MAGNETIC ABRASIVE FINISHING OF CUTTING TOOLS FOR TITANIUM ALLOY MACHINING

By

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To my family
ACKNOWLEDGEMENTS

I would like to thank the support of, my parents, my sister, and all my friends who have supported me throughout my education. I would also like to thank the support of my advisor, Dr. Hitomi Yamaguchi Greenslet, whom without I would not have been able to accomplish this endeavor. I would also like to thank my committee members: Dr. Curtis Taylor and Dr. David Arnold. Furthermore I would like to thank Dr. Raul E. Riveros and Arthur Graziano for teaching and assisting me during my undergraduate and graduate studies. This work was supported by TechSolve Inc. I would also like to thank Dr. Anil Srivastava for his continued support through this project.
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<td>BCC</td>
<td>Body Centered Cubic</td>
</tr>
<tr>
<td>BUE</td>
<td>Build Up Edge</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numerically Controlled</td>
</tr>
<tr>
<td>CVD</td>
<td>Chemical Vapor Deposition</td>
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<tr>
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<td>Electron Dispersive Spectroscopy</td>
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<tr>
<td>HCP</td>
<td>Hexagonal Close Packed</td>
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<td>HDPE</td>
<td>High Density Polyethylene</td>
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<td>Nd-Fe-B</td>
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Tool wear on cutting tools plays a large role in the machining cost for modern materials such as titanium alloys and other hard to machine metals. The cost of machining can be reduced by conditioning the tool surface using magnetic abrasive finishing (MAF) to reduce the friction between the tool and chip. Furthermore, MAF can be applied to a wide range of tool geometries in addition to coated tools without compromising the sharp tool edge (edge radius). Cutting experiments have demonstrated that some MAF processed tools exhibited tool lives of up to twice as long as unprocessed tools. Additionally, over processing of tools resulting in a change in surface texture results in a deterioration of tool life.
CHAPTER 1
INTRODUCTION

1.1 Titanium Cutting

1.1.1 Titanium Alloy

Titanium is the most commonly elected alloys for applications that demand a high strength-to-weight ratio, excellent biocompatibility, corrosion resistance, and a low coefficient of thermal expansion. These mechanical properties remain true at both ambient and elevated temperatures which further increase the applicability of titanium to a wide range of applications in the aerospace, medical, and marine industries. [1] There are four classes of titanium alloys: alpha (α), near-alpha, alpha-beta (α –β), and beta (β). Each class represents a different crystallographic structure with alpha denoting a hexagonal close packed (HCP) structure and beta denoting a body centered cubic (BCC) structure. The crystallographic structure of titanium alloys governs the mechanical properties of a particular alloy, the structure affected by a combination of which elements the alloy is integrated with and the operating temperature. Alpha phase titanium alloys have a combination of high corrosion resistance, high creep strength, improved weldability, and improved high temperature strength; however, they are not heat treatable. The beta phase alloys possess a higher density, improved ductility, improved formability, and increased heat treatment response, but lack the high temperature strength of alpha alloys.

Ti-6Al-4V contains both an alpha stabilizer (aluminum) and a beta stabilizer (vanadium) which results in an alpha-beta phase alloy. The effects of temperature on crystallographic structure for Ti-6Al-4V are shown in Figure 1-1. Alpha-beta alloys have good strength and ductility which, with heat treatment, exceeds the strength of alpha or
beta alloys. As a result, Ti-6Al-4V is the most commonly used titanium alloy in industry accounting for over 50% of titanium alloys used today. [2]

1.1.2 Titanium Cutting

Ti-6Al-4V is considered to be a hard-to-machine material due to a combination of the mechanical properties of the alloy and the chemical affinity with common cutting tools used for machining high strength materials. [3] Figure 1-2 presents an orthogonal cutting schematic that shows the cutting operation and chip flow. The low thermal conductivity of titanium results in extreme heat generated in the cutting interface due to a combination of insufficient heat transfer into the chip and poor heat dissipation into the bulk workpiece material during cutting. Furthermore, the work hardening and high temperature strength inherent to titanium alloys results in high machining forces during cutting. This in combination with elevated temperatures results in accelerated tool wear. Additionally the temperature dependence of the crystallographic structure or phase results in an unpredictable application and intensity of machining forces applied to the tooling. Finally the high chemical affinity between titanium and typical high strength cutting tool materials and coatings result in accelerated tool wear, resulting in diminished tool life. [4,5,6,7] The cost of machining is reliant on the efficiency of cutting tools due to the influence on the surface quality and dimensional accuracy; therefore, methods to extend the life of tools are a topic of prodigious debate and concern. [8,9]

1.2 Existing Technologies for Extending Tool Life

The modification of machining parameters or enhancements to the cutting tool are two approaches to extending tool life. In the past, the most practical method for extending tool life has been by simply reducing the cutting speed. A reduction in cutting speed results in a decrease in temperature due to both a reduction in cutting forces and
an increase in chip formation time. However, a reduction in cutting time has the undesirable effect of increased machining cost which is detrimental in high volume machining operations or complex machining. Another caveat of low speed cutting is the potential for built up edge (BUE) formation. [10] Therefore research into the enhancement of tool life in high speed machining operations is critical.

A common approach is by application and modification of cutting fluids to act as a lubricant or as a heat sink. However, a common misconception is that any addition of lubricant increases tool life which is not always the case. [11] Despite this finding, research has shown that application of coolant with modern technology such as ultrasonic, high pressure, cryogenic, and tool integrated cooling are effective at extending tool life. [3,12,13,14]

Recently research focus has shifted to modifying the tool itself as a means to improving tool life. Ceramic coatings applied on straight carbides either physical vapor deposition PVD or chemical vapor deposition CVD has been adopted by industry as the standard to reducing tool wear especially for high carbon steels. [15,16] However, due to the chemical affinity with coatings that contain titanium this approach is not ideal for titanium cutting. Furthermore texturing of the cutting surface has shown to improve tool life by improving the tribological properties at the tool chip interface thus reducing the heat generation due to friction. Texturing also has the potential to retain lubricant in the cutting area when compared to other as received surfaces. [16,17,18]

1.3 Objectives

Magnetic abrasive finishing (MAF) is capable of altering the surface texture of workpieces with complicated geometries made of hard materials with little cost compared to other texturing technologies such as high precision grinding and laser
texturing. Therefore investigation into the applicability of MAF to improving tool life by altering the surface texture and hence tribological properties of both uncoated and coated carbide tools is of interest. The finishing characteristics, such as the relationship between surface roughness and edge radius, are studied. Furthermore, the effects of the surface and edge conditions on the tool life are investigated with cutting tests of Ti-6Al-4V alloys. The tool wear, cutting force, and chip morphology are analyzed for both coated and uncoated cutting tools. Further studies into characterization of the magnetic particle brush were performed to clarify the finishing mechanism. The relative magnetic force of the brush and the brush particle formation with varying compositions of magnetic particles in the presence of a magnetic field are investigated.

