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Ductile-Regime Machining of Silicon Carbide and Quartz

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DUCTILE-REGIME MACHINING OF SILICON CARBIDE AND QUARTZ

by

Deepak Ravindra

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science in Engineering (Mechanical)
Department of Mechanical and Aeronautical Engineering

Western Michigan University
Kalamazoo, Michigan
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DEDICATION

This research work is dedicated to my loving parents, without whose love, encouragement, and support, I would have never accomplished what I did. Their priceless advice and hard work will always be treasured and appreciated for the rest of my life.
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Silicon carbide (SiC) and quartz are one of the advanced engineered ceramic materials designed to operate in extreme environments. One of the main reasons for the choice of these materials is due to its excellent electrical, mechanical and optical properties that benefit the semiconductor, MEMS and optoelectronic industry respectively. Manufacturing these materials is extremely challenging due to its high hardness, brittle characteristics and poor machinability. Severe fracture can result when trying to machine SiC and quartz due to its low fracture toughness. However, from past and current research efforts, it has been proven that ductile regime machining of brittle materials is possible. The main goal of the subject research is to improve the surface quality of a chemically vapor deposited (CVD) polycrystalline SiC and quartz to be used as optics devices. Besides improving the surface roughness of the material, the research also emphasizes increasing the material removal rate (MRR) and minimizing the diamond tool wear. Besides improving the quality, machining parameters to make this manufacturing process more time and cost efficient are also suggested.
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6.15 The optical microscope image above shows no visible wear at the cutting edge radius (1040x) .............................. 116
Although silicon carbide (SiC) has been around since 1891, it was not until the mid 1990's that this material was introduced into the precision manufacturing industry. SiC is well known for its excellent material properties, high durability, high wear resistance, light weight and extreme hardness. However, SiC is also known for its low fracture toughness, extreme brittleness and poor machinability.

SiC is an advanced engineered semiconductor and ceramic designed to operate in extreme environments. This material is pursued as a microelectronic (single crystal), a coating (CVD) and structural material due to its unique properties, such as:

- Larger energy bandgap and breakdown field allowing it to be used in high-temperature, high-power and radiation-hard environments
- Mechanically strength, expressed by its high Young’s modulus\(^1\)
- Desirable tribological properties, such as wear resistance and self-lubricating\(^2\)

All of these properties make SiC an exceptional candidate in harsh environments (high temperature, strong radiation, and corrosive and abrasive media). Some of the application fields where SiC is introduced include automobile, aerospace, petroleum, nuclear, military and biological/medical industries. Manufacturing this material is extremely challenging due to its high hardness, brittle characteristics and poor machinability. Severe fracture can result when trying to machine SiC due to its low

\(^1\) Young’s modulus
\(^2\) Self-lubricating
fracture toughness. However, from past experience it has been proven that ductile regime machining of silicon carbide is possible.3

Single Crystal Silicon Carbide (SiC) (4H)

SiC is commercially available in various forms and phases (polytypes) such as single crystal, polycrystalline (sintered and CVD) and amorphous. The most common polytypes of SiC are 2H, 3C, 4H, 6H, and 15R. The numbers refer to the number of layers in the unit cell and the letter designates the crystal structure, where C=cubic, H=hexagonal, and R=rhombohedral. Polished single crystal wafers are becoming more common in the high power, high temperature electronics device industry. In this research the 4H single crystal wafer (from Cree. Inc.) was used as it provides for an excellent reference surface for determining the DBT and to establish the corresponding critical depth of cut. Previous work involved 6H SiC (Patten, 2005). These wafers are extremely smooth (nm surface roughness) and also of high purity, containing few defects, which will help in determining the actual brittleness (DBT) of the material.5 The 4H single crystal SiC wafer is typically used for:

- Optoelectronic Devices
- High-Power Devices
- High Temperature Devices
- High-Frequency Power Devices
- III-V Nitride Deposition
Chemically Vapor Deposited Polycrystalline SiC (3C-β)

The fully dense cubic (beta) polycrystalline silicon carbide CVD coating (~250μm thick, applied on top of a SiC substrate) is a potential candidate to be used as mirrors for surveillance, high energy lasers (such as airborne laser), laser radar systems, synchrotron x-ray, VUV telescopes, large astronomical telescopes and weather satellites. The primary reasons CVD coated silicon carbide is preferred for these applications is that the material possesses high purity (>99.9995%), homogeneity, density (99.9% dense), chemical and oxidation resistance, cleanability, polishability and thermal and dimensional stability. Machining SiC is extremely challenging due to its extreme hardness (~27 GPa) and brittle characteristics. Besides the low fracture toughness of the material, severe tool wear (even of the single crystal diamond tool) also has to be considered. Previous researchers have successfully been able to precisely grind CVD-SiC (using high precision grinding) but this process is very expensive and the fine abrasive wheels often result in an unstable machine/process. Single point diamond turning (SPDT) was chosen as the material removal method as it offers increased process flexibility, better accuracy, quicker fabrication time and lower cost when compared to grinding and polishing to achieve nanometer surface roughness.

In order to fulfill the requirements to be qualified as a good candidate for optical mirrors, the surface finish for this material has to be close to mirror finish (Ra < 20nm). This is not easy to achieve from an as received CVD coated SiC work piece that has a fairly rough surface (in the case of the MLPC project (Chapter 5) the POCO Graphite SiC disk (SuperSiC-2) had a Ra value of approximately 3.6μm). Several machining techniques such as lapping, polishing, grinding, laser machining, and diamond turning are
being used today in an attempt to micro/nano machine this brittle material to a high quality, low roughness and damage free surface.

**Quartz (Fused Silica)**

The high demand in the optical and electronic industry has been consistently pushing and breaking the barriers in various nanotechnology areas such as SPDT. In fact, it was just in the 1960’s where precision engineering involved a maximum precision of about 10µm. Mirror finishing of brittle materials, such as glass, is a fairly new topic and process for SPDT due to the challenges (such as tooling, machining accuracy, brittle material properties, etc.) that had to be overcome in the precision manufacturing industry. Attempts have been made recently to machine glass in a similar manner to ductile metals by using SPDT. SPDT has shown positive effects when performed on materials used as aspherical shapes in optical products. Such advances are essential in order to economically produce high quality ceramic and glass parts.

Glasses exhibit excellent optical and mechanical properties (good thermal resistance, excellent corrosive resistance, high hardness, etc.), which are needed for advanced optical technology applications. However, severe challenges arise when attempting to machine these extremely brittle materials to obtain excellent surface finish for optical devices (Ra < 50 nm). The combination of hardness (~9.8GPa) and brittleness (low fracture toughness) plays an important factor in limiting glass materials from being easily machined using just a conventional machining technique (i.e. grinding, polishing, lapping etc.) without causing any brittle fracture. SPDT is one of the fabrication
techniques that meet the demand of today’s precision engineering requirements, which requires both fast production rate and higher surface quality for optical devices.

Quartz (fused silica) was also evaluated experimentally in this research. Quartz is an important optical material due to its material properties and its abundance in nature; quartz (SiO$_2$) is known as the most abundant nonmetallic mineral on earth. For this research, a synthesized fused silica (Spectrosil 2000$^{15}$) was used. Spectrosil 2000 is an ultra pure synthetic fused silica manufactured by Saint-Gobain Quartz PLC. This material possesses a chemical purity of 99.999% and is manufactured using an environmentally friendly process, which results in a material that is both chlorine-free and bubble-free. The bubble-free material enables a smoother surface finish after machining as it has very few/no impurities.

Manufacturing Process–Single Point Diamond Turning (SPDT)

A good manufacturing technique should provide both high product quality and cost effectiveness. There are several manufacturing techniques such as turning, milling, polishing, finishing, lapping and honing that are used to. Traditionally, turning and milling are considered roughing/semi-finishing operations. Polishing is used to obtain the final surface finish; this operation is carried out to remove micro-cracks, scratches and voids (these damages are usually caused by previous manufacturing operations). Lapping and honing generally are carried out for obtaining form and shape accuracy such as flatness and sphericity.

SPDT was chosen as the material removal method as it offers better accuracy, quicker fabrication time and lower cost when compared to grinding and polishing.$^{16}$
high demand in the optical and electronic industry has been consistently pushing and breaking the barriers in various nanotechnology areas such as SPDT. Such advances are essential in order to economically produce high quality semiconductor, ceramic and glass parts. SPDT is well known for providing advantages due to the level of precision of the equipment. SPDT was an ideal material removal process for these projects (discussed in this thesis) as it is capable of:

- machining in the ductile regime: able to control several parameters precisely such as depth of cut, cutting speed and feed, allowing ductile mode machining,
- very controlled material removal process: in the nanometer range,
- cost efficient; tools can be reused after relapping,
- time efficient: the limit of ductile regime machining can be pushed (vary the material removal rate by adjusting the depth of cut and feed rate) to minimize the number of passes, unlike polishing where only very little material can be removed at once, and
- provides good surface finish: best surface roughness, Ra, achieved in this research is about 38nm.

The equipment used to carry out all of the SPDT experiments was The Micro-Tribometer (UMT) from the Center for Tribology Research Inc. (CETR). This equipment was developed to perform comprehensive micro-mechanical tests of coatings and materials at the micro scale.17
Diamond Tooling

Diamond, the hardest material known to mankind, is an ideal candidate for tooling due to its ultra high-hardness (~100 GPa), high resistance to wear and good thermal conductivity. This extreme hardness of diamond is necessary when attempting to cut an extremely hard and abrasive material like SiC (H~ 26 GPa). The general hardness ratio (tool/workpiece) preferred in industry is about 10 although in the case of diamond and SiC we only get a hardness ratio of about 4 (it is about 10 for quartz). This fairly low hardness ratio, between the tool and workpiece, results in tool wear which will be discussed in the later section of this thesis. The outstanding crystalline structure (tetragonal arrangement of the C-C covalent bonds) of diamond makes it possible to fabricate tool tips with very sharp cutting edges (20 to 50 nm). The ability to fabricate single crystal diamond tools with extremely smooth finish (Ra ~ 3 nm), makes it ideal for SPDT ceramics to improve surface finish with a high degree of accuracy. Synthetic single crystal diamond (approximately same properties as natural diamond) tools from Chardon Tools Inc. were used for all projects discussed in this thesis. These synthetic diamonds are usually grown at high temperature and pressure from carbon feedstock. The effect of the brittleness and propensity of diamond to chip (resulting in tool breakage) is discussed in the later chapters. The brittleness of the diamond limits its applications (also diamond is conventionally limited to non ferrous metals, ref.) and necessitates larger included angle (to increase the edge strength) for SPDT of hard materials, such as ceramics.
Project Goals

Ductile to Brittle Transition (DBT) of a Single Crystal 4H-SiC Wafer by Performing Nanometric Machining

The main goal of this project was to determine the DBT depth for a single crystal 4H-SiC wafer. This piece of information is extremely important when attempting to machine semiconductors or ceramics, in this case SiC, in order to establish ductile mode machining conditions. In this project, nanometric cutting experiments were performed to determine the DBT depth for a single crystal 4H-SiC wafer. A specific cutting plane and direction were chosen and the crystal orientation was identified and evaluated to determine the DBT.

