometer using two posts. Table 2-1 shows the testing parameters for the mock finishing trials.

The Kistler 9257B was set up in a three component force measurement system using Kistler 5010B charge amplifier on each channel. A Butterworth 3384 filter was
used to filter for the analog to digital signals of each component force with a cutoff frequency of 20 kHz. This filter assisted in removing noise from the system caused by vibrations traveling through the rigid setup due to machine and ground vibrations, and was required due to the small magnitude of the forces measured.

The three component setup mitigates torque measured in the sensor and reports the forces along the primary axes of the spindle’s motion. Accordingly, the torque was removed from the force measurements during finishing. The normal and tangential forces were measured for each brush composition. To acquire these forces, the following sequence was repeated five times for each brush composition:

- Starting at a height at which the magnetic field did not attract the steel backing (100 mm) and with the spindle engaged, the particles were lowered to the workpiece surface.
- The particles were translated 40 mm in the positive and then negative direction along the y-axis, ending in the original location of engagement. During this time, the dynamic normal force during polishing was measured. Note that the tangential force was negligible as the moment around the pole tip was removed.
- Again, the particles were translated 40 mm in the positive and negative direction along the y-axis. However, after the first 5 mm of each pass the spindle was stopped, ensuring a normal distribution of particles within the brush. This precaution was necessary as the particles shift to one side of the pole tip while being dragged. The tangential force was measured during this test.
- The particles were lifted away from the surface to a height such that the magnetic field no longer attracted the steel backing (100 mm).

**Finishing Forces**

Figure 2-5 shows the averaged normal forces $F_N$ for each brush composition as well as the average normal force when the sequence was run with no particle brush on the pole tip. The magnitude of the forces is negative due to the magnetic attraction between the pole tip and plate pulling in the positive z direction. The mixtures of iron and steel particles had a linearly increasing magnitude as the brush varied from entirely
iron particles to steel particles. This can be attributed to the larger volume per particle of ferrous material, allowing each particle to transfer more of magnetic intensity to the next and pulling at the workpiece's steel backing. The 50 mesh steel grit particles created a normal force between that of 20 and 40 wt% iron mixtures, approaching the maximum value of the 25 mesh grit steel. The brushes composed entirely of iron powder, regardless of mean diameter, only varied by 0.1 N.

Figure 2-6 shows the average tangential force of each particle brush composition. It was found that most brushes created a tangential force ranging between 0.35 N to 0.45 N. The 60 wt% and 80 wt% iron mixtures created nearly double the tangential force of the other compositions with a magnitude near 0.65 N. The 50 mesh steel grit created the third largest tangential force at 0.5 N.

The tangential force is a result of surface friction acting upon normal force. The frictional coefficient is usually independent of surface area due to the bodies acting upon one another sharing the same contact area. While this is still the governing relation between the individual particles and the workpiece surface, it does not translate to comparing brush compositions.

Each brush has a different particle packing density where the number of particles in contact with the surface will vary for each composition. This creates a variance in contact area between the bodies, the bodies in question as the workpiece and all particles of each measured brush composition acting as a singularity. This contact area is difficult to predict as the particles do not behave as simple geometry and do not fall to the surface in a pattern similar to that of the effects of gravity alone. Due to these complications, a control mass was used instead of a control volume.
The results of the tangential force measurements support the hypothesis that at a particular mixing ratio, the larger particles will increase the normal force, or rigidity, of the brush while the smaller iron particles will increase the effective number of contact points with the surface. This creates a more efficient finishing regime when considering only total finishing forces, which would most likely directly increase material removal rate of the process.

Figure 2-1. Rake of a carbide cutting insert being finished with MAF. Photo courtesy of author.

Figure 2-2. Edge protection setup used to polish two cutting inserts simultaneously.
Figure 2-3. A mixture of 40% steel grit (707 µm diameter) and 60% iron powder (44-149 µm diameter) within a magnetic field, creating a polishing brush. Photograph courtesy of Mike Tan [23].

Figure 2-4. Experimental setup used to measure the finishing forces during MAF. Photo courtesy of author.
Table 2-1. Finishing conditions for testing brush composition

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<tr>
<td>Average Particle Diameter [µm]</td>
<td>707 mean</td>
<td>303 mean</td>
<td>177-595</td>
<td>149-297</td>
<td>44-149</td>
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<tr>
<td>Feed Rate [mm/min]</td>
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<tr>
<td>Feed Length [mm]</td>
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<td>Spindle Speed [rpm]</td>
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<td>Brush Mass [mg]</td>
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<td>300</td>
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Figure 2-5. Normal forces measured during MAF. Note that the iron and steel mixtures are of the 100-325 mesh iron powder and the 25 mesh steel grit.
Figure 2-6. Tangential forces measured during MAF. Note that the iron and steel mixtures are of the 100-325 mesh iron powder and the 25 mesh steel grit.
CHAPTER 3
CARBIDE INSERT FINISHING

Methods for Measuring Insert Surfaces

The carbide inserts pictured in Figure 3-1 display a labeling technique used to differentiate between each insert and insert corner during finishing experiments. Each finishing and subsequent cutting experiment consisted of separate sets of five cutting inserts numbered sequentially between one and five. Each insert has three corners, labeled with reference to the surface lay on the rake of the insert. As shown in Figure 3-1, the corner which has grinding marks running off of the rake toward the nose is labeled as “Corner C”. The corners above and to the left are labeled “Corner B” and “Corner A” respectively.