Figure 1-2. Schematic of orthogonal cutting
CHAPTER 2
SURFACE FINISHING OF CUTTING TOOLS USING MAGNETIC ABRASIVE FINISHING

2.1 Magnetic Abrasive Finishing

Magnetic abrasive finishing (MAF) is a finishing process that utilizes the manipulation of an abrasive and magnetic particle mixture with a magnetic field. In the presence of a magnetic field, the abrasive and magnetic particle mixture also known as the brush, conform to the lines of magnetic flux. As the pole tip rotates and transverses across the workpiece surface the chains of magnetic material follow the pole tip while conforming to the workpiece geometry. [20,21,22] This unique attribute of MAF opens the applicability of this process to many finishing operations such as: free form finishing [23], internal finishing of capillary tubes [24], MEMS fabricated silicon optics [25], conventional optics [26], and curved tube finishing. [27] The magnetic field sources is either a permanent magnet or an electromagnet depending on the specific finishing requirements. Electromagnets are ideal for finishing setups that require a varying magnetic field; however, due to joule heating careful control of the driving current is needed to ensure that resistance heating does not compromise the expected magnetic field intensity provided by the electromagnet. Permanent magnets are utilized when no variation in magnetic field intensity is necessary during the finishing process; furthermore, the lack of joule heating results in a constant magnetic field over extended periods of time. Additionally, a small rare earth magnet can provide a much higher magnetic field when compared to an electromagnet of similar dimensions (assuming the driving current is at the conventional 1 A-3 A range). The magnetic particles selected are typically ferromagnetic materials such as iron or steel due to the low cost and favorable magnetic properties such as high susceptibility and low coercivity. Stainless
steel, cobalt, and nickel are also used for some specific applications, but at a much higher cost. Magnetic particle sizes range from 100’s of micron sized steel grit to nano particles suspended in a fluid (ferrofluid). Typical abrasive particles selected are: synthetic diamond, aluminum oxide, or silicon carbide and are dependent on specific application requirements. Similarly abrasive particles range from the nanometer to micrometer scale. Additionally there are magnetic abrasive particles known as magnetic abrasives which are iron particles with embedded abrasive particles; such as iron with embedded alumina, iron with embedded diamond, and cobalt with embedded alumina.

Material removal is attained through the relative motion between the abrasive particle and the workpiece surface; this is realized by rotating the pole tip while translating the workpiece or by rotation of axis symmetric workpieces. Careful selection of the magnetic particle and abrasive particle is essential as it determines the finished surface roughness and texture through force and material removal control. Additionally due to the wide range of abrasive materials available, MAF can be effectively finish most workpiece materials such as ceramics, cemented carbides, and most metal alloys.

### 2.2 Finishing Machine

The finishing machine is a Mikron UCP 600 5-axis computer numerically controlled (CNC) vertical high speed machining center with a magnetic tool, shown in Figure 2-2. The magnetic tool is attached to a tool holder which is then loaded onto the spindle; the workpiece is seated on a jig on the workpiece table. Relative motion is attained through rotation of the magnetic tool and translation of the tool over the workpiece at the desired finishing location.
2.2.1 Magnetic Tool

The magnetic field source is three neodymium iron boron magnets each with a residual flux density of 1.26-1.29 T and coercive force >875 AT/m. A low carbon steel pole tip is attached to the magnets to increase the magnetic flux density in the desired location. The dimensions of the pole tip were selected such that the pole tip diameter is slightly larger than the width of the workpiece. Furthermore the pole tip was designed to maximize the magnetic flux density at the tip while offering minimal chance of physical contact between the magnetic tool and the workpiece and workpiece holder. The magnets and pole tip are then attached to an aluminum rod that is chucked into a tool holder that is compatible with the CNC.

2.2.2 Workpiece Holder

The workpiece holder serves three primary purposes, first and foremost the workpiece holder is to ensure that the lines of magnetic flux permeate through the workpiece at the desired finishing location. This can be accomplished either with a carefully designed jig made of magnetic material such as steel or with a non-magnetic, tough material such as titanium accompanied by a magnet. The workpiece holder also serves to hold the workpiece in a repeatable location to ensure the same finishing conditions are used per finishing attempt. Finally the workpiece holder serves to protect the edge of the tool to ensure that the tool does not get rounded. Improper design of the workpiece holder leads to ineffective material removal of the workpiece or excessive material removal of the holder.
2.3 Magnetic Force Acting on Particles

The behavior of a magnetic particle in the presence of a magnetic field can be derived from the magnetic charge model of a magnetic dipole [28]

\[ F = \nabla (m \cdot B) \]  

(2-1)

Where \( m \) is the magnetic moment of the particle and \( B \) is the magnetic field. Assuming the magnetic moment and magnetic B field are collinear and that the B field is not time variant and only varies with space, we are able to simply this expression to

\[ F = m \nabla B \]  

(2-2)

Finally applying the definition of magnetic B field and magnetic moment we get

\[ F = V \mu_0 \chi H_k \nabla H \]  

(2-3)

Where \( V \) is the volume of a magnetic particle, \( \mu_0 \) is the magnetic permeability in a vacuum, \( \chi \) is the susceptibility of the magnetic particle, \( H_k \) is the magnetic field intensity experienced by the particle (limited by saturation H), and \( \nabla H \) is the magnetic field gradient experience by the particle.

2.4 Magnetic Particle Brush Behavior

To study effects of mixing ratio of two kinds of magnetic particles, a magnetic force study was performed with a strain gage to measure the relative force exerted by a fixed weight of magnetic particles with different combinations of small and large particles. Table 2-1 shows the experimental conditions of the setup shown in Figure 2-3. Initial experiments have found that as the quantity of smaller iron particles increased the particle brush would spread out beyond the desired location; therefore, a holder was designed to ensure the particles were contained in the desired location. This provided a constant area during measurement such that the same quantity of particles would be
present at the predetermined distance away from the magnetic tool. Excessive particles outside this measurement area led to inconstant measurements as some particles would be closer to the pole tip than others resulting in increased force for some mixing ratios. Figure 2-4 shows the results with and without the holder, it is clear that a 40% steel grit to 60% iron particle combination yields the highest force relative to the other compositions. To determine why this occurs, a brush particle distribution observation experiment was devised.

The setup is shown in Figure 2-5, essentially the particles were placed in the predetermined gap between the pole tip and the workpiece. Once in place a glass slide was used to effectively split the brush which enabled the particle distribution to be viewed with a portable microscope. By observation, the small iron particles effectively coat the larger steel grit particles which leads to the highest magnetic force due to the combination of high volume particles with a high packing factor. In contrast the 100% steel grit mixture possesses a low packing factor; which, despite the high volume of ferrous material per particles, results in decreased magnetic force due to the extremely low magnetic susceptibility of air. While the 100% particles or 0% steel grit mixture results in a very high packing factor, each individual particle have a very small volume which results in a smaller force imparted per particle. Therefore, a 40% steel grit to 60% iron powder combination was selected for finishing.
Figure 2-1. MAF processing principle

Figure 2-2. Finishing setup. A) Finishing machine. B) Magnetic tool. C) Pole tip. (Photos courtesy of Michael Tan)
Figure 2-3. Experimental setup

Figure 2-4. Magnetic force with mixing ratio. A) With holder. B) Without holder.

Figure 2-5. Particle distribution with mixing ratio (Photos courtesy of Michael Tan)
Table 2-1. Magnetic force measurement experimental conditions

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<td>2 mm</td>
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<td>Magnetic flux density</td>
<td>330 mT</td>
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<tr>
<td>707 µm mean diameter steel grit</td>
<td>0 – 500 mg</td>
</tr>
<tr>
<td>40 – 144 µm iron particles</td>
<td>0 – 500 mg</td>
</tr>
<tr>
<td>Total weight of magnetic particles</td>
<td>500 mg</td>
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CHAPTER 3
SURFACE CHARACTERIZATION METHODS

3.1 Surface Topography

Surface topography encompasses the surface texture and shape. Essentially it consists of the low frequency features, commonly known as waviness, the high frequency features, commonly known as surface roughness, and the surface lay or texture. Surface roughness can be measured with three metrics. Arithmetic average roughness average $Ra$ is defined by the average distance from the centerline to the peak or valley of 10 different features. Root-mean-squared roughness $Rq$ increases the weight of values as distance from the center line increases. Maximum height roughness $Rz$ refers to the distance from the highest peak to the lowest valley of the measurement area. For this particular application, the surface is characterized $Ra$.