Improving the Surface Roughness of a CVD coated SiC Disk by Performing Ductile Regime Single Point Diamond Turning

The main goal of the second project carried out in this research is to improve the surface quality (minimize surface roughness) of a CVD polycrystalline SiC material to be used in an optics device such as a mirror. Besides improving the surface roughness of the material, the research also emphasized increasing the material removal rate (MRR) and minimizing the diamond tool wear. The mirror finish on the CVD-SiC surface produced by the SPDT method (after subsequent post process polishing to achieve the final surface roughness of < 10 nm Ra) will then be used for optical mirrors in a high powered laser device.
Developing a Hybrid Laser-SPDT Machining Process for Smoothing Ceramics (CVD-SiC)

The purpose of this experimental research program is to develop a hybrid laser-SPDT machining process for CVD SiC. The three main goals of this experiment are: 1) to improve the final surface quality (in terms of surface roughness), 2) increase the MRR and 3) minimize the tool wear. The idea of this project is to study the combination of both methods (laser ablation and SPDT) and identify which laser processing parameter (if any) best facilitates SPDT in order to make the precision manufacturing of ceramics more efficient. Both methods have been identified as successful material removal methods for SiC. Laser machining (carried out first) is expected to smooth the as-received SiC surface by removing the major peaks and rough spots. The laser ablated surface is then further improved by carrying out SPDT while minimizing the tool wear (due to a less rough surface, which reduces the abrasive wear of the diamond tool, after the laser ablation process).

Attempting to Machine and Improve the Surface Roughness of a Quartz Disk (Fused Silica) by Performing Ductile Regime Single Point Diamond Turning

The main goal of this final experimental research project is to establish a production-level process condition for quartz mirror fabrication via ductile mode machining. A 6” diameter Spectrosil 2000 disk (0.250” thick) was used to carry out the experiments. The very first task was to determine if this material can be diamond turned in the ductile regime with the current setup for SPDT (similar to setup used for the 6” TWS CVD-SiC). If ductile mode machining is possible (which it was), then SPDT of quartz will be (was subsequently) attempted to improve the surface roughness (desired
final surface roughness, Ra < 50nm) and monitor the tool wear. These results will be used to predict machining and tool wear data for a 14” diameter round quartz disk, which will be used as a nose cover for a high power Airborne Laser (ABL) device; (the machining of the 14” diameter disk will not be carried out at Western Michigan University).19
CHAPTER 2

BACKGROUND

Materials that are hard and brittle, such as semiconductors, ceramics and glasses, are amongst the most challenging to machine. When attempting to machine ceramics, such as silicon carbide (SiC), especially to improve the surface finish, it is important to carry out a ‘damage free’ machining operation. This often can be achieved by ductile mode machining (DMM) or in other words machining a particular hard and brittle material in the ductile regime. Material removal processes can be considered in terms of fracture dominated mechanisms or localized plastic deformation. A fracture dominant mechanism for ceramics, i.e., brittle fracture, can result in poor surface finish (surface damage) and also compromises on material properties and performance. A plastic deformation process can result in smooth and damage free surfaces, suitable for optical applications.

Ductile Regime Machining

The insight into the origins of the ductile regime during single point diamond turning (SPDT) of semiconductors and ceramics was provided in the research done by Morris, et al.\textsuperscript{20} A detailed study of machining chips (debris) and the resultant surface was analyzed using TEM to evaluate evidence of plastic material deformation. This seminal research concluded that the machining chips were plastically formed and are amorphous due to the back transformation of a pressure induced phase transformation (not due to oxidation), and contains small amounts of micro-crystalline (brittle) fragments.
According to the research carried out by Bifano et al.\textsuperscript{21}, there are two types of material removal mechanisms associated with the machining process: ductile - plastic flow of material in the form of severely sheared machining chips, and brittle - material removal through crack propagation. This previous research discusses several physical parameters that influence the ductile to brittle transition in grinding of brittle materials. The researchers were successful in performing ductile mode grinding on brittle materials. However, these researchers did not propose or confirm a model or suitable explanation for the origin of this ductile regime. Bifano et al. also proposed a model defining the ductile to brittle transition of a brittle material based on the material's brittle fracture properties and characteristics. A critical depth of cut model was introduced based on the Griffith fracture propagation criteria. The critical depth of cut ($d_e$) formula is as follows:

\[ d_e = \frac{(E.R)}{H^2} \]  

(2.1)

where \( E \) is the elastic modulus, \( H \) is the hardness and \( R \) is the fracture energy.

The value of the fracture energy \( (R) \) can be evaluated using the relation:

\[ R \approx K_c^2 / H \]  

(2.2)

where \( K_c \) is the fracture toughness of the material. The above two equations can be combined to represent the critical depth \( (d_e) \) as a measure of the brittle transition depth of cut:

\[ d_e \sim \left( \frac{E}{H} \right) \cdot \left( \frac{K_c}{H} \right)^2 \]  

(2.3)
The researchers were successful in determining a correlation between the calculated critical depth of cut and the measured depth (grinding infeed rate). The constant of proportionality was estimated as to be 0.15 and this is now added into Equation (2.3) to generate a more accurate empirical equation:

\[ d_c \sim 0.15 \cdot (E / H) \cdot (K_c / H)^2 \] .......................... (2.4)

In general, the modulus is constant, but the measured values of \( K_c \) and \( H \) are based upon the atmospheric (tensile stress) and high pressure (compressive stress) phases respectively. In reality, the expression should use the (higher) hardness of the atmospheric phase, rather than the more ductile high pressure phase, to determine the brittle fracture parameters (this also makes the analysis consistent). You can appreciate this more fully if you realize that the likely value of the hardness of the atmospheric phase, of Si or SiC, is much higher than the measured hardness (as a result of the HPPT); this higher hardness then reduces the critical depth proportionally.

**Chip Formation**

A critical depth, \( d_c \) is experimentally determined before any ductile mode machining operation is carried out. Any depth beyond or exceeding the critical depth, which is also known as the Ductile to Brittle Transition (DBT) depth, will result in a brittle cut. Since the equipment used in the current research program (UMT Micro-Tribometer by CETR) is a load controlled (and not a depth controlled) machine, thrust force calculations were carried out for corresponding required depths of cuts. The Blake and Scattergood\(^{22}\) ductile regime machining model (as shown in Fig. 2.1) was used to
predict the required thrust force for a desired depth of cut. In this model it is assumed that
the undesirable fracture damage (which extends below the final cut surface) will originate
at the critical chip thickness ($t_c$), and will propagate to a depth, $y_c$. This assumption is
consistent with the energy balance theory between the strain energy and surface energy.

In general, the ductile-to-brittle transition (DBT) is a function of variables such as tool
gallery (rake and clearance angle, nose and cutting edge radius), feed rate, cutting
speed and depth of cut.
High Pressure Phase Transformation (HPPT)

Although SiC is naturally very brittle, micromachining this material is possible if sufficient compressive stress is generated to cause a ductile mode behavior, in which the material is removed by plastic deformation instead of brittle fracture. This micro-scale phenomenon is also related to the High Pressure Phase Transformation (HPPT) or direct amorphization of the material. \(^2^3\) *Figure 2.2* shows a graphical representation of the highly stressed (hydrostatic and shear) zone that results in ductile regime machining.

Patten and Gao\(^2^4\) state that ceramics in general undergo a phase transformation to an amorphous phase after a machining process. This back transformation is a result of the HPPT that occurs when the high pressure (compression or hydrostatic pressure) and shear caused by the tool is suddenly released after a machining process. The HPPT is usually characterized by the amorphous remnant that is present on the workpiece surface and within the chip. This amorphous remnant is a result of this back transformation from the high pressure phase to the atmospheric pressure phase due rapid release of pressure in the wake of the tool. There are two types of material removal mechanisms: ductile mechanism and the brittle mechanism.\(^2^1\) For experiments conducted in this research, ductile mode machining was carried out making use of the HPPT phenomenon. In the ductile mechanism, plastic flow of material in the form of severely sheared machining chips occur, while material removal is achieved by the intersection and propagation of cracks in the brittle fracture mechanism. Due to the presence of these two competing mechanisms, it is important to know the DBT depths (or critical size) associated with these materials before attempting a machining operation.
Figure 2.2 shows a ductile cutting model indicating the zone of high compressive and shear stress, i.e. the zone of plastically deformed material in brittle materials. A -45° rake angle tool is demonstrated in the above schematic, which is very helpful to creating the conditions, pressure and shear, necessary to generate the high pressure ductile phases of semiconductors and ceramics.

Surface Characteristics/Finish

The surface characteristics and surface finish (roughness) are of major concern for all of the work in this thesis. The main goal for all SPDT operations on SiC and quartz carried out in this research is to improve the surface roughness. Surface characteristics are extremely important in this research as all materials require a mirror finish in order to have good optical qualities for high power laser devices (optical mirrors and windows). It is essential to understand the surface behavior, properties, pattern, characteristics and topography before carrying out any machining. In general, a surface roughness
measurement is done to understand the surface topography. For the CVD-SiC and quartz samples, the surface roughness was measured using a Mitutoyo surface profilometer before carrying out any machining operations. Four main surface roughness parameters were recorded for analysis purposes. These parameters include Ra (Roughness Average), Rq (Root Mean Square (RMS) Roughness), Rz (Average Peak-to-Valley of the Profile) and Rt (Maximum Height of the Profile).

The initial goal when trying to improve the surface roughness of a ceramic is to reduce the peak-to-valley (Rz) values of the workpiece. The effect of Rz values can be easily visualized in Figure 2.3, 2.4 and 2.5 where the peak-to-valley of a small section of the workpiece is schematically modeled. If the average of the peaks is fairly high (Rz ~ 8.5µm for the 6” CVD coated SiC explained in Chapter 4), then several machining passes have to be carried out in order to smooth the surface (where the maximum depth of cut is determined by the DBT depth ~ 550nm).
Figure 2.3: A model (not to scale) of the tool positioned before cutting through the peaks of the SiC surface.

Figure 2.4: Tool positioned after the first pass and at the beginning of the second pass before cutting through the peaks of the SiC surface.
Figures 2.3, 2.4 and 2.5 compare the surface topography (peaks and valleys on surface) before and after machining. In general, the surface is seen to be improving as long as the material is removed in the ductile regime (plastic deformation). The initial/roughing pass concentrates more on removing the highest peaks on the surface. The depth of cut of a smoother (flatter) surface as seen in Figure 2.5 reduces due to the greater contact area between the tool and workpiece surface, i.e., the actual depth of cut (which is established by prescribing the normal or thrust force in this experimental work), varies with the actual area of contact between the tool and workpiece. As the surface becomes smoother with each subsequent pass, the real area of contact increases, and with a fixed or constant normal/thrust force, the actual achieved depth of cut decreases as shown in the later part of this thesis.

There are several factors that could affect the surface quality of the workpiece while machining. These factors include tool geometry, tool wear, external vibration (from tool or spindle), cutting speed, feed, depth of cut and friction forces. Fritz Locke et
al., in Jahanmir’s book about machining of ceramics\textsuperscript{25}, describes the correlation between the machining parameters and the resultant surface finish. It is stated that the surface quality of the work piece tends to worsen at higher feeds and this finding is consistent with the results obtained from this research. The tool nose radius plays an important role in the surface finish of the workpiece. In general, a larger tool nose radius and a smaller feed yields in a better surface. This relationship is given by the equation:

$$H_{\text{max}} = \frac{f^2}{8R}, \text{ for } f \ll R \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldOTS
It is important to understand that even minor tool wear can result in a poorly machined surface as this wear is replicated onto the workpiece surface each and every revolution/feed. In order to be able to plastically deform brittle materials\textsuperscript{27}, an extremely sharp cutting edge radius of the single crystal diamond tools are used. Single crystal diamond tools work reasonably well when machining semiconductors as demonstrated by Jasinevicius et al.\textsuperscript{28} in their attempt in cut single crystal silicon. Usually, a worn or blunt tool increases the tensile stresses, which lead to brittle fracture (due to rubbing on the flank face). A blunt or worn tool also reduces the compressive stress below that needed to insure the HPPT necessary to achieve ductile regime machining.