Optical Profiling with Scanning White Light Interferometer

The carbide insert’s complex geometry and large peak-to-valley roughness indicated that optical profiling would be the most effective form of measurement. Figure 3-2 shows the Zygo NewView 7200 scanning white light interferometer (SWLI) used to create surface profiles with a vertical resolution of <0.1 nm. Due to the limitation of the wavelength of light the lateral resolution of the SWLI is restricted to 275.7 nm, preventing artifacts and imaginary data.

Measurement Locations and Masks

Each corner was measured on three sides: the flank, nose, and rake. Every measurement area was 176 µm x 132 µm due to the x40 magnification used on the SWLI. The measurements lie along the edge of the insert. To prevent false data past the edge of the insert from skewing results, a 100 x 100 µm mask was used to select data away from the extreme edge of the insert. Figure 3-3 depicts the measurement
locations, relative size of the measurement area, and masking size used while measuring the flank and nose of the inserts. Previously created measurement jigs allowed these surfaces to lie flat relative to the optic by supporting them with respect to the insert’s 11º relief angle. Figure 3-4 shows the measurement and mask locations used when measuring the rake. The top rake measurement location is labeled as “Position 1” and the location starting 264 µm below is “Position 2”.

It is important to note that during finishing experiments that involved all three surfaces, the rake was only measured at Position 1. However, later experiments that only involve rake finishing report both positions. The labeling system, when reporting for a specific insert, corner, and measurement position, can be shown in the following example: “3B-2”. This refers to cutting insert 3, at corner B, measurement position 2.

It has been shown that manipulation of a cutting inserts edge can cause drastic changes to a tool’s life. This project focuses on tailoring the inserts’ surfaces, not sharpening or strengthening the cutting edge. Edge radius measurements were performed by optically scanning the edge of the insert where the flank, nose, and rake surface intersect while being held at a 45º angle. Ten profile lines were taken across the peak formed by the cutting edge and a MATLAB program was used to approximate the radius of each peak and average said values. Figure 3-5 shows an example of an edge measurement as well as the ten profile lines used to create the reported average edge radius.

**Measurement Method and Observed Surface Parameters**

Table 3-1 reports the measurement parameters used during this project. A Gaussian spline band pass filter was implemented in each measurement to clarify the
effects of MAF to the inserts’ surfaces. A high cutoff of 0.83 \( \mu \text{m} \) was used to prevent noise in the measurement while a low cutoff of 20 \( \mu \text{m} \) removed the surface waviness.

Early experiments used ten profile lines along the flank, nose, and rake surface measurements to create an average \( Ra \) value for surface roughness. These measurements are reported using standard deviation as error bars. Later measurements report the arithmetic average distance from the center plane of the surface measurement, \( Sa \). Likewise, the skewness of the measured surfaces are reported as both the average \( Rsk \) with standard deviation error bars and later with the plane based skewness \( Ssk \).

**Exploring Multi-Surface Finishing with MAF to Extend Carbide Tool Life**

Previous experiments proved that surface tailoring of uncoated carbide cutting inserts with MAF could improve tool life while turning titanium alloy. In order to explore how MAF improves tool life, a multi-surface finishing test was completed along the flank, nose and rake. It was previously discovered that finishing the rake of the insert until very smooth (<10 nm \( Ra \)) was detrimental to tool life. This information led to shorter finishing times along the rake in future experiments in an effort to only modify the preexisting surface of the tools and not completely remove the grinding marks from manufacturing.

It is believed that MAF improves tool life is by positively impacting the tribological wear at the tool-chip interface during machining. It is assumed that creating smooth, flatter peaks along the surface without altering the valley geometry allows cutting fluid to remain at the tool’s surface longer, as seen in previous research that involved laser machining of carbide tool’s rakes. By removing uneven peaks and surface irregularities, a more even stress distribution along the tool’s surface will be encouraged. Removing the spikes in stress along the surface can result in crater wear prevention. Adhesion
during machining will target peaks along the surface of the rake and large grains of the tool's structure could be violently removed due to the stress concentration. Once these grains are removed, a crater would exist along the rake allowing the workpiece’s material to be “caught” during chip formation. This causes steep increases to friction and heat while continuing propagating crater wear. A lower skewness along the surface can indicate flat peaks with deep valleys; a situation assumed to be beneficial to lubricating fluid on a machining surface [23].

**Experimental Conditions**

Table 3-2 explains the finishing conditions for two experiments. These experiments were designed to test the repeatability of the tool life benefits caused by MAF. The particle brush consisted of 40 wt% 25 mesh steel grit (707 µm mean diameter) and 60 wt% 100-325 mesh iron particles (44-149 µm mean diameter). The diamond abrasive used was 0-1 µm diameter oil soluble diamond compound. Only four cutting inserts were polished during these experiments as the fifth one was used to test unfinished cutting tool life.

**Impact of MAF on Carbide Tool Surfaces**

Figures 3-6 and 3-7 show the average surface roughness, $Ra$, and skewness, $Rsk$, of inserts 1 and 2 from the first experiment. Likewise, Figures 3-8 and 3-9 show these results for inserts 3, 4, and 5. The initial and final surface roughness, $Sa$, and skewness, $Ssk$, of the inserts finished for the second experiment can be seen from Figure 3-10 through Figure 3-13. The initial surface roughness for the five inserts used in the first experiment was much higher than the inserts used in the second. This difference in roughness introduced the knowledge that while the manufacturing process remains constant for each carbide insert, the tool creating them can vary greatly. This
variance can cause the initial Sa of the carbide inserts to vary from 30 to 150 nm and higher. This reaffirmed the goal of the project as finding an MAF process that can be applied to all inserts to benefit tool life rather than finding the “perfect” surface to maximize tool life.