Surface roughness was evaluated with a Zygo NewView 7200 scanning white light interferometer (SWLI) with a lateral resolution of 275.7 nm and a vertical resolution of <0.1 nm. The workpiece was positioned such that a 100 µm x 100 µm area could be selected close to the cutting edge. Figure 3-1 shows the surface roughness measurement locations for each type of insert and Figure 3-2 shows the measurement jig used to position the flank normal to the instrument as shown in Figure 3-3. Ten 100 µm long profile lines shown in Figure 3-4 were used to calculate the roughness $Ra$. The measurement Conditions are listed in Table 3-1. SWLI measurement parameters; in order to filter out noise and waviness from the measured values, a Gaussian Spline filter (band pass) of 0.828 µm – 20 µm was applied. The high cutoff was selected to filter the noise of the instrument while the low pass cutoff was selected to meet the specifications for assessing surface textures as detailed in ISO 4287 and ISO 4288.
In machining, it has been shown that modification in the surface texture and properties results in an improvement in tool life by reducing rake friction and improving the chip compression factor and normal forces. It is theorized that the reduction in rake friction encourages smooth chip flow thus decreasing the tool-chip interface temperature hence reducing the rate of wear of the cutting tool. [17, 18, 19]

3.2 Edge Radius

The edge of the tool was measured with the SWLI on a measurement jig which positioned the tool such that the cutting edge is normal to the measurement direction as shown in Figure 3-5. Ten 100 µm lines were fitted to the edge data than exported into Matlab. A Matlab routine was developed with a least squares regression methodology to fit a circle onto the data for each line for a total of 10 measurements as shown in Figure 3-6.

Figure 3-1. Tool surface roughness measurement locations. A) Uncoated tool. B) Coated tool.
Figure 3-2. Jig for flank measurement. (Photo courtesy of Michael Tan)

Figure 3-3. Measurement setup for flank. A) Uncoated tool. B) Coated tool. (Photos courtesy of Michael Tan)

Figure 3-4. Measurement area. (Photo courtesy of Michael Tan)
Figure 3-5. Edge measurement jig. (Photo courtesy of Michael Tan)

(A) SWLI edge measurement data

(B) Matlab circle fit from 1 profile line

Figure 3-6. Edge measurement methodology.  A) SWLI edge data. B) Matlab data.

Table 3-1. SWLI measurement parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scanning white light interferometer</td>
<td>100 ×100 µm area mask</td>
</tr>
<tr>
<td></td>
<td>0.276 µm lateral resolution (x and y)</td>
</tr>
<tr>
<td></td>
<td>~0.1 nm vertical resolution</td>
</tr>
<tr>
<td>Filter applied</td>
<td>Gaussian spline: Band pass mode</td>
</tr>
<tr>
<td></td>
<td>High cutoff $\lambda_h$: 0.83 µm</td>
</tr>
<tr>
<td></td>
<td>(Removes most noise components)</td>
</tr>
<tr>
<td></td>
<td>Low cutoff $\lambda_c$: 20 µm</td>
</tr>
<tr>
<td></td>
<td>(1/5 analysis area side length)</td>
</tr>
</tbody>
</table>
CHAPTER 4
FINISHING CHARACTERISTICS OF CUTTING TOOLS

4.1 Uncoated Carbide Tools For Turning Operation

The uncoated tool shown in Figure 4-1 is a tungsten carbide with a cobalt binder (WC/Co) indexable tool used for turning operations selected for its low wear resistance. It possesses a fine grain, a low binder content (3–7 wt% Co) and exhibits weak magnetic properties. The specific application for this particular grade is for machining titanium, cast irons, austenitic stainless steels, non-ferrous metals, nonmetals, and most high-temperature alloys. Each insert has three corners and hence has three cutting areas per insert with three key areas of each corner responsible for cutting. The flank and nose of the tool interacts with the freshly cut surface, this particular tool has a relief angle of 11 degrees, which serves to minimize the contact between the tool and materials to be machined. Furthermore, tool life is generally measured in terms of maximum flank wear or \( VBmax \) as this area of the tool is easily identified either with the aid of a microscope or with imaging software. The rake face of the tool interacts with the material removed during the cutting operation, commonly known as the chip. The friction between the chip and the tool is believed to be a major proponent of tool wear [6].

4.1.1 Workpiece Holder

The workpiece holder for the flank and nose is machined from Ti-6Al-4V for its nonmagnetic properties and toughness compared to aluminum and is shown in Figure 4-2. A neodymium iron boron (Nd-Fe-B) magnet is inserted under the workpiece to ensure that the lines of magnetic flux permeate through the workpiece. This holder is than clamped onto a vise on the table of the high speed machining center. For the initial
rake finishing attempts the workpiece is then positioned on top of an aluminum jig with a Nd-Fe-B magnet positioned Behind the workpiece to direct the lines of magnetic flux through the workpiece. Once the workpiece is clamped onto the aluminum jig, it is then clamped onto a steel vise such that the rake is exposed to the magnetic tool.

This setup was later modified due to the close proximity of the workpiece to the steel vise resulting in unwanted finishing of the vise rather than the workpiece resulting in a reduced finishing efficiency. To alleviate these concerns the workpiece was encased in epoxy, with high density polyethylene tape adhered to the epoxy to prevent excessive wear of the epoxy. The workpiece was then positioned onto a steel block, the slight magnetic response of the workpiece ensures that the lines of magnetic flux permeate through the workpiece rather than around the workpiece due to the higher magnetic susceptibility of WC/Co when compared to air. Therefore, this setup has demonstrated a higher magnetic flux density at the finishing area when compared to the initial setup.

4.1.2 Edge Protection

Each workpiece holder or jig shown in Figure 4-3 is designed such that the edge of the tool remains unrounded during finishing, in the case of the flank finishing, the workpiece is positioned flush against the jig with the edge positioned 0.5 mm below the edge of the Ti jig. The lack of edge rounding is attributed to the clearance being less than the large particle diameter (700 µm mean diameter), thus the large particles responsible for the application of finishing force are unable to access the edge of the tool. For the initial rake finishing setup with the aluminum jig, a 2 mm thick silicon rubber was placed between the tool and the vise. Although the rubber effectively protects the edge of the tool, deformation of the rubber resulted in difficulties in accessing the very
tip of the workpiece with the magnetic brush. In the rake finishing setup with epoxy and high density polyethylene (HDPE), the edge is protected during finishing as long as the flank remains flush with the epoxy and HDPE. The HDPE layer protects the epoxy to ensure that the epoxy is not machined to guarantee that the tool remains flush against the epoxy. Any excessive material removal at this interface will expose the tool edge, resulting in rounding of the edge of the tool.

4.1.3 Magnetic Flux Density

Each finishing setup involved different jig materials and configurations, in order to compare the relative force experienced by the magnetic particle brush the magnetic flux density had to be measured. This is particularly important due to the correlation between the finishing force of the magnetic brush and the intensity of the magnetic field. The magnetic flux density in each finishing setup was measured with a hall probe, whose dimensions and measurement area shown in Figure 4-4, attached to a gauss meter. Figure 4-5 shows the measurement setup for the flank while Figure 4-6 and Figure 4-7 show the measurement setup for the rake. The probe itself is attached to a 3 axis stage, held in position with an aluminum holder. The entire apparatus (stage, probe holder, and probe) is placed inside the machining center to measure the magnetic field density in the finishing area. Each measurement was repeated three times, with the mean value listed in the finishing Conditions.