In SPDT three types of wear occur: rake-face wear (rake wear), clearance-face wear (flank wear) and tool cutting edge radius wear (rounding/flattening of tool tip). These two most critical types of wear, rake and clearance wear were proposed by Hurt and Decker in order to understand the role of wear in surface degradation.\textsuperscript{29} High compressive stresses exist on the rake face of the tool and are at the maximum at the cutting edge.\textsuperscript{30} It is observed that any wear on the clearance/flank face can potentially lead to increased surface roughness. This is consistent with the wear pattern from the SPDT experiments done in this research where the measured flank wear is always greater than the rake wear where the maximum contact area is between the flank face of the tool and the machined surface of the workpiece. In order to improve the surface of the workpiece at every pass, the cutting edge is resharpened by lapping whenever tool wear is observed. It is essential to control and minimize the wear of the diamond tools in order to improve the performance and quality of micromachining in terms of the surface finish.
and the cost to replace or repair the worn tool. The schematic shown in Figure 2.6 helps to explain the tool wear phenomenon in a typical cutting process.

Figure 2.6: Schematic model showing the rake and flank wear of the tool

The schematic above demonstrates the physics of chip rubbing that causes the rake face wear and contact with the machined surface causes the flank/clearance wear. This is consistent with the wear pattern from the SPDT experiments done in this research where the measured flank wear is always greater than the rake wear as the contact area between the tool and the machined area is significantly larger than the contact area between the tool and the chip.

Cutting Edge Radius and Geometry of Tool

The geometry of the tool also plays an important role in machined surface quality, cutting forces, pressure and stresses, ductile to brittle transition, and depth of cut. The two main considerations evaluated when deciding on the tool geometry in general are the rake angle and cutting edge radius. According to the research done by Blackley and Scattergood\textsuperscript{31}, the critical depth of cut for germanium increased with a more negative
rake angle ($0^\circ$, $-10^\circ$ and $-30^\circ$ rake angles were experimentally evaluated). The results of this research was further complimented by the research work of Shibata et al.\textsuperscript{32} where diamond turning of single crystal Si was attempted with both $-20^\circ$ and $-40^\circ$ rake angle tools. The results from this research suggested that the $-40^\circ$ rake tool produced a ductile cut at a 100 nm depth of cut. Figure 2.7 above can be used as a reference as it demonstrates the cross-sectional view the tool geometry and chip formation.

Yan et al. concluded in their research work that tool wear can be classified into two types: micro-chippings and gradual wear. The results suggest that gradual tool wear is caused by ductile mode machining and micro-chippings of the tool is caused by brittle mode machining. The tool is believed to fail in the ductile mode cutting when the flank wear land becomes excessive or rough due to the micro-grooves and step structures. The tool wear obtained from both modes of machining significantly influences the surface finish (surface roughness), cutting forces and chip formation.\textsuperscript{33}

Patten et al.\textsuperscript{23} varied the tool rake angle by adjusting the center line of the tool’s cutting edge. The relative amount of ductile cutting was found to increase and the brittle fracture decrease as the rake angle decreased from $0^\circ$ to $-45^\circ$. A more brittle behavior was observed as the depth of cut increased from 100nm to 500nm.

Finally, the cutting edge radius is also known to have an impact on the DBT of the material. This was reported by Fang et al.\textsuperscript{34} where the cutting edge radius is considered sharp as long as the depth of cut is larger than the edge radius. If the depth of cut is less than the cutting edge radius then an effective rake is created, Patten (2006). This research concluded that an excessive rake can create/generate higher forces, but may lead to enhanced deformation.
Machining Forces

Two main forces generated while machining ceramics are cutting force, $F_c$ and thrust force, $F_t$. The orthogonal cutting model generated by Blake and Scattergood is used to help visualize these forces.

Figure 2.7: Schematic of orthogonal cutting model showing the direction of forces.

The research done by Blake and Scattergood helps to establish a relationship between machining forces and understanding of the frictional force behavior while machining. This behavior is represented as:

$$F_t = \mu x F_n$$  \hspace{1cm} (2.1)

where the machining cutting force ($F_c$) is represented by the frictional force ($F_t$) and the thrust force ($F_t$) is represented by the normal force ($F_n$). Generally the coefficient of friction is less than 1, however it is possible to obtain an apparent coefficient ($\mu_a$) which is greater than 1 during machining. The apparent coefficient occurs when the cutting force is larger than the thrust force, generally at larger depths of cuts.
Patten and Gao state that higher cutting forces are a sign of ductile regime machining, as ductile mode machining takes more energy (and thus higher forces) to remove material by plastic deformation on a per unit or volume basis (or at the same depth of cut).²³ The energy required for brittle fracture is directly proportional to the crack surface area whereas the energy required for plastic deformation is directly proportional to the volume of the material removed. At larger depths of cut \( (d) \), the volume term \( (\sim d^3) \), and thus the energy required for plastic deformation, is greater than the surface area term \( (\sim d^2) \) and brittle fracture is more likely to occur, when the depth of cut exceeds the critical depth of cut. Conversely, at small depths of cut, when the depth of cut is less than the critical depth of cut, plastic deformation occurs more readily than brittle fracture.
CHAPTER 3

DUCTILE TO BRITTLE TRANSITION (DBT) OF A SINGLE-CRYSTAL 4H-SiC WAFER DETERMINED BY PERFORMING NANOMETRIC MACHINING

Introduction

Silicon carbide, like other brittle materials, is known for its poor machinability. However, ductile-regime machining is possible under certain conditions. This can be achieved if machining occurs at depths less than the critical depth of cut. Beyond this value, a Ductile-to-Brittle Transition (DBT) occurs and the material behaves in a brittle-fracture manner. The purpose of this research is to determine the DBT for a single-crystal 4H-SiC wafer by performing Nanometric cutting (Nanocuts) experiments. The depth of cut is adjusted over a range of 100nm to 1000nm in order to cover the entire ductile to brittle-regime and the corresponding material removal behavior (a 50nm cut was carried out but not reported as there were no other cuts at this depth to compare with). The Nanocuts were carried out using the Nanocut II, a second generation prototype experimental machining instrument. The Nanocuts were imaged and measured using an Atomic Force Microscope (AFM) and the height profile from the scanned images were used to determine the DBT. In this project, nanometric cutting experiments were performed to determine the DBT depth for a single crystal 4H-SiC (from Cree Inc.). A polished single crystal wafer was used in this experiment program, which provides for an excellent reference surface for determining the DBT and to establish the corresponding critical depth. These wafers are also of high purity with few defects. 36
Experimental Method

The Nanocut II (a second-generation prototype) was used to make the nanometer level cuts. The Nanocut II was designed to perform nanometer depth of cuts based on the commanded depth by the operator as executed by the control program. The main components of this equipment are the frame, PZT tube (provides x, y and z displacement), capacitance gage (displacement feedback), force sensors, sample holder, tool holder, and hysteretic positioners. The PZT tube is used to position the sample relative to the tool and to establish the depth of cut. The Z (depth of cut) position is determined via the capacitance gage, and the two orthogonal placed force sensors measure the cutting and thrust forces. There are four dual axis flexures used in the device to decouple the cutting and thrust forces and to support the tool stage positioning wedge actuators. Figure 3.1 shows a top view of the Nanocut II.

Figure 3.1: A top view of the Nanocut II used to perform the Nanocuts.
The series of cuts were performed on rectangular pieces, which were cleaved from a 3" (76.2mm) 4H-SiC wafer. The wafer was cleaved relative to its primary flat which is the \{10\bar{1}0\} plane with the flat face parallel to the \(<11\bar{2}0>\) direction. The rectangular sample size obtained from the wafer was about 12mm by 6mm. Identifying the crystal orientation is important to determine the preferred cutting direction. The SiC sample was mounted on the sample holder with an adhesive. To minimize any external vibration, noise and distortion, the Nanocut II was placed on an air vibration isolation table. A single-point diamond tool with a rake angle of -45 degrees and a clearance angle of 5 degrees was used to perform the cuts. For the results reported here, the diamond tool was oriented such that the Nanocuts were performed parallel to the primary flat (in the \(<10\bar{1}0>\) direction). Figure 3.2 below shows a schematic of the 4H SiC wafer obtained from Cree Inc.

Figure 3.2: Schematic of the 4H single crystal SiC wafer.

Two sets of experiments were carried out on different rectangular samples, taken from the same wafer and positioned at the same crystallographic orientation. The first set
contained cuts with commanded depths of 100nm and 500nm. The second set contained
cuts with commanded depth of 1000nm. The expected DBT was in the range of 100nm to
1000nm, and these experimental cut depths covered this entire region. Three cuts were
done for each commanded depth to obtain comparable data. The second set of deeper cuts
(1000nm and greater if necessary) would only be carried out if there were no brittle
characteristics in the first set of cuts (100nm and 500nm). The cuts were done in an array
pattern to help with imaging. Since the Nanocuts in this experiment are fairly small
(approximately 20µm in width and 120µm in length), identifying them in the microscope
can be challenging. *Figure 3.3* shows a schematic representing the pattern created with
the Nanocuts on the rectangular SiC samples; the 100nm and 500nm cuts were performed
on one sample and the 1000nm cuts were performed on a second sample. *Figure 3.4*
represents an actual image of three of the cuts (two at 100nm and one at 500nm) obtained
from an optical microscope at 40X magnification. The other 100nm and 500nm cuts are
outside the field of view at the magnification shown.

*Figure 3.4: Nanocut matrix of cuts (100nm, 500nm and 1000nm).*

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+ 100nm  500nm  1000nm
12mm x 6mm rectangular pieces were cleaved from the 3"wafer
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The cuts are made from right to left. The cuts are wider than they are long due to the geometry of the tool (10mm nose radius) and the maximum stroke of the PZT in the cutting direction (20-30 µm) establishes the length of cut.

Results and Discussion

*Figure 3.5* shows the thrust force and the cutting force for each corresponding depth of cut. The cutting forces are measured to be more than the thrust forces for all of the three reported depths of cuts. Both the cutting forces and the thrust forces increase as the depth of cut increases. The 50nm depth of cut is not reported in *Figure 3.5* as only one cut at that depth was successful and it could not be identified with the AFM. Each of the other reported depths had three successful/ repeatable cuts, for which the force data were averaged.
A typical height profile obtained from the ductile regime is generally “V” or “U” shaped representing an imprint of the diamond tool cutting edge. Figure 3.6 shows a typical height profile, obtained from an AFM, of a cut performed in the ductile region. The depth of this cut was measured to be 816nm and the programmed depth of cut was 1000nm. The actual depth of cut was measured to be less than the commanded or programmed depth of cut; this is a characteristic of the device and process and is consistent with previous results. The “V” shape seen in the height profile of Figure 3.6 is a characteristic of a ductile cut.
Figure 3.7: An AFM scanned section of a cut along with its height profile.

The programmed or commanded depth of this cut for the figure above was 1000nm, at the cross-section the measured depth is 816nm. *Figure 3.7* shows a height profile of a cut where there is an indication of a DBT. This is evident by the poorly defined ductile “V” shape in the height profile. The depth of cut was measured to be 836nm using an AFM and the programmed depth of cut is 1000nm.

*Figure 3.8* confirms that the material removal is in the brittle-regime and there is no clear definition in the height profile of this cut. The measured maximum depth of cut is 952nm.
and the programmed depth of cut of 1000nm. It can be seen in Figure 3.8 that there could be more than one peak in the brittle region as the fracture process results in uncontrolled material removal.