**Tool Life of Carbide Inserts while Turning Titanium**

The cutting test parameters can be seen in Table 3-3. During the first experiment, all cutting passes were 50.8 mm for each corner. During the second experiment, an additional goal of bringing the cutting tests toward a more rigorous cutting path commonly seen in industry was added. Half of the corners from the second test, one corner for each finishing condition, were used for eight inch cutting passes instead of the previous two inch passes. Each insert was inspected after every pass via digital microscope to check if the flank wear Vb had progressed past 381 µm (0.015 inch), as tool wear quickly propagated after this point. Once the maximum Vb had been reached or passed, the cutting tests were ended for that corner.

Figure 3-14 depicts the first experiment’s results of tool wear vs. cutting time. The thrust cutting forces measured during the first experiment is reported in Figure 3-15. Note that the forces reported near 70 minutes are incorrect, as these are not the average force experience by the tool, but the maximum. For the second test, the tool wear and cutting forces are reported separately based on the cutting pass length for the inserts. Figures 3-16 and 3-17 depict the second cutting test results for a 2 in. cutting pass, while Figures 3-18 and 3-19 show these results for an 8 in cutting pass. As expected, the cutting forces experienced by the inserts proportionally mirror their tool wear, validating the use of orthogonal cutting models for tool wear and cutting force.
Some inserts experienced catastrophic early failure, as seen by insert 3C in Figure 3-16, depicted by a tool wear curve that suddenly goes from low tool wear to ruin in one data point. Due to the incredibly difficult nature of machining titanium alloys, it is expected that tools will sometimes unexpected fail early. This could be attributed to many different causes: manufacturing impurities in the carbide, surface damage on the inserts, or most likely a spike in machining forces or heat due to irregular chip formation or tool entry to the cutting zone. The corners that fail early will be noted for their tool wear curve before such a failure.

It was observed that a great increase to tool life occurred due to rake finishing, while the unpolished inserts lasted either a comparatively mid-length or shorter time. Polishing the nose of the insert seemed to have little effect on tool life, unless combined with rake polishing. Finishing of all sides of the inserts appeared to be beneficial to tool life, although it was outperformed by finishing conditions 1 and 5.

As expected, the eight inch cutting tests propagated tool wear much quicker than previous cutting trials. These results were promising in that the MAF processed inserts showed an improvement to tool life for all finishing conditions. However, further testing would be required to show that a catastrophic failure hadn’t occurred for the unfinished insert. These tests confirmed that MAF can repeatedly improve the tool life of carbide cutting inserts used to turn titanium.

In order to bring the results of these tests towards industry application, future finishing tests were conducted while only finishing the rake surface. This is due to the rake finishing showing the best improvement to tool life from the lowest processing time
of 3.3 minutes. Not only did this reduce the time spent finishing the insert, but removes the set up time for two additional processes.

**Rake Surface Tailoring and Proving Project Scalability**

Finishing the rake of carbide inserts has shown repeated improvement to tool life with the shortest MAF processing time per insert. To bring MAF to industry application of carbide inserts, minimizing the processing time of each insert became a major goal. Reduced finishing time was explored in several steps. First, a polishing study was conducted to test how efficiently varying particle brush compositions machined the insert rake surface. Second, a step-based polishing experiment explored how a mixed particle brush effects the rake surface with respect to finishing time. Finally, a polishing and cutting plan was executed to explore how reduced finishing time effected tool life while only processing the rake of the insert. This plan also tested simultaneous polishing of two inserts. These experiments were designed to both explore how MAF attacks the surface of carbide inserts and to prove scalability of the project for applying MAF to industry made tools.

**Finishing Characteristics of Particle Brush Compositions on Carbide Insert Rake**

Previously, the dynamic finishing forces of varying particle brushes composed of iron and steel particles with mean diameter between 44 µm and 707 µm were measured. To bring this study further, polishing tests were conducted using these particles. These tests have a quantitative focus on surface roughness reduction, while also noting the qualitative nature of removing surface irregularities in an effort to improve the tribological wear at the tool-chip interface during machining. The mixed particle brushes will be explored in a later section, as they’re used to test reduce finishing time for rake polishing.
**Experimental conditions**

Table 3-4 shows the finishing parameters used to explore finishing with varying particle brushes. Each of the brushes were used to finish the rakes of three insert corners. The mass of the brushes was a constant 300 mg, and each brush finished for 60 passes (3.3 min). Initial and final surface measurements were taken at both rake positions.

**Surface roughness reduction and impact to surface geometry**

Figure 3-20 shows the reduction of $Sa$ for both rake positions each corner polished with 25 mesh steel grit (707 µm mean diameter). The oblique surface plots for these corners can be seen in Figure 3-21. Although the 25 mesh steel grit had the largest normal force, their effect on the surface roughness was limited as they only attacked the highest peaks. This can be attributed to how few points of contact the particles made with the surface as well as their limited ability to penetrate and polish inside the valleys due to their size.

Figure 3-22 shows the reduction of $Sa$ for both rake positions on each corner polished with 50 mesh steel grit (303 µm mean diameter). The oblique surface plots for these corners can be seen in Figure 3-23. The 50 mesh steel caused the greatest average reduction in surface roughness. The peaks of the surface have been finished such that they have very flat tops.