4.1.4 Experimental Conditions

There are six finishing Conditions selected for the uncoated triangular carbide tools, each Condition aims to find the correlation between a selected factor and tool life and are shown in Table 4-1. Condition 1 is a proof of concept finishing attempt and serves to determine the feasibility of MAF as a method for extending tool life by
changing the surface texture of the flank, nose, and rake of eight corners or inserts. The next two finishing Conditions, Conditions 2 and 3, serve to determine the correlation between surface roughness and tool life. Conditions 4, 5, and 6 aim to determine the specific effects of finishing specific areas involved in cutting. Table 4-2 shows all the finishing Conditions while Figure 4-8 illustrates the pole tip motion for each finishing area. The motion for the nose was omitted as the flank finishing Condition encompasses the nose. Figure 4-9 shows the finishing setup for the flank, rake, and rake with epoxy and HDPE.

The experimental protocol for each finishing experiment is as follows:

1. Weigh a designated quantity of steel grit, iron particles, and abrasive paste onto a petri dish.
2. Prepare the workpiece and load magnetic tool into machining center. Apply a small quantity (<1mg) of abrasive paste to the surface of the workpiece and a drop (0.1ml) of lubricant.
3. Thoroughly mix steel grit, iron particles, and abrasive paste and apply to pole tip of magnetic tool.
4. Run selected finishing program and lubricate slurry as needed.

4.1.5 Surface Roughness

The surface roughness and edge radius measurements for the Condition 1 finishing experiments are shown in Figure 4-10, the oblique plots for each finishing area on each insert is shown in Figure 4-11. The variability of surface roughness on the rake is due to the difficulty in replicating the ideal positioning and experimental setup for the rake. This can be attributed to obstruction of the brush by the silicone rubber edge protection material or the close proximity to the steel vise drawing the magnetic flux away from the workpiece.
The surface roughness and edge radius from finishing with Condition 2 are shown in Figure 4-12. The objective of Condition 2 is to determine the effect of increasing finishing time on surface roughness and to investigate the effect of reduced surface roughness on tool life. The oblique plots are shown in Figure 4-13, it is evident that MAF successfully decreases the surface roughness of uncoated triangular carbide tools with minimal rounding of the cutting edge.

The surface roughness and edge radius from finishing with Condition 3 are shown in Figure 4-14. Condition 3 aims to investigate the effect of reduced finishing time on surface roughness and the effect of increased surface roughness on tool life. The oblique plots of the before and after surfaces are shown in Figure 4-15. Despite the reduction in finishing time, the surface roughness still decreases by 50% of its original value.

The surface roughness and edge radius from finishing with Condition 4 are shown in Figure 4-16. Condition 4 aims to investigate the effect of finishing only the flank and rake on tool life. The oblique plots of the before and after surfaces are shown in Figure 4-17, the surface roughness goal is in the range of 30-40 nm Ra, which aims to mimic the finished surface roughness in Condition 1.

The surface roughness and edge radius from finishing with Condition 5 are shown in Figure 4-18. Condition 5 aims to investigate the effect of finishing only the flank on tool life. The oblique plots of the before and after surfaces are shown in Figure 4-19.

The surface roughness and edge radius from finishing with Condition 6 are shown in Figure 4-20. Condition 6 aims to investigate the effect of finishing only the
flank on tool life. The oblique plots of the before and after surfaces are shown in Figure 4-21.

### 4.2 Coated Carbide Tools for Milling Operation

The coated tool selected to evaluate the effectiveness of MAF on coated tools are TiAlN-coated round carbide tools for milling operations and are shown in Figure 4-22. The coating offers improved wear resistance and strength and is typically used to increase the life of the tool when machining high-temperature alloys and stainless steel. In addition to these advantages, at high cutting temperatures coating materials that contain unlike Al₂O₃, Ti based coatings offer better performance at high temperatures; therefore, despite the increased susceptibility to built up edge (BUE) formation due to the high chemical affinity with titanium, titanium based coatings are preferred to Al₂O₃ when machining titanium.[30] Furthermore, the stability of oxides formed on the coating surface such as AlOₓ and TiOₓ during high temperature cutting is theorized to aid in the machining process and serves to provide protection from tribo-oxidation for coated regions exposed to high temperatures and air. [31] These indexable inserts are ground before the coating is applied with PVD and possess a chip breaker to reduce the contact between the machined chip and the rake face. The morphology of the coated surface depends on the coating application method selected; compared with CVD, PVD offers negligible deterioration to the toughness and transverse roughness strength that effects carbide tools at the high temperatures necessary to apply CVD coatings. [32-33] Modern developments in low-temperature CVD application have enabled the application of CVD without these detrimental effects on the carbide substrate. [34]
4.2.1 Workpiece Holder

The design requirements for round coated insert workpiece holder are the same as stated for the uncoated triangular workpiece holder. The workpiece holder for flank finishing is shown in Figure 4-23, the steel cylinder below the workpiece ensures that the magnetic flux permeates through the workpiece. A titanium washer is positioned flush against the rake of the tool. The edge of the tool remains protected by preventing the magnetic particle chain from passing over the edge of the tool. The steel nut serves to distance the workpiece from the steel vise to prevent unwanted contact when the table is tilted. The flux density measurement setup is shown in Figure 4-24.

Figure 4-25 shows the rake finishing jig, a steel holder is positioned around the workpiece to protect the rake by ensuring that the particles do not pass over the edge of the workpiece. Due to the diameter of the steel holder, it was not necessary to distance the workpiece from the vise as with the flank workpiece holder. Due to the increase in distance between the pole tip and the steel cylinder for the rake finishing setup, a Nd-Fe-B magnet was positioned below the workpiece rather than the steel cylinder to increase the magnetic flux density at the workpiece surface by magnetizing the workpiece. The flux density measurement setup is shown in Figure 4-26. As with the uncoated triangular tool, the rake finishing setup for the rake of the coated round tool was modified for better repeatable positioning and setup. The relief angle on the flank of the coated round tool resulted in a tendency of the tool to “pop out” of the aluminum holder, careful adjustment prevented this from occurring but proved to be time consuming. The epoxy and HDPE tape alleviated this concern while slightly decreasing the magnetic flux density, the measurement setup is shown in figure 4-24.
4.2.2 Experimental Conditions

There are four finishing conditions selected for finishing of the TiAlN-coated round tools shown in Table 4-3. These experiments were performed in two blocks, the first block consisted of Condition 1 and Condition 2. These conditions finish both the rake and the flank of the tool; Condition 1 aims to change the texture of the tool while Condition 2 aims to change both the texture and reduce the surface roughness of the tool. Conditions 3 and 4 finish only the rake of the tool. Condition 3 has an increased finishing time over Condition 1 in an attempt to further reduce the surface roughness, while Condition 4 has a decreased finishing time in order to obtain a rougher surface roughness compared to Condition 1. The details of each finishing condition are shown in Table 4-4. Most of the finishing parameters such as spindle speed, spindle feed rate, gap between pole tip and workpiece, magnetic particle size and composition, and abrasive type and size are the same as the conditions for the uncoated triangular tool.

The experimental protocol is identical to that of the uncoated tools; however, a different tool geometry requires a different pole tip motion as shown in Figure 4-28. For the flank finishing in Conditions 1 and 2, the workpiece table is tilted to position the flank normal to the pole tip and rotated to obtain a surface speed of 1 mm/s. Similarly in the rake finishing setup the workpiece table is rotated to obtain a surface speed of 1 mm/s. In Conditions 3 and 4, the rake is divided into two sections. Since half of the workpiece is to be finished per condition, the pole tip simply transverses across the workpiece. This division serves to increase the number of finishing conditions per workpiece such that only two workpieces were finished to get four different experimental conditions. The finishing setup is shown in Figure 4-29.
4.2.3 Surface Roughness

The finished surface roughness and edge radius from Conditions 1 and 2 are shown in Figure 4-30. The surface roughness from Condition 1 was reduced while the oblique plots in Figure 4-31 shows a definite change in surface texture. Similarly the surface texture and roughness are modified in Condition 2.