**Figure 3.9:** An AFM scanned section of a cut where the brittle characteristic of the material is observed.

The edges along the cuts can also be evaluated to determine the ductile or brittle cutting conditions. The ductile cut has a much more defined and straight edge as seen in Figure 3.7 compared to the jagged edges seen in a brittle cut shown in Figures 3.8 & 3.9. A clearer picture of the uneven edges along a brittle cut is shown in Figure 3.10. The jagged edges and chipped material along the left edge of the cut are caused due to crack propagation, and uncontrolled material removal in the brittle regime. This brittle material is clearly seen in Figure 3.11, where the cross section of a brittle cut is analyzed using the Wyko RST interferometric microscope. The actual depth varies from zero at the ends (top and bottom of the cuts, outside the field of view) to a maximum in the middle. The cutting direction for the cut below is from right to left as indicated.
As seen in Figure 3.12, the brittle characteristics are clearly shown by the height profile graph from an AFM image. The programmed depth for this particular cut is 1000nm (1µm) but the maximum depth measured in this cut is 1.17µm. This characteristic (programmed depth < actual depth) was also observed by Hung and Fu in their experiment to study the ductile-regime machining of silicon, where the micro-cracks could extend deeper than the depth of cut below the machined surface.39
Purely brittle characteristics are observed where the maximum measured depth of cut (1170nm) is more than the commanded/programmed depth of cut (1000nm). In the case of a cut under extreme brittle conditions of SiC, there is no direct control of resultant material removal; i.e. the command depth does not provide a one-to-one correspondence to the actual depth of cut. It is this stage (beyond the DBT) where crack initiation, propagation and growth occur. These events can lead to catastrophic brittle failure of the material.

**Conclusion**

Although SiC is well known for its brittle characteristics, it is still possible to plastically deform this material at small scales (nominally less than a micrometer) to achieve ductile machining.\textsuperscript{23,40,41} In order to machine a semiconductor or ceramic in the ductile-regime, it is crucial to know its DBT depth. The DBT depth was found to be between 820nm-830nm as measured on a single crystal 4H-SiC wafer, cut along the
The DBT is an important parameter as it defines the border between where the material fails catastrophically by fracture from that at which it yields by plastic deformation. The cutting forces and thrust forces increase as the depth of cut increases as expected. The force data did not specifically contribute to the determination of the DBT (perhaps in this case, with the −45 tool, the brittle fracture occurred in the wake of the tool, i.e., in the trailing tensile stress field, and out of the force measurement loop). The fracture characteristics observed beyond the depth of 830nm are a result of brittle machining conditions. This fracture then leads to pitting and micro-cracks resulting in significant and uncontrolled subsurface damage.
CHAPTER 4

IMPROVING THE SURFACE ROUGHNESS OF A CVD COATED SiC DISK BY PERFORMING DUCTILE REGIME SINGLE POINT DIAMOND TURNING

Introduction

Silicon carbide (SiC) is one of the advanced engineered ceramics materials designed to operate in extreme environments. One of the main reasons for the choice of this material is due to its excellent electrical, mechanical and optical properties that benefit the semiconductor, MEMS and optoelectronic industry respectively. Manufacture of this material is extremely challenging due to its high hardness, brittle characteristics and poor machinability. Severe fracture can result when trying to machine SiC due to its low fracture toughness. However, from past experience it has been proven that ductile regime machining of silicon carbide is possible. The main goal of the subject research is to improve the surface quality of a chemically vapor deposited (CVD) polycrystalline SiC material to be used in an optics device such as a mirror. Besides improving the surface roughness of the material by removing material in the ductile regime, the research also emphasized increasing the material removal rate (MRR) and minimizing the diamond tool wear. The surface quality was improved using a Single Point Diamond Turning (SPDT) machining operation from 1158nm to 88nm (Ra) and from 8.49µm to 0.53µm (Rz; peak-to-valley). Several parameters such as feed rate, spindle speed and depth of cut were changed to determine the optimum machining conditions to achieve the desired surface roughness, MRR and acceptable tool wear. Processes and procedures to minimize tool wear will be discussed as it is one of the major factors of this machining operation.
Experimental Method

Before the actual machining was carried out, an experimental test matrix was designed based on previous experiments and some preliminary calculations. Since the equipment used was a load controlled (and not a depth controlled) machine, thrust force calculations were carried out for corresponding required depths of cuts. The Blake and Scattergood ductile regime machining model was used to predict the required thrust force for a desired depth of cut. Scratching tests results from the master’s thesis of Biswarup Bhattacharya were also used as a guideline as these scratches were done to determine the Ductile to Brittle Transition of a similar material.

The equipment used to carry out all of the machining experiments was the Micro-Tribometer (UMT) from the Center for Tribology Research Inc. (CETR). This equipment was developed to perform comprehensive micro-mechanical tests of coatings and materials at the micro scale. Figure 4.1 below shows the equipment setup for the 6” CVD coated SiC disk (the similar setup was used for the polished 2” SiC disk). A single crystal diamond tool with a 3mm nose radius, -45 degree rake angle and 5 degree clearance angle was used for the cutting tests. The MASTERPOLISH 2 Final Polishing Suspension (contains alumina and colloidal silica with a pH ~9) from Buehler, Inc. was used as the cutting fluid for all experiments involving diamond turning SiC.
Figure 4.1: Machining setup for the 6" CVD coated SiC disk.
SPDT of a polished 2” CVD coated SiC disk: Preparatory Machining Tests

Results from previous experiments (Biswarup Bhattacharya Masters Thesis, 2005) which involved scratching and SPDT of CVD SiC, were used as guidelines to establish the experimental plan for this initial set of machining tests. The test matrix was designed for a 2” diameter polished CVD coated SiC disk and a series of cutting tests were conducted on this workpiece. The reason these test runs were conducted was to observe the equipment stability, tool condition after machining, thrust force and depth of cut correlation and surface finish of the workpiece after machining. The as received surface for the 2” test SiC disk was polished (Ra~35nm), the results obtained from the test runs, such as the DBT, could be determined and this would help in establishing the parameters for the final machining of the 6” CVD coated SiC disk.

Table 4.1: Test matrix for the 2” polished CVD coated SiC.

<table>
<thead>
<tr>
<th>Depth of cut</th>
<th>Load Range (mN)</th>
<th>Spindle Speed (rpm)</th>
<th>Feed rate (μm/rev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 nm</td>
<td>20.16</td>
<td>60</td>
<td>5 to 1</td>
</tr>
<tr>
<td>500 nm</td>
<td>80.64</td>
<td>60</td>
<td>5 to 1</td>
</tr>
<tr>
<td>1 μm</td>
<td>321.77</td>
<td>60</td>
<td>5 to 1 &amp; 50 to 10</td>
</tr>
<tr>
<td>2 μm</td>
<td>1287.07</td>
<td>60</td>
<td>5 to 1 &amp; 50 to 10</td>
</tr>
</tbody>
</table>

Table 4.1 shows the list of input parameters that was planned for the 2” polished test disk. The load range is the thrust force applied for a desired depth of cut (based upon the master’s thesis of Biswarup Bhattacharya). The spindle rpm was limited to a maximum of 60rpm to avoid any external vibration (from the tool and spindle) that could degrade the surface of the SiC disk. The machining cuts were carried out on different sections of the
2” disk (as shown in Figure 4.2), and for each section the feed was varied from 5µm/rev to 1µm/rev or 50µm/rev to 10µm/rev depending on the cut. Since one of the project goals was to increase the material removal rate, higher feeds were utilized for the 1µm and 2µm depths of cuts. As the cutting speed is a function of radius \((Cutting\ Speed, V = (2\pi\ r) \times \omega)\), the minimum speed is at the inner section whereas the maximum speed is at the outer most radius of that particular section: the cutting occurred from inside (ID) to outside (OD). The cutting speed changes linearly along the entire section.

Figure 4.2: Figure of a model of the 2” diameter polished SiC disk.

Various depths of cuts are shown in the figure above. The centre and outer most section are kept unmachined to be used as a reference or base point to measure the depth of the machined sections. The outer 1µm and 2µm depths of cut were carried out with the higher feed rates (10 – 50 µm/rev).
Preliminary machining of a 6" CVD coated SiC

One of the first steps in establishing the machining parameters for the 6" disk was to measure the as received surface roughness (Ra and Rz (peak-to-valley)) using a surface profilometer. Since the target Ra value for the final machined part was below 100nm, it is important to realize that this cannot be achieved in a single pass (as received Ra ~ 1.158 µm and Rz ~ 8.486 µm) in order to avoid brittle fracture. This is due to the limitation of the ductile-to-brittle transition depth of the material that cannot be exceeded at anytime, in order to maintain ductile regime machining and avoid brittle fracture that could degrade the surface. The initial goal was to reduce the peak-to-valley (Rz) values of the workpiece. The effect of Rz values can be easily visualized in Figure 4.3 where the peak-to-valley of a small section of the workpiece is modeled. If the averages of peaks are about 8.5µm, then several machining passes have to be carried out in order to smooth the surface (where the maximum depth is determined by the DBT depth ~ 550nm). In this particular experiment, the maximum programmed depth of cut at any particular machining pass was not more than. The actual depth of cut is always expected to be less than the programmed depth of cut (in most cases for SiC the actual depth of cut is about half of the programmed depth of cut) due to the elastic properties of the material and tool system. At this depth of cut, the tool would hold up well (the tool did not chip or break), and the cut would still be in the ductile regime and the cuts will not cause additional valleys or cracks to be generated, in addition to what was already in the as received disk.
The peaks in this figure are greatly exaggerated (model not drawn to scale) in order to help in visualizing the process. At this point, a 10mm wide test region was machined (on a test CVD coated SiC disk) with various machining conditions to help in predicting results and expose any potential problems for the final machining experiment.

**Table 4.2: Machining parameters for the 1mm wide test region.**

<table>
<thead>
<tr>
<th>Pass #</th>
<th>Programmed Depth</th>
<th>Feed</th>
<th>Spindle Speed</th>
<th>Fz (Thrust Force)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2µm</td>
<td>30µm/rev</td>
<td>6rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>2</td>
<td>2µm</td>
<td>30µm/rev</td>
<td>6rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>3</td>
<td>2µm</td>
<td>30µm/rev</td>
<td>6rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>4</td>
<td>2µm</td>
<td>5µm/rev</td>
<td>30rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>5</td>
<td>2µm</td>
<td>5µm/rev</td>
<td>12rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>6</td>
<td>2µm</td>
<td>5µm/rev</td>
<td>12rpm</td>
<td>1287.07mN</td>
</tr>
</tbody>
</table>

The Ra and Rz values for the as received disk were 1.231µm and 8.92µm (the Ra and Rz values have slight variations from the previously mentioned 1.158µm and 8.468µm as this test was carried out on the reverse side of the disk). From Table 4.2 it can be seen that the thrust force (Fz) was the same for all passes due to the desired 2µm
depth of cut that was intended for all passes, i.e. the effect of the surface roughness (real contact area), was not included in the determination of the required thrust force needed to achieve the desired depth of cut. The spindle rpm was kept slow (6rpm) for the first three passes to achieve the higher feed rates. The spindle rpm was then increased in pass 4 but this resulted in a slight vibration of the tool. The spindle speed was then decreased in pass 5 and 6 respectively to reduce the tool vibration. This was the first time single point diamond turning was attempted on such a rough CVD SiC surface. The data obtained from this test region would be used for determining machining conditions for the actual experiments as these surfaces (preliminary and final machining tests) are comparable in roughness values. The tool and surface roughness (Table 4.5) were measured after every pass and analyzed to determine the parameters for the following pass.

**Final machining of a 6” CVD coated SiC**

Once reliable data was obtained from the preliminary tests, the machining parameters for the final machining on the 6” SiC disk were determined. *Table 4.3* below shows the planned machining parameters for the 6” CVD coated SiC.
Table 4.3: Machining parameters for the 6" CVD coated SiC.