Figure 3-24 shows the reduction of $Sa$ for both rake positions on each corner polished with 30-80 mesh iron powder (177-595 µm diameter). The oblique surface plots for these corners can be seen in Figure 3-25. The 30-80 mesh iron powder had the lowest average reduction in surface roughness. It is predicted that the larger particle size of the iron powder along with the relatively constant normal sacrificed the powder’s
ability to machine the surface by lowering the amount of contact points and making it
difficult to machine deeper than the peaks.

Figure 3-26 shows the reduction of $Sa$ for both rake positions on two corners
polished with 50-100 mesh iron powder (149-297 $\mu$m diameter). The oblique surface
plots for these corners can be seen in Figure 3-27. Due to a user error, one corner (1C-1) was ruined when the pole tip crashed into the surface. The 50-100 mesh iron powder
performed well while reducing surface roughness, but could not finish the peaks and
irregularities strong enough to flatten the surface.

Figure 3-28 shows the reduction of $Sa$ for both rake positions on each corner polished
with 100-325 mesh iron powder (44-149 $\mu$m diameter). The oblique surface plots for
these corners can be seen in Figure 3-29. These small particles could machine deeper
into the valleys as well at the peaks. However, due to the low force per particle the
peaks and irregularities remained while their surfaces became smoother.

The average surface reduction for each particle brush, including the 60 wt% 100-325 mesh iron powder and 40 wt% 25 mesh steel grit mixture, can be seen in Figure 3-30.

The 50 mesh steel grit and the 60 wt% iron mixed particle brush outperformed all
other finishing conditions in terms of surface roughness reduction. However, initial
roughness varied greatly between the experiments. The initial $Sa$ for the 50 mesh steel
grit inserts ranged between 99 and 136 $\mu$m, while the initial $Sa$ for the 60 wt% iron
mixed particle brush ranged between 50 and 66 $\mu$m. The mixture showed the ability to
effectively reduce the surface roughness even at lower initial $Sa$. It is common for
smoothing rates to slow down drastically as they approach 20 nm $Sa$. It could also
penetrate slightly past the peaks and create smooth edges along them, as seen later in Figure 3-33 and Figure 3-34. Thus, the mixture was chosen above the 50 mesh steel grit to test for reduced rake finishing time.

**Exploring Reduced Processing Time for Rake Finishing**

To test the effects of reduced finishing of the cutting insert rake on tool life, five experiments were completed. The first was a continuation of the particle brush composition polishing tests that explored the effects of the mixed particle brush on surface roughness and skewness. This test was modified by stopping the polishing process every 10 passes to examine the rake surface. The next four tests focused on polishing sets of inserts to be used in a cutting test.

**Experimental conditions**

Table 3-5 shows the finishing conditions of five experiments used to explore reduced finishing time of the rake. All five experiments use a 60 wt% 100-325 mesh iron powder and 40 wt% 25 mesh steel grit mixed particle brush weighing a total of 300 mg. Experiment one modified the previous particle brush composition polishing experiments by taking surface measurements every 10 passes (0.55 min) to a maximum of 60 passes (3.3 min).

Experiment 2 prepared 6 corners for cutting tests by polishing for 10, 20, and 40 passes on two corners for each finishing time. This experiment tests if the inserts actually benefit from large changes to the surface topography at a higher finishing time, or if quickly removing irregularities from the surface is enough to prevent crater wear propagation.

Experiment 3 tests the scalability of MAF’s ability to improve tool life by utilizing a new edge protection system that allows two inserts to be polished at once. The results
of this experiment are denoted by an "s" after the pass number of the insert label, i.e. "4B-20s". To test simultaneous polishing, 20 and 60 passes were used on two corners. These finishing times were chosen by the need to prove repeatability of previous cutting tests (60 passes) and due to experiment 1 showing that 20 passes created a noticeable difference to surface texture with the lowest machining time.

Experiments 4 and 5 are repeatability tests using the same finishing conditions as Experiments 2 and 3 respectively. These experiments also allowed for more unfinished corners (Insert 1 of 5) to be used for cutting tests to provide evidence of MAF’s proposed benefit to tool life.

**Effects of mixed particle brush on carbide insert rake**

The surface roughness reduction per 10 passes from Experiment 1 can be seen in Figure 3-31. The changes to surface skewness per 10 passes are shown in Figure 3-32. The oblique plots of corner 1A can be seen in Figure 3-33, while the oblique plots of corner 1B are shown in Figure 3-34. The surface roughness reduction was linear for both corners, while the surface skewness increased near the cutting edge (rake position 1) and decreased when away from the edge (rake position 2). This skewness trend can be attributed to the 5° rake angle along the tools, as the grinding pattern from manufacturing tends to leave shallower valleys toward the edge of the cutting insert.

The oblique plots from Experiment 1 depict a story of how the abrasive particles are finishing the surface. Note that the irregular peaks standing out of some valleys are actually artifacts from light being trapped or scattered inside said valleys. After 10 passes, the peaks of the surface were beginning to be rounded and the surface is becoming more regular. After 20 passes, the peaks are being deformed as higher points of the surface are being removed or rounded. At 40 passes, most irregular peaks have
been removed and the surface between valleys is much smoother than the initial surface. At 60 passes, almost all peaks have been removed or greatly reduced, leaving smoothed and rounded mounds with valleys between.