The change in surface roughness and edge radius from Conditions 3 and 4 are shown in Figure 4-32. It is clear that an increase in finishing time results in a decrease in finished surface roughness accompanied by significant change in surface texture as shown in Error! Reference source not found.. Similarly, decreasing the finishing time results in significant reduction in the surface roughness and a change in surface texture.

Table 4-1. Uncoated carbide finishing conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Finished area</th>
<th>Number of corners</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flank, Nose, Rake</td>
<td>8</td>
<td>Initial finishing attempts</td>
</tr>
<tr>
<td>2</td>
<td>Flank, Nose, Rake</td>
<td>3</td>
<td>Extended finishing time</td>
</tr>
<tr>
<td>3</td>
<td>Flank, Nose, Rake</td>
<td>3</td>
<td>Reduced finishing time</td>
</tr>
<tr>
<td>4</td>
<td>Flank, Rake</td>
<td>3</td>
<td>Epoxy edge protection</td>
</tr>
<tr>
<td>5</td>
<td>Flank</td>
<td>3</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>Rake</td>
<td>3</td>
<td>Epoxy edge protection</td>
</tr>
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Table 4-2. Finishing conditions

<table>
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<tr>
<th>Conditions</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>Flank</td>
<td>588</td>
<td>603</td>
<td>413</td>
<td>603</td>
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<td>413</td>
</tr>
<tr>
<td>Nose</td>
<td>588</td>
<td>603</td>
<td>413</td>
<td>588</td>
<td>603</td>
<td>588</td>
</tr>
<tr>
<td>Rake</td>
<td>460</td>
<td>460</td>
<td>413</td>
<td>460</td>
<td>460</td>
<td>460</td>
</tr>
<tr>
<td>Magnetic flux density [mT]</td>
<td>588</td>
<td>603</td>
<td>413</td>
<td>603</td>
<td>603</td>
<td>413</td>
</tr>
<tr>
<td>Passes</td>
<td>120</td>
<td>90</td>
<td>150</td>
<td>125</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td>Finishing time [min]</td>
<td>20</td>
<td>15</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>Finishing length [mm]</td>
<td>10</td>
<td></td>
<td></td>
<td>12</td>
<td></td>
<td></td>
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<tr>
<td>707 µm mean diameter steel grit wt%</td>
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<td></td>
<td></td>
<td></td>
<td>43</td>
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<tr>
<td>40–144 µm iron particles wt%</td>
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<td>57</td>
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<tr>
<td>0–0.1 µm Diamond abrasive [mg]</td>
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<tr>
<td>Poletip-workpiece clearance [mm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spindle speed [min⁻¹]</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Spindle feed rate [mm/s]</td>
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Table 4-3. Finishing experimental plans

<table>
<thead>
<tr>
<th>Condition</th>
<th>Finishing Area</th>
<th>Number of cutting edges</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flank, Rake</td>
<td>1</td>
<td>Change texture</td>
</tr>
<tr>
<td>2</td>
<td>Flank, Rake</td>
<td>2</td>
<td>Change texture and reduce roughness</td>
</tr>
<tr>
<td>3</td>
<td>Rake</td>
<td>2</td>
<td>Increase finishing time</td>
</tr>
<tr>
<td>4</td>
<td>Rake</td>
<td>2</td>
<td>Decrease finishing time</td>
</tr>
</tbody>
</table>

Table 4-4. Finishing conditions

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<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finishing area</td>
<td>Flank</td>
<td>Rake</td>
<td>Flank</td>
<td>Rake</td>
</tr>
<tr>
<td>Magnetic flux density [mT]</td>
<td>581</td>
<td>612</td>
<td>581</td>
<td>612</td>
</tr>
<tr>
<td>Passes</td>
<td>60</td>
<td>180</td>
<td>110</td>
<td>180</td>
</tr>
<tr>
<td>Total finishing time [min]</td>
<td>50</td>
<td>150</td>
<td>90</td>
<td>150</td>
</tr>
<tr>
<td>Finishing length [mm]</td>
<td>50</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>707 µm mean diameter steel grit [mg]</td>
<td>120</td>
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<td></td>
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</tr>
<tr>
<td>40–144 µm iron particles [mg]</td>
<td>180</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0–0.1 µm Diamond abrasive [mg]</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Poletip clearance [mm]</td>
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<td>Spindle speed [rpm]</td>
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<td>Spindle feed rate [mm/s]</td>
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</tr>
</tbody>
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Figure 4-1. Uncoated triangular carbide tool. A) Dimensions of tool. B) Cutting Area. (Photo courtesy of Michael Tan)
Figure 4-2. Jig for finishing of triangular uncoated carbide tool (Photo courtesy of Michael Tan)

Figure 4-3. Tool edge protection A) Flank setup. B) Rake setup. C) Rake epoxy setup.

Figure 4-4. Hall probe dimensions
Figure 4-5. Setup for flank magnetic flux density measurement

Figure 4-6. Setup for rake magnetic flux density measurement
Figure 4-7. Setup for modified rake magnetic flux density measurement (epoxy + HDPE)

Figure 4-8. Uncoated tool poletip motion during finishing. A) Flank motion. B) Rake motion. C) Rake epoxy motion.
Figure 4-9. Uncoated tool finishing setup. A) Flank setup. B) Rake setup. C) Rake with epoxy setup. (Photos courtesy of Michael Tan)

Figure 4-10. Finishing results from Condition 1. A) Surface Roughness $Ra$, B) Edge Radius

(i) Flank 6.6 nm $Ra$

(ii) Nose 15.8 nm $Ra$

(iii) Rake 47.7 nm $Ra$
(i) Flank 22.6 nm Ra
(ii) Nose 18.1 nm Ra
(iii) Rake 32.9 nm Ra

(B) Insert 2

(i) Flank 29.1 nm Ra
(ii) Nose 16.7 nm Ra
(iii) Rake 13.2 nm Ra

(C) Insert 3

(i) Flank 8.2 nm Ra
(ii) Nose 22.1 nm Ra
(iii) Rake 39.1 nm Ra

(D) Insert 4

(i) Flank 10.7 nm Ra
(ii) Nose 11.2 nm Ra
(iii) Rake 44.9 nm Ra

(E) Insert 5
Figure 4-11. Oblique plots of inserts finished with Condition 1. (A)–(H) Inserts finished on Flank + Nose + Rake. (Photos courtesy of Michael Tan)
Figure 4-12. Finishing results from Condition 2. A) Surface Roughness $Ra$, B) Edge Radius

(A) Insert 1 Flank

(i) Before Finishing 124.1 nm $Ra$

(ii) After finishing 22.7 nm $Ra$

(B) Insert 1 Nose

(i) Before Finishing 137.8 nm $Ra$

(ii) After finishing 44.3 nm $Ra$
(C) Insert 1 Rake

(i) Before Finishing 151.7 nm Ra

(ii) After finishing 46.7 nm Ra

(D) Insert 2 Flank

(i) Before Finishing 162.8 nm Ra

(ii) After finishing 20 nm Ra

(E) Insert 2 Nose

(i) Before Finishing 140 nm Ra

(ii) After finishing 40.6 nm Ra

(F) Insert 2 Rake

(i) Before Finishing 158.3 nm Ra

(ii) After finishing 74.5 nm Ra
Figure 4-13. Oblique plots of inserts finished with Condition 2. (A)–(I) Inserts finished with increased finishing time. (Photos courtesy of Michael Tan)
Figure 4-14. Finishing results from Condition 3. A) Surface Roughness $Ra$, B) Edge Radius