<table>
<thead>
<tr>
<th>Pass #</th>
<th>Programmed Depth</th>
<th>Feed</th>
<th>Spindle Speed</th>
<th>Fz (Thrust Force)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2µm</td>
<td>30µm/rev</td>
<td>6rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>2</td>
<td>2µm</td>
<td>30µm/rev</td>
<td>6rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>3</td>
<td>2µm</td>
<td>30µm/rev</td>
<td>6rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>4</td>
<td>2µm</td>
<td>30µm/rev</td>
<td>6rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>5</td>
<td>2µm</td>
<td>30µm/rev</td>
<td>6rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>6</td>
<td>2µm</td>
<td>5µm/rev</td>
<td>12rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>7</td>
<td>2µm</td>
<td>5µm/rev</td>
<td>12rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>8</td>
<td>2µm</td>
<td>5µm/rev</td>
<td>12rpm</td>
<td>1287.07mN</td>
</tr>
<tr>
<td>9</td>
<td>500nm</td>
<td>5µm/rev</td>
<td>12rpm</td>
<td>81.32mN</td>
</tr>
<tr>
<td>10</td>
<td>250nm</td>
<td>5µm/rev</td>
<td>12rpm</td>
<td>20.99mN</td>
</tr>
<tr>
<td>11</td>
<td>1µm</td>
<td>1µm/rev</td>
<td>60rpm</td>
<td>320.79mN</td>
</tr>
<tr>
<td>12</td>
<td>500nm</td>
<td>1µm/rev</td>
<td>60rpm</td>
<td>81.32mN</td>
</tr>
<tr>
<td>13</td>
<td>500nm</td>
<td>1µm/rev</td>
<td>60rpm</td>
<td>81.32mN</td>
</tr>
<tr>
<td>14</td>
<td>500nm</td>
<td>1µm/rev</td>
<td>60rpm</td>
<td>81.32mN</td>
</tr>
<tr>
<td>15</td>
<td>500nm</td>
<td>1µm/rev</td>
<td>60rpm</td>
<td>81.32mN</td>
</tr>
<tr>
<td>16</td>
<td>250nm</td>
<td>1µm/rev</td>
<td>60rpm</td>
<td>20.99mN</td>
</tr>
</tbody>
</table>

A new/relapped diamond tool was used at the start of every pass. The workpiece surface and tools were measured and imaged after every pass to determine the tool condition and to measure the tool wear. For every feed rate used, the spindle rpm was at its slowest possible speed to minimize any tool vibration. Once again the thrust force (Fz) values are an input parameter to obtain the desired depth of cut.

Results and Discussion

SPDT of a polished 2” CVD coated SiC disk: Preparatory Machining Tests

All of the machining cuts done on the 2” polished surface were in the ductile regime, i.e. there was no evidence of any brittle fracture associated with these machining
The cutting forces, $F_x$, increases as the feed rate and depth of cut increased. From Figure 2.1, it is evident that the total cross-section area of the chip is a function of the depth of cut and the feed, $f$. The chip cross-sectional area increases as the depth of cut or/and the feed is increased. However, the depth of cut has a larger influence in the change of cutting forces than the feed. Table 4.4 below shows the surface roughness obtained for different depths of cuts and feed. The 250nm depth of cut with the lowest possible feed (1µm/rev) yields the best surface finish as expected.
Table 4.4: Ra for various depths of cuts and feeds carried out on the 2” polished CVD coated SiC.

<table>
<thead>
<tr>
<th>Depth of Cut</th>
<th>Feed(um/rev)</th>
<th>Surface Roughness (Ra)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250nm</td>
<td>1</td>
<td>40nm</td>
</tr>
<tr>
<td>250nm</td>
<td>2</td>
<td>40nm</td>
</tr>
<tr>
<td>250nm</td>
<td>3</td>
<td>41nm</td>
</tr>
<tr>
<td>250nm</td>
<td>4</td>
<td>42nm</td>
</tr>
<tr>
<td>250nm</td>
<td>5</td>
<td>42nm</td>
</tr>
<tr>
<td>500nm</td>
<td>1</td>
<td>46nm</td>
</tr>
<tr>
<td>500nm</td>
<td>2</td>
<td>49nm</td>
</tr>
<tr>
<td>500nm</td>
<td>3</td>
<td>50nm</td>
</tr>
<tr>
<td>500nm</td>
<td>4</td>
<td>55nm</td>
</tr>
<tr>
<td>500nm</td>
<td>5</td>
<td>58nm</td>
</tr>
<tr>
<td>1μm</td>
<td>1</td>
<td>87nm</td>
</tr>
<tr>
<td>1μm</td>
<td>2</td>
<td>90nm</td>
</tr>
<tr>
<td>1μm</td>
<td>3</td>
<td>96nm</td>
</tr>
<tr>
<td>1μm</td>
<td>4</td>
<td>99nm</td>
</tr>
<tr>
<td>1μm</td>
<td>5</td>
<td>106nm</td>
</tr>
<tr>
<td>2μm</td>
<td>1</td>
<td>110nm</td>
</tr>
<tr>
<td>2μm</td>
<td>2</td>
<td>112nm</td>
</tr>
<tr>
<td>2μm</td>
<td>3</td>
<td>118nm</td>
</tr>
<tr>
<td>2μm</td>
<td>4</td>
<td>125nm</td>
</tr>
<tr>
<td>2μm</td>
<td>5</td>
<td>128nm</td>
</tr>
<tr>
<td>1μm</td>
<td>10</td>
<td>220nm</td>
</tr>
<tr>
<td>1μm</td>
<td>20</td>
<td>225nm</td>
</tr>
<tr>
<td>1μm</td>
<td>30</td>
<td>234nm</td>
</tr>
<tr>
<td>1μm</td>
<td>40</td>
<td>235nm</td>
</tr>
<tr>
<td>1μm</td>
<td>50</td>
<td>247nm</td>
</tr>
<tr>
<td>2μm</td>
<td>10</td>
<td>266nm</td>
</tr>
<tr>
<td>2μm</td>
<td>20</td>
<td>277nm</td>
</tr>
<tr>
<td>2μm</td>
<td>30</td>
<td>277nm</td>
</tr>
<tr>
<td>2μm</td>
<td>40</td>
<td>297nm</td>
</tr>
<tr>
<td>2μm</td>
<td>50</td>
<td>308nm</td>
</tr>
</tbody>
</table>

The data from *Table 4.4* is plotted in two separate charts. One of the charts (*Figure 4.5*) shows the effect of the depth of cut on the surface roughness of the workpiece and the other chart (*Figure 8*) shows the effect of feed rates on the surface roughness.
Figure 4.5: The effect of the depth of cut over the Ra for the 2” polished SiC disk.

The feed rates were varied from 1 µm/rev to 5 µm/rev for all depths of cuts which would compliment with the five data points plotted for each depth of cut.

Figure 4.6: The effect of the increment in feed rates over the Ra for the 2” polished SiC disk.
The feed rates were varied from 1 to 50 µm/rev for two depths of cuts (1µm, shown in yellow and 2µm, shown in red) respectively. These depths of cuts are represented by two different colors respectively on the chart. In this case, the feed rate has a larger impact on the surface roughness than the depth of cut, as the depth of cut was only varied by a factor of 2x, but the feed was varied by a factor of 50x. This is very evident from Figure 4.6 where the surface roughness is compared for two depths of cut with varying feed rates.

*Preliminary machining of a 6” CVD coated SiC*

The goal for the preliminary machining tests, on a sample 10mm region was not to make it a mirror finish but to predict tool wear and test the machining parameters proposed for the final machining experiment. A total of 6 passes were carried out and the results of these passes are discussed in this section.

<table>
<thead>
<tr>
<th>Pass #</th>
<th>Programmed Depth</th>
<th>Actual Depth</th>
<th>Feed</th>
<th>Spindle Speed</th>
<th>Ra</th>
<th>Rq(RMS)</th>
<th>Rz(Peak-to-Valley)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Received</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>1231nm</td>
<td>1351nm</td>
<td>8.92µm</td>
</tr>
<tr>
<td>1</td>
<td>2µm</td>
<td>1.90µm</td>
<td>30µm/rev</td>
<td>6rpm</td>
<td>471nm</td>
<td>587nm</td>
<td>2.13µm</td>
</tr>
<tr>
<td>2</td>
<td>2µm</td>
<td>1.40µm</td>
<td>30µm/rev</td>
<td>6rpm</td>
<td>422nm</td>
<td>535nm</td>
<td>1.86µm</td>
</tr>
<tr>
<td>3</td>
<td>2µm</td>
<td>1.30µm</td>
<td>30µm/rev</td>
<td>6rpm</td>
<td>292nm</td>
<td>364nm</td>
<td>1.18µm</td>
</tr>
<tr>
<td>4</td>
<td>2µm</td>
<td>1.04µm</td>
<td>5µm/rev</td>
<td>30rpm</td>
<td>232nm</td>
<td>279nm</td>
<td>706nm</td>
</tr>
<tr>
<td>5</td>
<td>2µm</td>
<td>973nm</td>
<td>5µm/rev</td>
<td>12rpm</td>
<td>211nm</td>
<td>268nm</td>
<td>744nm</td>
</tr>
<tr>
<td>6</td>
<td>2µm</td>
<td>943nm</td>
<td>5µm/rev</td>
<td>12rpm</td>
<td>185nm</td>
<td>228nm</td>
<td>822nm</td>
</tr>
</tbody>
</table>

Note that the surface roughness values for the as received disk were 1.231µm for the Ra and 8.92µm for the Rz. From *Table 4.5* and *Figure 4.7* it is evident that the surface roughness (Ra) and peak-to-valley (Rz) values reduced significantly (almost by half) just after the first pass. During the first pass the highest or largest peaks are removed and the actual depth of cut is also greater, which correlates to the fact that the Rz value decreased
by almost half. If the peaks are visualized as shown schematically in Figure 4.3, then it can be explained that lesser force is required to remove the upper section (more depth) of the triangles as lesser material is involved, i.e. the real area of contact is less at the higher roughness values. Since the actual depth of cuts in this set of experiments were all measured to be more than the DBT depth of the material (~550nm), there could be signs of some brittle mode machining but as long as the micro-cracks do not propagate beyond the \( y_c \) (surface damage depth) for the depth of cut (based on Figure 2.1; Blake and Scattergood model), the surface finish will continue to improve or remain unchanged.

The data plotted in Figure 4.7 could be an evidence of brittle mode machining whereby the surface roughness values remain unchanged in passes 4, 5 and 6 which could be a result of additional valleys on the work piece surface.

Figure 4.7: Ra and Rz values experiments carried out on a 10mm in diameter test region.

![Surface Finish vs. Pass Numbers](image)

Figure 4.7 shows that the surface roughness (Ra) is constantly improving after every pass, which is an indication that the cuts were being carried out in the ductile regime. The Ra value decreased significantly after pass 1 due to the highest peaks on the surface.
that had been removed. Figure 4.7 also confirms that the peak-to-valley value dropped most after the first pass. This was expected as less force is required to remove the top of the peaks (due to the smaller actual area of contact, i.e. more valleys and voids). The Rz value did not change much in passes 4, 5 and 6 (Rz < 1 µm). This is because the focus at this point was not so much to get a mirror finish but to experiment with the machining conditions (feed rate). It is possible that when the Rz value is below 1 µm and the depth of cut is still held at 2 µm, the machining operation could be making additional valleys resulting in an unchanged (or nearly so) peak-to-valley measurement. This is what that is believed to be happening in passes 4, 5 and 6. Figure 4.8 below shows the cutting force data obtained from all six passes.

Figure 4.8: Cutting forces for experiments (with its corresponding feeds in parenthesis) carried out on a 10mm in diameter test region.

![Cutting Forces vs. Pass Numbers](chart)

The chart suggests that the first three passes resulted in higher forces due to a higher feed rate (30 µm/rev). The remaining three passes (pass 4 through 6) the feed rate was reduced.
to 5µm/rev in order to further improve the surface finish (in general, a smaller feed will result in lower cutting forces and a better surface finish). The error bars represent the change in forces (std. dev.) attributed due to the unevenness, i.e. lack of flatness, of the sample. The overall outcome of the preliminary tests were successful whereby the surface (Ra) consistently improved after every pass and useful data was obtained to help carry on with the final machining.