The average edge radius measurements for both Experiments 2 and 3 are seen in Figure 3-35. Inserts 2A and 5C were unpolished therefore the initial and final radii reported for these corners are the same. No major changes to edge radius had occurred, supporting the fact that the HDPE tape edge protection is preventing the inserts from being sharpened or dulled by MAF.

The changes to surface roughness and skewness for the 10, 20, and 40 pass corners from Experiment 2 can be seen in Figure 3-36, Figure 3-37, and Figure 3-38 respectively. The surface roughness reduction and change to skewness for the simultaneous 20 and 60 pass corners from Experiment 2 are displayed in Figure 3-39 and 3-40. The unpolished corners surface parameters from Experiments 1-3 can be seen in Figure 3-41.

Figure 3-42 displays the average edge radius measurements for Experiments 4 and 5. Again, there were no major changes to edge radius.

Figure 3-43, Figure 3-44, and Figure 3-45 contain the changes to surface roughness and skewness for the 10, 20, and 40 pass corners from Experiment 4, respectively. The simultaneous 20 and 60 pass surface roughness and skewness data is shown in Figure 3-46 and Figure 3-47. The unpolished corners from Experiments 4 and 5 have their surface roughness and skewness reported in Figure 3-48.

**Effects on tool life from reduced rake processing time**

Table 3-6 reports the cutting parameters used for Experiments 1 through 5. For these tests, a chip breaker was mounted to the tool. Also, each subsequent pass ended
0.5 mm (0.02 in) before the previous cutting pass had. These changes helped simulate a cutting environment commonly seen in industry while also helping prevent premature failure of the tool due to inconsistent chip behavior such as “bird’s nesting”.

Figure 3-49 shows the flank wear \( V_b \) with respect to cutting time for the inserts from Experiments 1-3. Figure 3-50 shows the thrust cutting forces experienced by these inserts. The flank wear and cutting force for Experiments 4 and 5 are shown in Figure 3-51 and Figure 3-52 respectively. As expected, the cutting forces mirrored the tool wear of each insert.

Two of the eight unpolished inserts lasted longer than 55 min before reaching \( V_b \) \( max \). Two of the 10 pass corners performed very well while the other two either failed with the unpolished group or failed catastrophically within the first 20 minutes. A single 20 pass corner performed exceptionally while the other three failed near the unpolished group. Similarly, the 20s pass corners only had one that lasted longer than the unpolished inserts. All corners that were polished for 40 passes performed exceptionally well, outlasting all but one outlying unpolished corner. The 60s inserts were predicted to outlast most of the corners due to previous results. While they did last longer than most unpolished inserts, they were outperformed by the 40 pass corners. The corner from Experiment 1 outlasted most unpolished inserts, but fell in the middle of the group.

While the 20s pass inserts did not perform well, neither did the individually finished 20 pass corners. The 60s pass corners worked as expected, mimicking cutting times from previous cutting tests. This proves that simultaneous polishing of multiple inserts can achieve similar results as individually tailored inserts; a major step toward scalability of the project. The 40 pass corners more consistently lasted longer than all
others. This lowers the required processing time by 33% while showing an even greater benefit to tool life.

Figure 3-1. Labeling technique used to distinguish insert number and corner.

Figure 3-2. Zygo NewView 7200 used for optical profiling. Photo courtesy of author.
Figure 3-3. Flank and Nose measurement locations with mask. Photo from Techsolve.

Figure 3-4. Rake measurement positions with mask.
**Figure 3-5.** An example of edge measurement with ten profile lines used to find average edge radius.

**Table 3-1.** Measurement parameters for scanning white light interferometer

<table>
<thead>
<tr>
<th>Measurement area and resolution</th>
<th>Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 ×100 µm area mask</td>
<td>Gaussian spline: Band pass mode</td>
</tr>
<tr>
<td>0.276 µm lateral resolution (x and y)</td>
<td>High cutoff $\lambda_s$: 0.83 µm (Removes most noise components)</td>
</tr>
<tr>
<td>~0.1 nm vertical resolution</td>
<td>Low cutoff $\lambda_c$: 20 µm (1/5 analysis area side length)</td>
</tr>
</tbody>
</table>

**Table 3-2.** Finishing conditions for flank, nose, and rake polishing experiments

<table>
<thead>
<tr>
<th>Polishing Condition</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insert Corner</td>
<td>1A,2A</td>
<td>1B,2B</td>
<td>3A,4A</td>
<td>3B,4B</td>
<td>3C,4C</td>
</tr>
<tr>
<td>Area</td>
<td>N</td>
<td>N+R</td>
<td>F+N+R</td>
<td>F*+N+R</td>
<td>R</td>
</tr>
<tr>
<td>Passes</td>
<td>60</td>
<td>60</td>
<td>40,60,60</td>
<td>40,60,60</td>
<td>60</td>
</tr>
<tr>
<td>Finishing Time [min]</td>
<td>10</td>
<td>10,10</td>
<td>3.3,6.6,3.3</td>
<td>3.3,6.6,3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Feed Rate [mm/min]</td>
<td>60</td>
<td>60</td>
<td>120,90,180</td>
<td>120,90,180</td>
<td>180</td>
</tr>
<tr>
<td>Finishing Length [mm]</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap [mm]</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spindle Speed [rpm]</td>
<td></td>
<td>600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abrasive [mg]</td>
<td></td>
<td></td>
<td>4 (0-1 µm diameter)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel Grit [mg]</td>
<td></td>
<td>120</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Iron Powder [mg]</td>
<td></td>
<td>180</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lubricant [mL / 4 min]</td>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

F: Flank, N: Nose, R: Rake, F*: Reverse of Flank
Figure 3-6. Average roughness of inserts 1 and 2 from the first flank, nose, and rake finishing experiment.