(A) Insert 1 Flank

(i) Before Finishing 142.2 nm $Ra$

(ii) After finishing 79.3 nm $Ra$

(B) Insert 1 Nose

(i) Before Finishing 156.4 nm $Ra$

(ii) After finishing 44.2 nm $Ra$
(C) Insert 1 Rake

(i) Before Finishing 155 nm $Ra$
(ii) After finishing 47.6 nm $Ra$

(D) Insert 2 Flank

(i) Before Finishing 155 nm $Ra$
(ii) After finishing 47.6 nm $Ra$

(E) Insert 2 Nose

(i) Before Finishing 144 nm $Ra$
(ii) After finishing 70.3 nm $Ra$

(F) Insert 2 Rake

(i) Before Finishing 192.2 nm $Ra$
(ii) After finishing 89.9 nm $Ra$
Figure 4-15. Oblique plots of inserts finished with Condition 3. (A)–(I) Inserts finished with reduced finishing time. (Photos courtesy of Michael Tan)
Figure 4-16. Finishing results from Condition 4. A) Surface Roughness $Ra$, B) Edge Radius

(A) Insert 1 Flank

(i) Before Finishing 99 nm $Ra$

(ii) After finishing 31.6 nm $Ra$

(B) Insert 1 Rake

(i) Before Finishing 83.1 nm $Ra$

(ii) After finishing 33.2 nm $Ra$
Figure 4-17. Oblique plots of inserts finished with Condition 4. (A)–(F) Inserts finished on Flank and Rake. (Photos courtesy of Michael Tan)
Figure 4-18. Finishing results from Condition 5. A) Surface Roughness $Ra$, B) Edge Radius

(A) Insert 1 Flank

(i) Before Finishing 120.8 nm $Ra$

(ii) After finishing 65 nm $Ra$

(B) Insert 2 Flank

(i) Before Finishing 104.3 nm $Ra$

(ii) After finishing 44.3 nm $Ra$
Figure 4-19. Oblique plots of inserts finished with Condition 5. (A)–(C) Inserts finished on Flank. (Photos courtesy of Michael Tan)

Figure 4-20. Finishing results from Condition 6. A) Surface Roughness $Ra$, B) Edge Radius

(A) Insert 1 Rake
Figure 4-21. Oblique plots of inserts finished with Condition 6. (A)–(C) Inserts finished on Rake. (Photos courtesy of Michael Tan)

Figure 4-22. TiAlN-coated round carbide tool (Photo courtesy of Michael Tan)
Figure 4-23. Jig for flank finishing (Photo courtesy of Michael Tan)

Figure 4-24. Setup for round flank magnetic flux density measurement

Figure 4-25. Jig for rake finishing (Photo courtesy of Michael Tan)
Figure 4-26. Setup for round rake magnetic flux density measurement

Figure 4-27. Setup for round modified rake magnetic flux density measurement (epoxy + HDPE)
Figure 4-28. TiAlN-coated round tool finishing motion. A) Flank. B) Rake. C) Rake epoxy.

Figure 4-29. TiAlN-coated round tool finishing setup A) Flank. B) Rake. C) Rake epoxy. (Photos courtesy of Michael Tan)
Figure 4-30. Finishing results from Conditions 1 and 2. A) Surface Roughness $Ra$, B) Edge Radius

(A) Flank (Condition 1: Finishing time for flank 50 min)

(i) Before Finishing 144.3 nm $Ra$

(ii) After finishing 51.9 nm $Ra$

(B) Rake (Condition 1: Finishing time for rake 150 min)

(i) Before Finishing 186 nm $Ra$

(ii) After finishing 79 nm $Ra$

(C) Flank (Condition 2: Finishing time for flank 90 min)

(i) Before Finishing 206.4 nm $Ra$

(ii) After finishing 68.9 nm $Ra$

(D) Rake (Condition 2: Finishing time for flank 150 min)

(i) Before Finishing 206.4 nm $Ra$

(ii) After finishing 68.9 nm $Ra$
Figure 4-31. Oblique plots of round finished inserts with Conditions 1 and 2. (A)–(B) Inserts finished with Condition 1. (C)–(D) Inserts finished with Condition 2. (Photos courtesy of Michael Tan)

Figure 4-32. Finishing results from Conditions 2 and 3. A) Surface Roughness $Ra$, B) Edge Radius
Figure 4-33. Oblique plots of round finished inserts with Conditions 3 and 4. (A)–(B) Inserts finished with Condition 3. (C)–(D) Inserts finished with Condition 4. (Photos courtesy of Michael Tan)
CHAPTER 5
TOOL LIFE ANALYSIS

5.1 Turning Operations

5.1.1 Experimental Conditions

The effects of the finishing process on tool wear were evaluated by cutting tests. For the uncoated triangular tools, turning tests on a 50.8 mm diameter Ti-6Al-4V titanium alloy rod are performed for both the as-received and MAF-processed inserts. The turning tests were conducted with a CNC turning center interfaced with a PC and a three-dimensional dynamometer for force data acquisition as shown in Figure 5-1. [4] The forces acquired by the dynamometer are shown in the cutting schematic in figure 5-1. The specific cutting conditions are shown in Table 5-1. To evaluate tool wear, images of the tool flank were captured after every pass using an optical microscope connected to a digital camera and PC. The maximum flank wear $V_{B_{\text{max}}}$ was measured by the images taken after every pass, the turning operation was terminated once $V_{B_{\text{max}}}$ exceeded 762 µm for Conditions 1,2,5,6 and 400 µm for Conditions 3 and 4.

5.1.2 Tool Wear and Cutting Forces

Figure 5-2 shows the measured flank wear for Condition 1 (flank, rake, and nose finishing). It shows that the MAF processed tools exhibit tool lives up to twice as long as the unprocessed tool. Figure 5-3 shows the representative changes in average cutting force with time during the turning operation. It is clear that the trends in cutting force closely follow the trends of $V_{B_{\text{max}}}$.

Figure 5-4 presents the photographs of the worn tools from Condition 1. Scanning electron microscope (SEM) observation and Energy Dispersive Spectroscopy (EDS) of the worn section of the tools show little to no
detection of tungsten and a significant increase in the presence of titanium indicating strong workpiece adhesion onto the tooling.

Figure 5-5 shows the measured flank wear for Condition 2 (flank, rake, and nose extended finishing). Due to the large variance in the tool life of the unprocessed tool it is unclear if the processed tools exhibited better or worse performance. More cutting experiments at this condition are required to make concrete conclusions to the effects of tool life. Figure 5-6 shows the representative changes in total cutting force with time during the turning operation. It is clear that the trends in cutting force closely follow the trends of $V_B^{\text{max}}$. Figure 5-7 presents the photographs of the worn tools from Condition 2.

Figure 5-8 shows the measured flank wear for Condition 3 (flank, rake, and nose reduced finishing). Due to the large variance in the tool life of the unprocessed tool it is unclear if the processed tools exhibited better or worse performance; however, when compared to Condition 2 it is evident that a rougher surface roughness results in an increased tool life compared to a smoother surface roughness. More cutting experiments at this condition are required to make concrete conclusions to the effects of tool life. Figure 5-9 shows the representative changes in total cutting force with time during the turning operation. It is clear that the trends in cutting force closely follow the trends of $V_B^{\text{max}}$. Figure 5-10 presents the photographs of the worn tools from Condition 3.