**Final machining of a 6” CVD coated SiC**

Based on the results from the two previous (preparatory and preliminary) experiments, the final machining was carried out. The results for the final machining experiment are discussed in this section.

<table>
<thead>
<tr>
<th>As RECED</th>
<th>PROGRAMMED AC</th>
<th>ANUAL DEPTH</th>
<th>FED., (µm/REV)</th>
<th>SPINDLE SPEED</th>
<th>RPM</th>
<th>RAl</th>
<th>Ra, (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2µm</td>
<td>1.31µm</td>
<td>30</td>
<td>6rpm</td>
<td>489</td>
<td>635nm</td>
<td>8.49</td>
</tr>
<tr>
<td>2</td>
<td>2µm</td>
<td>1.20µm</td>
<td>30</td>
<td>6rpm</td>
<td>333</td>
<td>429nm</td>
<td>1.98</td>
</tr>
<tr>
<td>3</td>
<td>2µm</td>
<td>1.14µm</td>
<td>30</td>
<td>6rpm</td>
<td>393</td>
<td>500nm</td>
<td>2.43</td>
</tr>
<tr>
<td>4</td>
<td>2µm</td>
<td>1.06µm</td>
<td>30</td>
<td>6rpm</td>
<td>378</td>
<td>487nm</td>
<td>2.25</td>
</tr>
<tr>
<td>5</td>
<td>2µm</td>
<td>1.00µm</td>
<td>30</td>
<td>6rpm</td>
<td>393</td>
<td>497nm</td>
<td>2.49</td>
</tr>
<tr>
<td>6</td>
<td>2µm</td>
<td>844nm</td>
<td>5</td>
<td>12rpm</td>
<td>291</td>
<td>365nm</td>
<td>1.7</td>
</tr>
<tr>
<td>7</td>
<td>2µm</td>
<td>833nm</td>
<td>5</td>
<td>12rpm</td>
<td>276</td>
<td>351nm</td>
<td>1.63</td>
</tr>
<tr>
<td>8</td>
<td>2µm</td>
<td>611nm</td>
<td>5</td>
<td>12rpm</td>
<td>289</td>
<td>385nm</td>
<td>1.51</td>
</tr>
<tr>
<td>9</td>
<td>500nm</td>
<td>360nm</td>
<td>5</td>
<td>12rpm</td>
<td>275</td>
<td>345nm</td>
<td>1.67</td>
</tr>
<tr>
<td>10</td>
<td>250nm</td>
<td>80nm</td>
<td>5</td>
<td>12rpm</td>
<td>261</td>
<td>328nm</td>
<td>1.47</td>
</tr>
<tr>
<td>11</td>
<td>1µm</td>
<td>578nm</td>
<td>1</td>
<td>60rpm</td>
<td>178</td>
<td>219nm</td>
<td>0.8</td>
</tr>
<tr>
<td>12</td>
<td>500nm</td>
<td>211nm</td>
<td>1</td>
<td>60rpm</td>
<td>150</td>
<td>186nm</td>
<td>0.71</td>
</tr>
<tr>
<td>13</td>
<td>500nm</td>
<td>255nm</td>
<td>1</td>
<td>60rpm</td>
<td>114</td>
<td>140nm</td>
<td>0.69</td>
</tr>
<tr>
<td>14</td>
<td>500nm</td>
<td>220nm</td>
<td>1</td>
<td>60rpm</td>
<td>83</td>
<td>108nm</td>
<td>0.53</td>
</tr>
<tr>
<td>15</td>
<td>500nm</td>
<td>216nm</td>
<td>1</td>
<td>60rpm</td>
<td>86</td>
<td>106nm</td>
<td>0.52</td>
</tr>
<tr>
<td>16</td>
<td>250nm</td>
<td>163nm</td>
<td>1</td>
<td>60rpm</td>
<td>83</td>
<td>103nm</td>
<td>0.51</td>
</tr>
</tbody>
</table>
The overall results are consistent with the preliminary experiments done whereby the maximum improvement in surface finish was after the first pass, i.e. the roughing pass. All spindle speeds were chosen to be the slowest possible for the desired feed. The slowest speeds were chosen in order to eliminate any vibration from the spindle and tool that could make the surface finish worse. Once there is no significant improvement measured at one particular feed, the feed rate is then reduced. The depth of cut for a particular pass was chosen based on the remaining Rz value from the previous pass. The depth of cut was chosen so that it will not exceed the current Rz value and also it must be less than the DBT of the material (~550nm). The initial eight passes yielded in actual depths of cuts that are larger than the DBT depth of the material. This is a good indication of some brittle mode machining, however, from Figure 2.1, it is understood that any micro-cracks that do not extend beyond the surface damage depth (y_c) for that depth of cut will not make the surface roughness worse. To help understand the effects of certain parameters on the surface roughness of the workpiece several other charts are provided (Figures 4.9, 4.10 and 4.11).
Figure 4.9: Surface roughness values as a function of feed rates (µm/rev) for the final machining experiment.

![Surface Roughness (Ra) vs. Feed](image)

Figure 4.10: Surface roughness values as a function of the depth of cut the final machining experiment.

![Surface Roughness (Ra) vs. Depth of Cut](image)
The x-axis represents the programmed depth of cut with the correspond feed in parentheses. The various colors represent different depths of cuts whereby the depth decreases from left to right. After comparing Figure 4.9 and 4.10, it is evident that the feed rates have a larger effect on surface roughness values than the depth of cut. This is clearly observed in Figure 4.9 where the significant drops in Ra happen when the feed rate is reduced. This trend is not observed in Figure 4.10 indicating that the depth of cut does not play as big of a role as the feed rate in improving the surface roughness of the material. In Figure 4.10, the Ra increases for the first 500nm depth of cut (Pass 9) and also the first 250nm depth (Pass 10), because the starting surface roughness values were higher as the data is not displace sequentially by pass number as is done in Figure 4.9. In Figure 4.11, the pass numbers are plotted in an increasing order to show that the peak-to-valley value consistently decreases as more material was removed each time.

Figure 4.11: Rz values and their corresponding programmed depths of cuts for final machining.

The general trend for the Rz values after every pass is consistent with the preliminary tests. The first pass drops the Rz value significantly as lesser force is required to remove
the surface material at the top of the peaks (refer to Figure 4.3). The Rz value provides a
good guideline to determine the programmed depth of cut for a particular pass. The
programmed depth of cut will not exceed the existing Rz value or the DBT depth of the
material.

Figure 4.12: Cutting forces with their corresponding depth of cut and feed in parenthesis.

The deeper cuts (2µm) have higher forces compared to the 1µm 500nm, and
250nm depths of cut. The cutting forces gradually decrease from pass 1 to pass 8 as the
surface roughness improves and the feed rates were reduced. The first pass yields the
maximum cutting force as the surface is extremely rough and the peak-to-valley values
are high. This is also due to the actual depth that was greater than the programmed depth
and a larger chip cross-sectional area was formed. Since this is still an experimental
process carried out to develop machining parameters, there are several machining passes
that will not be necessary when performing the actual manufacturing operation. This will
be discussed in detail in the conclusion section. Besides obtaining measurements from the surface profilometer after every pass, the workpiece was also imaged under an optical microscope. This was done to look for surface damage and also to observe the improvement in surface quality (more reflectivity due to lower roughness).

Figure 4.13: Image of various passes taken under a microscope at 50x magnification.

The region between Pass 4 and 5 seen in Figure 4.13 was a result of tool chatter (the experiment was aborted as soon as tool vibration was detected). In order to be able to measure (surface roughness and depth of cut) and image the surface, a small strip is kept at the outer edge before beginning the next pass (as seen in Figure 4.13). Figure 4.13 shows an improvement of surface finish (reflectivity) after every pass. The other machining passes (Pass 7 through 16) were outside the filed of view of this image.
Once the surface has become fairly smooth (in this case after pass 3 or Ra < 400nm), the feedmarks will be visible and could be measured as shown in Figure 4.14. The programmed feed compares well to the actual (resultant feed) for all cases where a measurement is possible (where the surface was smooth enough to detect the feed marks).

Figure 4.15: Surface finish comparison of the as received workpiece (left) and the surface after pass 11 (right).
From *Figure 4.15* (taken at 1000x), it is obvious that the surface finish has been improved and the surface is much more reflective. The high peaks as seen in the as received workpiece surface are no longer visible after the final machining experiment.

The final study carried out in this work was to determine the amount of tool wear obtained after every machining pass. Even though a single crystal diamond tool was used for this experiment, significant tool wear was measured due to the extreme hardness and abrasiveness of silicon carbide.

*Figure 4.16*: The cutting force as a function of the wear length measured across the tool cutting edge radius.

![Graph showing cutting force vs. measured tool wear across cutting radius.](image)

A sample measurement of wear obtained from an image is shown in *Figure 4.18*. The corresponding pass numbers and depth of cuts are indicated in parentheses for Figure
4.16. The horizontal wear measured at the tool tip/cutting edge is a function of the depth of cut, feed and starting surface roughness of the workpiece. However, the depth of cut seems to play a dominant role in the measured wear across the cutting edge radius. The deeper the cut, the longer the horizontal measured wear. For pass #1, the wear measured across the cutting edge was the highest due to the extremely rough surface of the as received workpiece. The wear length across the tool cutting radius was measured by both an optical microscope and a scanning electron microscope (SEM). Although different microscopes were used, the values compare quite well resulting in a difference of less than 5%.

**Figure 4.17**: Measured rake and flank wear at the cutting edge.

The data presented in *Figure 4.17* are for various feed rates and their corresponding depths of cuts indicated in parentheses. The rake and flank wear is a function of both feed and depth of cut, but from *Figure 4.17* it is observed that the feed rate plays a bigger role in rake and flank wear compared to the depth of cut. The flank
and rake wear increase as the feed rate is reduced. From Figure 4.17 it is clear that the wear increases everytime the feed is dropped and then the wear gradually reduces (due to the improving surface roughness) until the feed is further reduced. This is because of the longer track length that is covered by the diamond tool at the lower feed rates, i.e. as the feed is reduced, for a given width of cut; the tool travels a correspondingly longer distance resulting in more tool wear. Another important observation is that the flank rate is significantly greater than the rake wear for all machining conditions conducted in this experiment.

Figure 4.18: An image of a flattened tool tip taken under an optical microscope at 200x.

The wear length across the cutting radius can be measured from Figure 4.18 as the contact area between the tool and workpiece is clearly visible on the tool images. The images are taken directly perpendicular to the rake face.
Figure 4.19: SEM images of the cutting edge of the diamond tool after machining (290x).
Figure 4.20: SEM images of the cutting edge of the diamond tool after machining (1140x).

Figure 4.19 was taken at 290x and Figure 4.20 was taken at 1140x. This tool was used in for Pass #1 (also known as the roughing pass) where the programmed depth of cut was 2\(\mu\)m with a 30\(\mu\)m/rev feed. The large measured wear on the tool is due to the initial rough surface of the disk.

Figure 4.21: SEM images of the cutting edge radius of the diamond tool after machining (167x).
Figure 4.22: SEM images of the cutting edge radius of the diamond tool after machining (1110x).