Figure 3-7. Average skewness of inserts 1 and 2 from the first flank, nose, and rake finishing experiments.
Figure 3-8. Average roughness of inserts 3 and 4 from the first flank, nose, and rake finishing experiment.

Figure 3-9. Average skewness of inserts 3 and 4 from the first flank, nose, and rake finishing experiments.

Figure 3-10. Surface roughness of inserts 1 and 2 from the second flank, nose, and rake finishing experiment.
Figure 3-11. Skewness of inserts 1 and 2 from the second flank, nose, and rake finishing experiment.

Figure 3-12. Surface roughness of inserts 3 and 4 from the second flank, nose, and rake finishing experiment.

Figure 3-13. Skewness of inserts 3 and 4 from the second flank, nose, and rake finishing experiment.
Table 3-3. Machining parameters for cutting titanium rod with carbide inserts

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece</td>
<td>Ti-6Al-4V Titanium Rod</td>
</tr>
<tr>
<td>Cutting Speed</td>
<td>100 m/min (328 ft/min)</td>
</tr>
<tr>
<td>Feed Rate</td>
<td>0.075 mm/rev (0.003 in/rev)</td>
</tr>
<tr>
<td>Depth of Cut</td>
<td>1.02 mm (0.04 in)</td>
</tr>
<tr>
<td>Cut Length Per Pass</td>
<td>50.8 mm (2 in) or 203.2 mm (8 in)</td>
</tr>
<tr>
<td>Cutting Fluid</td>
<td>Trim Sol E206 (10% concentration)</td>
</tr>
</tbody>
</table>

Figure 3-14. Tool life of inserts finished in the first flank, nose, and rake experiment.
Figure 3-15. Thrust cutting forces of inserts polished in the first flank, nose, and rake experiment.

Figure 3-16. Tool life during 2 in passes of inserts finished in the second flank, nose, and rake experiment.
Figure 3-17. Thrust cutting forces during 2 inch passes of inserts polished in the second flank, nose, and rake experiment.

Figure 3-18. Tool life during 8 in passes of inserts finished in the second flank, nose, and rake experiment.
Figure 3-19. Thrust cutting forces during 8 in passes of inserts polished in the second flank, nose, and rake experiment.

Table 3-4. Finishing conditions for testing brush composition

<table>
<thead>
<tr>
<th>Insert Corner</th>
<th>1A,4C,5B</th>
<th>2C,3B,4A</th>
<th>3C,4B,5A</th>
<th>1C,2B,3A</th>
<th>1B,2A,5C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brush Composition</td>
<td>25 Mesh Steel Grit</td>
<td>50 Mesh Steel Grit</td>
<td>30-80 Mesh Iron Powder</td>
<td>50-100 Mesh Iron Powder</td>
<td>100-325 Mesh Iron Powder</td>
</tr>
<tr>
<td>Average Particle Diameter [µm]</td>
<td>707 mean</td>
<td>303 mean</td>
<td>177-595</td>
<td>149-297</td>
<td>44-149</td>
</tr>
<tr>
<td>Area</td>
<td>Rake</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passes</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finishing Time [min]</td>
<td>3.3</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Feed Rate [mm/min]</td>
<td>180</td>
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<td></td>
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</tr>
<tr>
<td>Finishing Length [mm]</td>
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<td></td>
</tr>
<tr>
<td>Gap [mm]</td>
<td>2</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Spindle Speed [rpm]</td>
<td>600</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Abrasive [mg]</td>
<td>4 (0-1 µm diameter)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brush Mass [mg]</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lubricant [mL]</td>
<td>0.1/4 minutes</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Figure 3-20. Reduction of surface roughness caused by 25 mesh steel grit.

(i) Initial Surface

(i) $S_a$: 111.9 nm  $S_{sk}$: -1.055

(ii) Finished Surface

(ii) $S_a$: 75.5 nm  $S_{sk}$: -1.641

(a) Corner 1A-1

(i) $S_a$: 121.4 nm  $S_{sk}$: -0.696

(b) Corner 1A-2

(ii) $S_a$: 71.8 nm  $S_{sk}$: -1.857
Figure 3-21. Oblique plots of rake surfaces finished with 25 mesh steel grit.
Figure 3-22. Reduction of surface roughness caused by 50 mesh steel grit.

(i) Initial Surface

- $S_a$: 115.1 nm
- $S_{sk}$: -0.789

(ii) Finished Surface

- $S_a$: 57.8 nm
- $S_{sk}$: -1.807

(a) Corner 2C-1

(i) Initial Surface

- $S_a$: 100.7 nm
- $S_{sk}$: -1.115

(ii) Finished Surface

- $S_a$: 45.9 nm
- $S_{sk}$: -2.460

(b) Corner 2C-2
Figure 3-23. Oblique plots of rake surfaces finished with 50 mesh steel grit.
Figure 3-24. Reduction of surface roughness caused by 30-80 mesh iron particles.

(i) Initial Surface

(ii) Finished Surface

(a) Corner 3C-1

(b) Corner 3C-2
Figure 3-25. Oblique plots of rake surfaces finished with 30-80 mesh iron powder.
Figure 3-26. Reduction of surface roughness caused by 50-100 mesh iron particles.