Figure 5-11 shows the measured flank wear for Condition 4 (flank and rake). Finishing of the rake and flank seems to result in tool lives slightly lower than that of unprocessed tools. However, due to a lack of data points it is impossible to confirm this hypothesis without additional cutting experiments with this finishing condition. Figure 5-
12 shows the representative changes in total cutting force with time during the turning operation. It is clear that the trends in cutting force closely follow the trends of $V_{B_{\text{max}}}$.

Figure 5-13 presents the photographs of the worn tools from Condition 4.

Figure 5-14 shows the measured flank wear for Condition 5 (flank only). Finishing of only the flank seems to result in tool lives significantly lower than that of unprocessed tools. However, due to a lack of data points it is impossible to confirm this hypothesis without additional cutting experiments with this finishing condition. Figure 5-15 shows the representative changes in total cutting force with time during the turning operation. It is clear that the trends in cutting force closely follow the trends of $V_{B_{\text{max}}}$.

Figure 5-16 presents the photographs of the worn tools from Condition 5.

Figure 5-17 shows the measured flank wear for Condition 5 (rake only). Finishing of only the Rake seems to result in tool lives slightly lower than that of unprocessed tools. However, due to a lack of data points it is impossible to confirm this hypothesis without additional cutting experiments with this finishing condition. Figure 5-18 shows the representative changes in total cutting force with time during the turning operation. It is clear that the trends in cutting force closely follow the trends of $V_{B_{\text{max}}}$.

Figure 5-19 presents the photographs of the worn tools from Condition 6.

5.1.3 MAF Processed Tool Life Comparison

The tool lives of the different MAF tools are shown in Figure 5-20, each condition selected correspond to different finishing areas. Finishing of the flank and rake appears to have the greatest positive effect on tool life followed by finishing of the flank, nose, and rake. However, finishing of only one of the key cutting areas such as only the flank or only the rake appears to have a negative effect on tool life. One hypothesis is that the uneven coefficient of friction between the tool-chip interface and tool-workpiece
interface results in unpredictable vibrations during cutting resulting in unfavorable cutting conditions. It is important to note that the workpiece mechanical properties play a significant role in tool life.

5.1.4 Chip Morphology

The interaction between the tool and the chip is believed to play a significant role in tool wear. The chips produced from the cutting operation were typical serrated chips which is commonly found when machining Ti-6Al-4V. The serrated chip formation is attributed to a combination of the stick-slip interaction between the rake and chip, and the phase change resulting from the extreme temperatures during cutting. The change from alpha to beta phase of the meta-stable alloy results in an increased number of slip planes; which, due to the shearing of the workpiece material, results in the unique saw-tooth serrated chip formation. [35,36,37]

The chip morphology of the chips formed under Condition 1 compared to the unprocessed chip indicates an increase in shear angle as shown in Figure 5-21. Additionally, the back of the chip from MAF processed tools results in a reduction in surface roughness when compared to the unprocessed chip. This holds true for most of the chips formed; however, in some cases the roughness at the back of the chip was higher than that of the unprocessed tool. This may be attributed to premature wear of the tool during processing resulting in higher friction between the chip and rake thus imparting a higher surface roughness on the machined chip.

Figure 5-22 shows the chip morphology from Condition 2, as expected the surface roughness on the back of the chip increase as tool wear progresses. Additionally, the chip formation as wear progresses grows increasingly random and uneven, possibly due to the unpredictable vibrations and cutting conditions resulting
from cutting with a worn tool. Compared to the chip from the unprocessed tool in Condition 1, the chip formed from a MAF processed tool with an extended finishing time appear to have a higher surface roughness at the back of the chip. This is in agreement with the lower tool life of the tools that produced these chips.

Figure 5-23 shows the chip morphology from Condition 3. Unexpectedly the roughness of the chips formed from MAF processed tool with a reduced finishing time are lower than the chip formed from a tool with an extended finishing time. Figure 5-24 shows the chip morphology from Condition 4. The surface roughness on the back of the chips formed from finishing the rake and flank is similar to those formed from processing the flank, nose, and rake with a reduced finishing time. Figure 5-25 and Figure 5-26 show the resultant chip from Conditions 5 and 6, respectively. It is clear that finishing only flank or only the rake result in the highest chip roughness which is an agreement with the shorter tool life of the tools used to form these chips.

5.2 Milling Operations

5.2.1 Experimental Conditions

The effects of finishing on tool wear were evaluated by milling a Ti-6Al-4V titanium alloy block using the unprocessed and MAF-processed tools. The milling tests were conducted using a vertical machining center interfaced with a PC and a three-dimensional dynamometer for force data acquisition. The experimental Conditions are shown in Table 5-2. To evaluate the tool wear, images of the tool flank were captured after every 152.4 mm pass using an optical microscope connected to a digital camera and PC. The maximum flank wear \((V_B^{max})\) was measured using the digital images, and the milling operations were terminated once \(V_B^{max}\) exceeded 300 \(\mu m\).
5.2.2 Tool Wear and Cutting Forces

Figure 5-27 shows the maximum flank wear of Conditions 1 and 2 plotted with time. It shows that the MAF-processed tools had useable tool lives up to 1.5 as long as the untreated tool. Figure 5-28 shows the average cutting force (composed of the tangential, radial, and axial forces) with time. The unprocessed tools exhibit slightly higher forces than the MAF processed tools, another interesting observation is the sudden increase in \( VB_{max} \) when a sudden decrease in force was detected. This may be attributed to sudden fracture or breaking of the tool. Figure 5-29 shows the tool wear photographs of the tools from Conditions 1 and 2.

5.2.3 Chip Morphology

Figure 5-30 shows images and roughnesses of the chips produced from the milling operation. According to both the unprocessed and MAF-processed tools, the chip curl diameter and thickness is shown to increase as tool wear progresses. This is attributed to the increase in friction encountered with degraded tool surfaces. A comparison between the initial chip thickness of unprocessed and MAF-processed tools show a clear difference in both chip curl diameter and thickness. The MAF-processed tools exhibit a smaller chip radius and smaller thickness, this may be attributed to a higher shear angle of these chips.

Table 5-1. Uncoated carbide experimental protocol

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>50.8 mm (2in) diameter Ti-6Al-4V alloy rod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Speed</td>
<td>100 m/min</td>
</tr>
<tr>
<td>Feed rate</td>
<td>0.075 mm/rev</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Cut length per pass</td>
<td>50 mm</td>
</tr>
<tr>
<td>Cutting fluid</td>
<td>Trim Sol: 5 vol %</td>
</tr>
</tbody>
</table>
Table 5-2. Round coated carbide tool cutting experimental conditions

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>6” x 4” Ti-6Al-4V alloy block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Speed</td>
<td>48.8 m/min</td>
</tr>
<tr>
<td>Feed rate</td>
<td>11.7 cm/min</td>
</tr>
<tr>
<td>Axial DOC</td>
<td>2.54 mm</td>
</tr>
<tr>
<td>Radial DOC</td>
<td>20.32</td>
</tr>
<tr>
<td>Cutting fluid</td>
<td>Trim Sol: 8 vol %</td>
</tr>
</tbody>
</table>

Figure 5-1. Cutting experimental setup. A) Turning schematic. B) Photograph of cutting experiment. (Photo courtesy of Michael Tan)

Figure 5-2. Changes in maximum flank wear with time from Condition 1.
Figure 5-3. Changes in average cutting force with time from Condition 1.