The tool showed in Figure 4.21 and 4.22 was used for Pass #16; 250nm depth of cut with a 1\(\mu\)m/rev feed. Comparing Figures 4.19 & 4.20 with 4.21 & 4.22, we see that the wear observed in Figures 4.21 and 4.22 are much lesser. This is due to a couple of reasons such as a lower depth of cut and a smoother surface to start off with.
Figure 4.19 is taken at 290x magnification in order to measure the entire horizontal wear across the cutting edge. Figure 4.20 is taken at 1140x which will give good image resolution to measure the flank and rake wear. For the rake and flank measurement, the cutting edge radius line is used as a reference point whereby the wear measured above the cutting edge radius is reported as rake wear and wear measured below the cutting edge radius is reported as the flank wear. Some of the features (particles) seen in the SEM images are silicon carbide chips that have stuck to the diamond surface of the tool.

Figure 4.23: Comparison of the 6” CVD-SiC before and after SPDT.

![Before and After Images](image)

Note that the machined disk is more reflective, indicating a better surface finish (lower Ra) than the as received disk. The rings in the machined disk are artifacts due to the various feed rates uses (i.e. multiple non overlapping passes).
Conclusion

The single point diamond turning experiments were successful in reducing the surface roughness of a CVD coated silicon carbide disk. The Ra was brought down by over one order of magnitude \((from \ 1158\text{nm} \ to \ 83\text{nm})\). The most important consideration when machining in the ductile regime is not to exceed the critical depth or the DBT depth of the material, in order to avoid brittle fracture, which leads to higher surface roughness. It is possible to machine nominally brittle materials by plastic deformation at small scales i.e. below the critical depth or the DBT (the DBT for this material was approximately 550nm). Since the goal of this research was to develop machining parameters appropriate for ductile mode machining of CVD SiC, there were several additional steps (machining passes) that had to be carried out in order to confirm or verify the processing parameters. For the actual manufacturing process, many steps (passes) can be eliminated to make the actual production process more cost and time efficient.

**Table 4.7: Recommended machining parameters commercial manufacturing process.**

<table>
<thead>
<tr>
<th>Pass #</th>
<th>Actual Depth of Cut</th>
<th>Feed (µm/rev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.3µm</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>1.2µm</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>845nm</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>255nm</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>210nm</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>160nm</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.7 shows the recommended machining parameters for various passes to improve the surface finish of a CVD coated SiC disk by single point diamond turning. A total of 6 passes have been suggested for the final manufacturing process to improve the surface roughness of silicon carbide. When an additional machining pass is found not to change/improve the surface roughness significantly, that pass is removed in the final recommendation as shown in Table 4.7. The best surface finish was obtained with the
lowest feed rate attempted (1 µm/rev) but initially a higher feed rate was used (30 µm/rev) to maximize the material removal rate and minimize tool wear. The trade off at lower feed rates is that the measured tool wear is much more than at the higher feeds as shown in the results (refer to Figure 4.17), but the resultant surface finish is improved (refer to Figure 4.9). The tool wear can be reduced by using a suitable cutting fluid to reduce frictional effects and also by reducing the feed rates once the surface becomes reasonably smooth as suggested in Table 4.7.
CHAPTER 5

DEVELOPING A HYBRID LASER-SPDT MACHINING PROCESS FOR SMOOTHING CERAMICS (CVD-SILICON CARBIDE)

Introduction

The purpose of this experiment is to develop a hybrid laser-SPDT (Single Point Diamond Turning) machining process for chemically vapor deposited (CVD) SiC. The three main goals of this experiment are: 1) to improve the final surface quality (in terms of surface roughness), 2) increase the material removal rate (MRR) and 3) minimize the tool wear. The idea of this project is to study the combination of both methods (laser ablation and SPDT) and identify which laser processing parameter (if any) best facilitates SPDT in order to make the precision manufacturing of ceramics more efficient. Both methods have been identified as successful material removal methods for SiC.

The POCO SuperSiC-2 was used for all experiments in this chapter. The as received SiC samples were laser ablated by Mound Laser & Photonics Center (MLPC) using a SuperRAPID picosecond pulsed laser. Removing material in SiC using a picosecond pulsed laser has several advantages such as less material damage, reduced thermal load (avoids the unnecessary heating of the surrounding material\textsuperscript{46}) and increased accuracy due to its short pulse lengths. This shorter pulse length also results in earlier evaporation of the material and reduced melt pool size by preferentially heating and softening the material. Pulsed picosecond laser also reduces the heat-affected zones (HAZ) due to the lower heat load when compared to pulsed laser radiation with nano and microsecond pulse length.\textsuperscript{47,48}
The second material removal process (SPDT) was done at the Western Michigan University Precision Engineering Laboratory. The main focus of this material removal process was to ensure that all machining of SiC was done in the ductile regime. The machining parameters from the Third Wave System 6” CVD-SiC project (Chapter 4) were used as guidelines as the work piece material for both projects were identified to be the same (SiC from POCO Graphite Inc. was used for both projects).

Experimentation Process

_Laser Ablation of CVD-SiC (by Mound Laser & Photonics Center):_

The CVD coated SiC samples were laser ablated by MLPC using a SuperRAPID pico-second pulsed laser operating at 1064nm wavelength (IR). _Figure 5.1 and 5.2 below shows both samples prepared by MLPC after the laser ablation process._

_Figure 5.1: POCO SiC sample marking how plateaus have been treated by laser ablation. (Picture courtesy of MLPC)_.

![Image of laser ablated SiC samples](image-url)
The number before the hyphen, e.g., 80, indicates the frequency in kHz. The number after the hyphen, e.g., 1 or 5, indicates the number of pulses in a burst group. The number below the frequency-burst label indicates the depth of material removed from the top of the plateau in microns. The plateau labeled “Bad” (plateau 3) will be ignored as ablation algorithm errors had occurred during the process.

**Figure 5.2: 60-1 POCO SiC square sample with a 32mm diameter laser ablated region.**

“60” in *Figure 5.2* represent the frequency in kHz and “1” indicates the number of pulses in a burst group.

**Preparatory Experiment Process – Surface Roughness Measurement:**

After the laser ablation process, the surface roughness of each Plateau/sample area was measured using a Mitutoyo surface profilometer before carrying out any additional (SPDT) machining operations. Four main surface roughness parameters were recorded for analysis purposes. These parameters include Ra (Roughness Average), Rq (Root Mean Square (RMS) Roughness), Rz (Average Peak-to-Valley of the Profile) and Rt (Maximum Height of the Profile).
Single Point Diamond Turning Setup:

The equipment used to carry out all of the SPDT experiments was The Micro-Tribometer (UMT) from the Center for Tribology Research Inc. (CETR). This equipment was developed to perform comprehensive micro-mechanical tests of coatings and materials at the micro scale. Figure 5.3 below shows the equipment setup for the 2” CVD coated SiC disk (the similar setup was used for the 60-1 square sample). A single crystal diamond tool with a 1mm nose radius, -45 degree rake angle and 5 degree clearance angle was used for the cutting tests.

Figure 5.3: Experimental setup for SPDT the laser ablated SiC disk.

The clay seen in Figure 5.3 above was used to mount the sample in the sample holder during the turning operation. The MASTERPOLISH 2 Final Polishing Suspension
(contains alumina and colloidal silica with a pH ~9) from Buehler, Inc. was used as the cutting fluid for all experiments involving diamond turning SiC.\

**Single Point Diamond Turning Operation:**

There were two sets of experiments carried out in order to obtain comparative results. The first set of experiments was carried out with a 1 µm/rev feed in order to obtain measurable tool wear and improve the surface roughness. Due to the rough surface of the as received silicon carbide, the tools wore rapidly for some plateaus/samples. The second set of experiments were carried out at a higher feed (5 µm/rev) in order to extend the tool life for those plateaus that had minimal tool life in the first set of experiments.

**SPDT Carried Out at a 1 µm/rev Feed (1 µm Depth of Cut):**

This initial set of experiments was carried out on the 2” diameter CVD-SiC disk (with 6 plateaus) and the 60-1 square CVD-SiC disk. Both of these samples are shown in Figure 5.1 and 5.2 respectively. An initial surface roughness measurement was carried out on all plateaus and the square disk. These surface roughness measurements were done on a Mitutoyo surface profilometer (averages of 3 traces were recorded for all plateaus/sample). All plateaus and the square disk were machined at a 1 µm programmed depth of cut with a 1 µm/rev feed. The 1 µm depth of cut was chosen as this depth was identified to be within the ductile regime of the material. The low feed (1 µm/rev) was chosen to obtain a better surface finish and facilitate measurable tool wear. The machining parameters for this part are summarized in Table 5.1 below.
Table 5.1: Machining parameters that were used for all the plateaus/sample.

<table>
<thead>
<tr>
<th>Plateau #</th>
<th>Feed</th>
<th>Programmed D.O.C</th>
<th>Applied Thrust Force (Fz)</th>
<th>Spindle RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Plateaus &amp; Sample 60-1</td>
<td>1 µm/rev</td>
<td>1 µm</td>
<td>321.77mN</td>
<td>60 rpm</td>
</tr>
</tbody>
</table>

The applied thrust force (load range) is an input value for a desired depth of cut (based on the Blake and Scattergood model\textsuperscript{50}, the master’s thesis of Biswarup Bhattacharya\textsuperscript{6}; and the work done for Third Wave Systems on the 6” CVD coated SiC as summarized in chapter 4 of this thesis). The spindle rpm was limited to a maximum of 60 rpm to minimize vibration (from the tool and spindle) that could degrade the surface of the SiC disk. The cutting direction was kept constant for all plateaus/sample (cutting from the outside towards the center) and the experiment was planned to be aborted if the tool failed at any point (this can be observed by the dramatic drop in cutting forces monitored while machining). After the machining experiment is complete, the work piece surface, tool and forces were analyzed.

SPDT Carried Out at a 5µm/rev Feed (1µm Depth of Cut):

A second set of experiments was carried out on the 2” diameter CVD-SiC disk (Figure 5.1). This section details cutting tests performed at a higher feed (5µm/rev) in an attempt to extend the tool life for those plateaus that had minimal tool life (low total cutting length) when machined at a 1µm/rev feed. Some plateaus were machined at a 1µm depth of cut with a 5µm/rev feed. The reason the feed was increased (from 1µm/rev to 5µm/rev) was to determine if the tool life could be extended, and thus produce a longer track length than the previous set of data. This higher feed has been previously demonstrated to provide a ductile mode cutting operation. If a longer track length is
achieved, then more valid surface roughness data can be obtained as the machined area increases proportionally with the track length. The machining parameters for this part are summarized in Table 5.2 below.

Table 5.2: Machining parameters that were used for some of the plateaus shown in Fig 5.1.

<table>
<thead>
<tr>
<th>Plateau #</th>
<th>Feed</th>
<th>Programmed D.O.C</th>
<th>Applied Thrust Force (Fz)</th>
<th>Spindle RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plateaus #4, #5, #6 &amp; Cntrl. Avg.</td>
<td>5 µm/rev</td>
<td>1 µm</td>
<td>321.77mN</td>
<td>12 rpm</td>
</tr>
</tbody>
</table>

The spindle RPM was further reduced in this set of experiments (from 60rpm to 12rpm). This was possible as 12rpm was the slowest possible speed for a 5µm/rev feed. Once again the idea of maintaining the slowest possible spindle speed was to reduce any external vibration that could potentially degrade the work piece surface.

Results and Discussion

Laser Ablation of CVD-SiC (by Mound Laser & Photonics Center):

A total of 7 plateaus were laser machined on the 2” round sample, but one (labeled “Bad”) will not be used. Besides the 2” round sample, a square sample with a 32mm diameter area was laser machined. The SEM pictures below show the surface before and after the laser ablation process.
Figure 5.4 shows the laser ablated surfaces on the plateaus of the POCO SiC sample taken at 1000x magnification. The numbers on top of the pictures going horizontally represents the frequency used and the numbers on the left arranged vertically represents the number of pulses in a burst group (SEM images courtesy of MLPC). The designations “1b” and “5b” refers to the number of pulse in a single burst.