(i) Initial Surface

Initial Surface

Finished Surface

(ii) Finished Surface

(a) Corner 2B-1

(i) $S_a : 132.4 \text{ nm} \quad S_{sk} : -0.844$

(ii) $S_a : 79.4 \text{ nm} \quad S_{sk} : -1.035$

(b) Corner 2B-2

(i) $S_a : 142.6 \text{ nm} \quad S_{sk} : -1.407$

(ii) $S_a : 88.1 \text{ nm} \quad S_{sk} : -2.324$
Figures 3-27. Oblique plots of rake surfaces finished with 50-100 mesh iron powder.

(c) Corner 3A-1

(i) $S_a: 141.4$ nm $S_{sk} : -0.920$

(ii) $S_a: 90.3$ nm $S_{sk} : -1.419$

(d) Corner 3A-2

(i) $S_a: 109.1$ nm $S_{sk} : -0.789$

(ii) $S_a: 59.1$ nm $S_{sk} : -1.878$

Figure 3-28. Reduction of surface roughness caused by 100-325 mesh iron particles.

![Graph showing surface roughness comparison](image)
(i) Initial Surface

(i) $S_a : 141.7 \text{ nm} \quad S_{sk} : -0.868$

(ii) Finished Surface

(ii) $S_a : 102.3 \text{ nm} \quad S_{sk} : -1.358$

(a) Corner 1B-1

(i) $S_a : 167.9 \text{ nm} \quad S_{sk} : -1.032$

(ii) $S_a : 111.4 \text{ nm} \quad S_{sk} : -1.648$

(b) Corner 1B-2

(i) $S_a : 67.3 \text{ nm} \quad S_{sk} : -0.248$

(ii) $S_a : 59.9 \text{ nm} \quad S_{sk} : -1.188$

(c) Corner 2A-1

(i) $S_a : 130.3 \text{ nm} \quad S_{sk} : -0.858$

(ii) $S_a : 99.6 \text{ nm} \quad S_{sk} : -1.430$

(d) Corner 2A-2
Figure 3-29. Oblique plots of rake surfaces finished with 100-325 mesh iron powder.

(i) $S_a : 96.1 \text{ nm } S_{sk} : -0.854$

(ii) $S_a : 70.2 \text{ nm } S_{sk} : -0.396$

(e) Corner 5C-1

(i) $S_a : 167.5 \text{ nm } S_{sk} : -1.330$

(ii) $S_a : 129.2 \text{ nm } S_{sk} : -1.426$

(f) Corner 5C-2

Figure 3-30. Average reduction of surface roughness % for each brush composition.
Table 3-5. Finishing conditions for exploring reduced rake finishing time

<table>
<thead>
<tr>
<th>Experiment</th>
<th>1</th>
<th>2,4</th>
<th>3,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insert Corner</td>
<td>1A,1B</td>
<td>2B,3C</td>
<td>2C,3B</td>
</tr>
<tr>
<td>Passes</td>
<td>10 x 6</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Finishing Time [min]</td>
<td>0.55 x 6</td>
<td>0.55</td>
<td>1.1</td>
</tr>
<tr>
<td>Area</td>
<td>Rake</td>
<td>Rake</td>
<td>Rake</td>
</tr>
<tr>
<td>Finishing Length [mm]</td>
<td>10</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>Feed Rate [mm/min]</td>
<td></td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>Gap [mm]</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spindle Speed [rpm]</td>
<td>600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abrasive [mg]</td>
<td>4 (0-1 µm diameter)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel Grit [mg]</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron Powder [mg]</td>
<td>180</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lubricant [mL / 4 min]</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3-31. Surface roughness of insert rakes finished for 6 intervals of 10 passes.

Figure 3-32. Skewness of insert rakes finished for 6 intervals of 10 passes.
(i) Corner 1A-1

(i) $S_a$: 61.4 nm, $S_{sk}$: -0.732

(ii) Corner 1A-2

(ii) $S_a$: 57.5 nm, $S_{sk}$: -0.934

(a) Unfinished

(i) $S_a$: 54.7 nm, $S_{sk}$: -0.783

(ii) $S_a$: 51.9 nm, $S_{sk}$: -0.924

(b) Finished 10 passes

(i) $S_a$: 47.9 nm, $S_{sk}$: -1.103

(ii) $S_a$: 48.5 nm, $S_{sk}$: -1.014

(c) Finished 20 passes

(i) $S_a$: 45.7 nm, $S_{sk}$: -0.924

(ii) $S_a$: 42.9 nm, $S_{sk}$: -1.354

(d) Finished 30 passes
Figure 3-33. Oblique plots of corner 1A positions showing the effects of finishing with mixed particle brush for six intervals of ten passes.
(i) Corner 1B-1

(i) $S_a: 50.2$ nm, $S_{sk}: -1.388$

(ii) Corner 1B-2

(ii) $S_a: 66.0$ nm, $S_{sk}: -1.757$

(a) Unfinished

(i) $S_a: 45.5$ nm, $S_{sk}: -1.186$

(ii) $S_a: 66.0$ nm, $S_{sk}: -1.757$

(b) Finished 10 passes

(i) $S_a: 42.4$ nm, $S_{sk}: -1.226$

(ii) $S_a: 59.2$ nm, $S_{sk}: -1.811$

(c) Finished 20 passes

(i) $S_a: 39.8$ nm, $S_{sk}: -1.283$

(ii) $S_a: 54.4$ nm, $S_{sk}: -1.957$

(d) Finished 30 passes

(i) $S_a: 39.8$ nm, $S_{sk}: -1.283$

(ii) $S_a: 52.3$ nm, $S_{sk}: -1.917$
Figure 3-34. Oblique plots of corner 1B positions showing the effects of finishing with mixed particle brush for six intervals of ten passes.