(i) Flank wear

(ii) Rake wear

(A) Unfinished Insert
(i) Flank wear

(ii) Rake wear

(B) Insert 1

(i) Flank wear

(ii) Rake wear

(C) Insert 2

(i) Flank wear

(ii) Rake wear

(D) Insert 3
(i) Flank wear

(ii) Rake wear

(E) Insert 4

(i) Flank wear

(ii) Rake wear

(F) Insert 5

(i) Flank wear

(ii) Rake wear

(G) Insert 6
Figure 5-4. Photographs of tool wear from Condition 1. (A)-(I) Inserts finished with Condition 1. (Photos courtesy of Michael Tan)
Figure 5-5. Changes in maximum flank wear with time from Condition 2.

Figure 5-6. Changes in average cutting force with time from Condition 2.
Figure 5-7. Photographs of tool wear from Condition 2. (A)-(C) Inserts finished with Condition 2. (Photos courtesy of Michael Tan)
Figure 5-8. Changes in maximum flank wear with time from Condition 3.

Figure 5-9. Changes in average cutting force with time from Condition 3.
Figure 5-10. Photographs of tool wear from Condition 3. (A)-(C) Inserts finished with Condition 3. (Photos courtesy of Michael Tan)
Figure 5-11. Changes in maximum flank wear with time from Condition 4.

Figure 5-12. Changes in average cutting force with time from Condition 4.
Figure 5-13. Photographs of tool wear from Condition 4. (A)-(B) Inserts finished with Condition 4. (Photos courtesy of Michael Tan)
Figure 5-14. Changes in maximum flank wear with time from Condition 5.

Figure 5-15. Changes in average cutting force with time from Condition 5.
Figure 5-16. Photographs of tool wear from Condition 5. A) Insert finished with Condition 5. (Photo courtesy of Michael Tan)

Figure 5-17. Changes in maximum flank wear with time from Condition 6.
Figure 5-18. Changes in average cutting force with time from Condition 6.

(i) Flank wear
(ii) Rake wear

(A) Insert 1
Figure 5-19. Photographs of tool wear from Condition 6. (A)-(B) Inserts finished with Condition 6. (Photos courtesy of Michael Tan)

Figure 5-20. Comparison of the tool wear with time.
(A) Unfinished insert chip

(B) Insert 1 chip

(C) Insert 2 chip

(D) Insert 3 chip

(i) Chip

(ii) Chip (side-view)

(iii) Back of chip (oblique plot)

10 mm

0.15 mm

30 nm $Ra$

21.1 nm $Ra$

17.7 nm $Ra$

109.2 nm $Ra$

10 mm

0.15 mm

Ra
Figure 5-21. Chip morphology from Condition 1. (A)-(H) Chips from inserts finished with Condition 1. (Photos courtesy of Michael Tan)
(A) Insert 1 chip from first pass

(B) Insert 1 chip from last pass

(C) Insert 2 chip from first pass

(D) Insert 2 chip from last pass
Figure 5-22. Chip morphology from Condition 2. (A)-(F) Chips from inserts finished with Condition 2. (Photos courtesy of Michael Tan)
Figure 5-23. Chip morphology from Condition 3. (A)-(F) Chips from inserts finished with Condition 3. (Photos courtesy of Michael Tan)
(A) Insert 2 chip from first pass

(B) Insert 2 chip from last pass

(C) Insert 3 large radius chip from first pass

(D) Insert 3 small radius chip from first pass

(E) Insert 3 large radius chip from last pass
Figure 5-24. Chip morphology from Condition 4. (A)-(F) Chips from inserts finished with Condition 4. (Photos courtesy of Michael Tan)

(F) Insert 3 small radius chip from last pass

Figure 5-25. Chip morphology from Condition 5. (A)-(C) Chips from inserts finished with Condition 5. (Photos courtesy of Michael Tan)
(A) Insert 2 chip from first pass

(B) Insert 2 chip from last pass

(C) Insert 3 large radius chip from first pass

(D) Insert 3 small radius chip from first pass
Figure 5-26. Chip morphology from Condition 6. (A)-(F) Chips from inserts finished with Condition 6. (Photos courtesy of Michael Tan)

Figure 5-27. Changes in round maximum flank wear with time
Figure 5-28. Changes in round average cutting force with time
Figure 5-29. Tool wear photographs from Conditions 1 and 2. (A)-(D) Tools finished with Conditions 1 and 2. (Photo courtesy of Michael Tan)
(i) Chip
(ii) Chip (side-view)
(iii) Back of chip (oblique plot)

(C) Condition 1 insert 1 chip from first pass

124 nm Ra

(i) Chip
(ii) Chip (side-view)
(iii) Back of chip (oblique plot)

(D) Condition 1 insert 1 chip from last pass

160 nm Ra

(i) Chip
(ii) Chip (side-view)
(iii) Back of chip (oblique plot)

(E) Condition 2 insert 1 chip from first pass

139 nm Ra

(F) Condition 2 insert 1 chip from last pass

106 nm Ra
Figure 5-30. Chip morphology from Conditions 3 and 4. (A)-(B) As-received inserts. (C)-(H) MAF Inserts. (Photos courtesy of Michael Tan)
6.1 Concluding Remarks

MAF has been shown to successfully reduce the roughness and change the texture of complicated tools made of tough materials such as tungsten carbide and TiAlN-coated carbides. Furthermore, this research has shown that MAF can be applied to cutting tools without rounding the edge of the tool. Cutting tests on uncoated carbide tools finished with Condition 1 have shown a substantial increase in tool life attributed to the smoothing of the existing surface texture of the tool.

To investigate the correlation of surface roughness with tool life, it has been found that an excessive reduction in surface roughness may result in the degradation of the existing surface texture resulting in a reduction in tool life. Comparing the uncoated tools with the MAF processed tools in Conditions 2 (extended finishing time to produce finer surfaces) and 4 (rake and flank finishing), it is evident tool life decreases with extended processing. The tools finished with Condition 3 exhibited longer tool lives than those finished with Condition 2. This is attributed to the higher surface roughness and the remnant as-received surface texture. Furthermore, the processing of only the flank (Condition 5) or only the rake (Condition 6) has been shown to further reduce the life of the tool, this may be attributed to the uneven wear characteristics of the tool-workpiece interface and the tool-chip interface.

The coated tool exhibited the same correlation between surface texture and tool life; specifically that extended processing results in a reduction in tool life. One possible explanation is that the surface texture due to excessive MAF processing results in a larger contact area between the tool and the workpiece during cutting. This results in
excessive adhesion and diffusion between the tool and chip. Furthermore, the smooth texture from over processing may prevent cutting lubricants from remaining on the tool surface encouraging direct contact between the tool surface and chip. It is evident that MAF has the potential to greatly increase tool life, the specific conditions in which this objective may be realized requires further investigation.

6.2 Future Work

The future research efforts need to be focused on determining the fine correlation between tool surface topography, cutting force, chip morphology, and tool life. Moreover, the MAF processing mechanism needs to be clarified to achieve a fine control of the processing characteristics. To complete these objectives, further experimentation on the relationship between tool life and surface roughness (without the modification of the as-received surface texture) needs to be performed. Once the correlation between tool surface roughness and tool life is known, further investigation into the effect of different surface textures and tool life can be investigated. Additionally, the effects on tool life from finishing the nose of the uncoated triangular tools is to be investigated. Modeling of the MAF processing setup should be carried out with magnetic field simulation software (MagNet) to verify the magnetic field density measurements and to determine if any optimizations in the finishing jig are available.
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Michael Tan was born in Los Angeles, California to Marciano and Marylyn Tan. He moved to Okinawa, Japan at an early age until the age of 14. In 2002 Michael moved to Florida and obtained his Bachelor of Science in Aerospace Engineering and Bachelor of Science in mechanical engineering in 2011. In January of 2012, under the guidance of Dr. Hitomi Yamaguchi Greenslet, Michael pursued a Master of Science in mechanical engineering. Upon graduating, Michael plans to work in the manufacturing industry.