(i) $S_a : 34.8$ nm, $S_{sk} : -1.178$

(ii) $S_a : 49.3$ nm, $S_{sk} : -1.964$

(e) Finished 40 passes

(i) $S_a : 32.9$nm, $S_{sk} : -1.125$

(ii) $S_a : 44.3$ nm, $S_{sk} : -2.163$

(f) Finished 50 passes

(i) $S_a : 30.8$ nm, $S_{sk} : -1.103$

(ii) $S_a : 42.1$ nm, $S_{sk} : -2.219$

(g) Finished 60 passes
Figure 3-35. Edge radius of finished inserts from Experiments 2 and 3.

Figure 3-36. Surface roughness and skewness of insert rakes finished for 10 passes.

Figure 3-37. Surface roughness and skewness of insert rakes finished for 20 passes.
Figure 3-38. Surface roughness and skewness of insert rakes finished for 40 passes.

Figure 3-39. Surface roughness and skewness of insert rakes finished for 20 passes.

Figure 3-40. Surface roughness and skewness of insert rakes finished for 60 passes.
Figure 3-41. Surface roughness and skewness of the unpolished rakes used in Experiments 2 and 3.

Figure 3-42. Edge radius of finished inserts from Experiments 4 and 5.

Figure 3-43. Surface roughness and skewness of insert rakes finished for 10 passes.
Figure 3-44. Surface roughness and skewness of insert rakes finished for 20 passes.

Figure 3-45. Surface roughness and skewness of insert rakes finished for 40 passes.

Figure 3-46. Surface roughness and skewness of insert rakes finished for 20s passes.
Figure 3-47. Surface roughness and skewness of insert rakes finished for 60s passes.

Figure 3-48. Surface roughness and skewness of unpolished insert rakes used in Experiments 4 and 5.

Table 3-6. Machining parameters for cutting titanium rod with carbide inserts

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>Ti-6Al-4V Titanium Rod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Speed</td>
<td>100 m/min (328 ft/min)</td>
</tr>
<tr>
<td>Feed Rate</td>
<td>0.075 mm/rev (0.003 in/rev)</td>
</tr>
<tr>
<td>Depth of Cut</td>
<td>1.02 mm (0.04 in)</td>
</tr>
<tr>
<td>Cut Length Per Pass</td>
<td>203.2 mm (8 in) minus 0.5 mm/pass (0.02 in/pass)</td>
</tr>
<tr>
<td>Cutting Fluid</td>
<td>Trim Sol E206 (10% concentration)</td>
</tr>
</tbody>
</table>

Note: A chip breaker was used during machining.
Figure 3-49. Tool life for cutting inserts finished in Experiments 1, 2, and 3.

Figure 3-50. Thrust cutting forces for inserts finished in Experiments 1, 2, and 3.
Figure 3-51. Tool life for cutting inserts finished in Experiments 4 and 5.

Figure 3-52. Thrust cutting forces for inserts finished in Experiments 4 and 5.
CONCLUSIONS

Concluding Remarks

Particle brush composition has been shown to have a large effect on dynamic finishing forces. While normal force does not vary much with particle composition, tangential force can vary greatly depending on how the brush transfers the normal force to the surface of a workpiece. Mixing large and small ferrous particles, as seen with the 40 wt% 25 mesh steel grit (707 µm mean diameter) and 60 wt% 100-325 mesh iron powder (44-149 µm diameter) used for finishing carbide inserts, can provide a more rigid brush that also attacks the workpiece surface more frequently than non-mixed particle compositions. These mixed particle brushes can also polish within valleys of a surface, creating a smoother surface without completely destroying the original surface lay.

Previous results indicated that MAF could increase the tool life of carbide tools used to machine titanium. Originally, all surfaces of the carbide inserts were polished for a total finishing time of up to an hour, while showing up to a 100% increase in tool life while taking two inch passes during turning. It has been proven that only the rake needs to be tailored for a total of 2.2 min to see increases to tool life of up to 30 min during the much more strenuous cutting conditions of 8 inch passes commonly seen in industry applications. This shows a large return in time investment for single corner when comparing finishing time to cutting time increase. In an effort to bring this process to industry, simultaneous polishing has shown to be create similar tool life improvements to individually tailored inserts.
**Looking Forward**

In an effort to discover the mechanics behind MAF’s ability to increase tool life, a focus on quantifying any improvement to lubrication life on the insert’s rake due to MAF will be explored, both with tribology experiments and during machining. The titanium chips from repeatability tests will also be analyzed and compared to cutting forces to predict any change in friction during machining using orthogonal cutting models.

Additional ways to simultaneously finish inserts will be designed to increase the efficiency of the process and progress the scalability of MAF on carbide tools.
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Patrick Hendershot was born in St. Louis, Missouri. He moved to Tallahassee, Florida when he was four years old and graduated with his associate’s degree from Tallahassee Community College in 2010. He then got accepted to the University of Florida’s College of Engineering and earned his bachelor’s degree in mechanical engineering. Patrick enjoys optimizing manufacturing processes and designing ways for them to be applied in new ways. He hopes to start a career manufacturing in the biomedical industry manufacturing prosthetic inserts.