Figure 5.5: SEM images of the original and laser ablated surfaces (20000x).
Figure 5.4 shows the laser ablated surfaces on the plateaus of the POCO SiC sample taken at 20,000x magnification. The images are arranged in the same order as Figure 5.4 (SEM images courtesy of MLPC). Figure 5.4 suggests that the laser ablation process had smoothed the original coarse texture of the SiC surface (note the sharp edges/peaks in the upper left image in Figure 5.5 of the CVD SiC grains). This visible observation is true for all the attempted laser ablation conditions attempted. At the highest magnification (20,000x), the microtexture is more resolved. The pattern seems to be almost identical for all conditions except the 80-5 where smaller grits are noticed (believed to be due to the low depth of ablation; 9µm).

**SPDT Carried Out at a 1µm/rev Feed (1µm Depth of Cut):**

Surface Finish after SPDT at 1µm/rev feed:

After the initial machining was carried out, the surface roughness of the machined regions was measured again using the surface profilometer. *Table 5.3, Figure 5.6, Figure 5.7 and Figure 5.8* compares the as received surface roughness with the roughness after the single point diamond turning (SPDT) operation was carried out.

*Table 5.3: Surface profile of individual samples after Pass 1.*

<table>
<thead>
<tr>
<th>Plateau/Sample</th>
<th>Actual d.o.c (µm)</th>
<th>Ra(before) (µm)</th>
<th>Ra (after) (µm)</th>
<th>Rz (before) (µm)</th>
<th>Rz (after) (µm)</th>
<th>Rt (before) (µm)</th>
<th>Rt (after) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 (80-1)</td>
<td>1.87</td>
<td>4.239</td>
<td>2.09</td>
<td>16.981</td>
<td>4.750</td>
<td>27.804</td>
<td>12.044</td>
</tr>
<tr>
<td>#2 (160-1)</td>
<td>2.76</td>
<td>3.801</td>
<td>1.65</td>
<td>13.231</td>
<td>3.003</td>
<td>30.227</td>
<td>11.841</td>
</tr>
<tr>
<td>#4 (500-5)</td>
<td>2.65</td>
<td>4.149</td>
<td>1.861</td>
<td>15.022</td>
<td>4.681</td>
<td>31.248</td>
<td>7.874</td>
</tr>
<tr>
<td>#5 (80-5)</td>
<td>2.12</td>
<td>4.259</td>
<td>2.449</td>
<td>14.957</td>
<td>4.710</td>
<td>30.858</td>
<td>8.587</td>
</tr>
<tr>
<td>#6 (500-1)</td>
<td>1.84</td>
<td>4.352</td>
<td>2.556</td>
<td>16.315</td>
<td>3.892</td>
<td>31.69</td>
<td>12.628</td>
</tr>
<tr>
<td>#7 (Control Avg)</td>
<td>1.97</td>
<td>3.608</td>
<td>1.576</td>
<td>15.309</td>
<td>2.856</td>
<td>24.274</td>
<td>9.667</td>
</tr>
<tr>
<td>Square (60-1)</td>
<td>1.53</td>
<td>2.948</td>
<td>1.496</td>
<td>14.521</td>
<td>6.825</td>
<td>24.291</td>
<td>10.824</td>
</tr>
</tbody>
</table>
The measurements in Table 5.3 were obtained from a Mitutoyo surface Profilometer. These values are an average of 3 runs done across the sample in 3 different directions. Plateau #3 is not included, as MLPC had identified it as being “bad”, i.e. incorrectly processed.

**Figure 5.6:** A chart comparing the as received Ra values with the Ra values obtained after Pass 1 was carried out.

Pass 1 has improved the surface roughness (Ra) of each sample. The numbers show that the Ra value has dropped by about 50% for all samples just after one pass. The data is arranged from lowest to highest surface roughness for comparison purposes.
Figure 5.7: A comparison of the as received Rz values with the Rz values obtained after Pass 1.

![Bar chart showing the comparison of as received and Pass 1 Rz values for different samples](image)

The as received Rz values are arranged in ascending order for the data presented in Figure 5.7. Pass 1 has removed the high peaks of each sample. The numbers show that the Rz value has dropped by almost 75% for all samples after just one pass. This significant drop in Rz values from the 1st pass is consistent with past experiments (Bhattacharya6).

Figure 5.8: A chart showing the change in the Rz values after the SPDT was carried out.

![Bar chart showing the change in Rz values after SPDT](image)
In general the final Rz values decreased by about 75% after the SPDT operation and the final Rz values are dependent on the as received Rz value before the SPDT operation (i.e. the lower the as received Rz value, the lower the final Rz value). Figures 5.9 and 5.10 below show images of the SiC surface taken using a Nikon optical microscope. In general, the images show that there is a change in surface finish after the SPDT operation whereby the surface after machining appears to be more reflective suggestion a smoother surface.

**Figure 5.9: Image compares the machined region (right) with the unmachined region (left) for Plateau #1 (80-1).**

This image in *Figure 5.9* was taken at a 50x magnification using an optical microscope. Note that the machined region is more reflective, indicating a better surface finish (lower Ra) than the unmachined area.
This image in Figure 5.10 was taken at a 200x magnification using an optical microscope. The shiny/reflective areas are the highest points machined on the surface, and these regions are smoother than the underlying material. Although the final surface roughness value is dependent on the as received surface roughness value, in general, the data suggests that the overall surface roughness (Ra and Rz) of the machined regions have significantly improved (Ra dropped by 50% and Rz dropped by almost 75%) after the SPDT operation.

Force Data Obtained from the SPDT at 1μm/rev feed:

The total cutting track length (length of cut) and cutting forces were obtained for every machining experiment and displayed in Table 5.4. Cutting forces can vary due to several reasons, such as surface roughness of the work piece and the initial tool positioning. In general, the lower the force the better the overall performance.
Table 5.4: The total cutting track length and force data obtained after carrying out Pass 1 on each plateau/sample.

<table>
<thead>
<tr>
<th>Plateau/Sample</th>
<th>Track Length (m)</th>
<th>*Fz (Thrust Force) mN</th>
<th>**Fx (Cutting Force) mN</th>
<th>***COF</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 (80-1)</td>
<td>60.31</td>
<td>321.8</td>
<td>50.99</td>
<td>0.16</td>
</tr>
<tr>
<td>#2 (160-1)</td>
<td>44.73</td>
<td>321.8</td>
<td>62.1</td>
<td>0.19</td>
</tr>
<tr>
<td>#4 (500-5)</td>
<td>4.84</td>
<td>321.8</td>
<td>113.4</td>
<td>0.35</td>
</tr>
<tr>
<td>#5 (80-5)</td>
<td>9.07</td>
<td>321.8</td>
<td>64.01</td>
<td>0.20</td>
</tr>
<tr>
<td>#6 (500-1)</td>
<td>0.32</td>
<td>321.8</td>
<td>90.8</td>
<td>0.28</td>
</tr>
<tr>
<td>#7 (Cntrl Avg)</td>
<td>38.09</td>
<td>321.8</td>
<td>63.12</td>
<td>0.20</td>
</tr>
<tr>
<td>Square (60-1)</td>
<td>505.8</td>
<td>321.8</td>
<td>16.81</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Note:

* The thrust force (Fz) is set by the operator to achieve a 1 µm depth of cut.

** The cutting force (Fx) is obtained from the force sensor during the cutting operation.

*** The coefficient of friction (COF) is just a calculated ratio of (Fx/Fz).

**** Using the total tool life, or track length, as a critical parameter the (80-1) plateau and the 60-1 square sample performed well. However the tool used for the 80-1 Plateau lasted the entire cut, i.e., it did not wear out, and thus the ultimate tool life could not be determined from this test result.
Cutting forces can vary due to a couple of reasons such as surface roughness and initial tool positioning, but in general the lower the force the better the overall performance. The data is arranged from lowest to highest cutting force.

Tool Wear from the SPDT at 1μm/rev feed:

A tool wear study was conducted after the machining experiments. Since a new tool was used for every new plateau/sample, it was possible to record all tool wear data individually for further analysis. The general pattern in the data suggest that the tool wear is a function of track length covered (a longer track length results in more tool wear as shown in Figure 5.12 & 5.13), and cutting force (larger cutting forces yield a greater tool wear as shown in Figure 5.14). Using the total tool life, or track length, as a critical parameter the 80-1 plateau and the 60-1 square sample performed best overall, followed by the 160-1 plateau. However the tool used for the 80-1 plateau lasted the entire cut (on
a much smaller sample compared to the square 60-1 sample) and thus the ultimate tool life could not be determined from this test result.

Table 5.5: Table of the measured tool wear after machining each plateau/sample.

<table>
<thead>
<tr>
<th>Plateau/Sample</th>
<th>Fx (Cutting Force) mN</th>
<th>Track Length (m)</th>
<th>Total time (mins)</th>
<th>Length across cutting radius (μm)</th>
<th>Rake Wear (μm)</th>
<th>Flank Wear (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 (80-1)</td>
<td>59.99</td>
<td>60.31</td>
<td>50.00</td>
<td>368.08</td>
<td>9.16</td>
<td>21.36</td>
</tr>
<tr>
<td>#2 (160-1)</td>
<td>62.1</td>
<td>44.73</td>
<td>37.08</td>
<td>342.20</td>
<td>8.42</td>
<td>19.86</td>
</tr>
<tr>
<td>#4 (500-5)</td>
<td>113.4</td>
<td>4.84</td>
<td>2.77</td>
<td>176.35</td>
<td>7.88</td>
<td>18.38</td>
</tr>
<tr>
<td>#5 (80-5)</td>
<td>64.01</td>
<td>9.07</td>
<td>5.28</td>
<td>273.60</td>
<td>7.38</td>
<td>17.21</td>
</tr>
<tr>
<td>#6 (500-1)</td>
<td>90.8</td>
<td>0.32</td>
<td>0.17</td>
<td>156.00</td>
<td>7.00</td>
<td>16.33</td>
</tr>
<tr>
<td>#7 (Control Avg)</td>
<td>63.12</td>
<td>38.09</td>
<td>25.70</td>
<td>296.18</td>
<td>7.59</td>
<td>17.70</td>
</tr>
<tr>
<td>Square (60-1)</td>
<td>16.81</td>
<td>505.8</td>
<td>198.00</td>
<td>386.25</td>
<td>13.26</td>
<td>31.24</td>
</tr>
</tbody>
</table>

The wear reported in Table 5.5 was measured off images obtained from a Scanning Electron Microscope (SEM). An example of a wear measurement taken from a tool is shown in Figure 9.

All plateaus and the square samples were machined under the same machining conditions. A new tool was used for every new plateau/square. There were two attempts made (2 different tools) for plateau #7. This was done to rule out that the wear of the tool was due to a tool defect. Plateau #7 was the control sample, i.e. the original non laser ablated surface. It was expected that the tool life would in general be improved with laser ablation.
Table 5.6: Wear length measured across the cutting edge radius using two different microscopes; SEM & Optical.

<table>
<thead>
<tr>
<th>Plateau/Sample</th>
<th>Tool #</th>
<th>Track Length (m)</th>
<th>Length across cutting radius (µm) (SEM)</th>
<th>Length across cutting radius (µm) (Optical)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 (80-1)</td>
<td>8561</td>
<td>60.31</td>
<td>368.08</td>
<td>363</td>
<td>1.40</td>
</tr>
<tr>
<td>#2 (160-1)</td>
<td>8562</td>
<td>44.73</td>
<td>342.20</td>
<td>338</td>
<td>1.24</td>
</tr>
<tr>
<td>#4 (500-5)</td>
<td>8558</td>
<td>4.84</td>
<td>176.35</td>
<td>173</td>
<td>1.94</td>
</tr>
<tr>
<td>#5 (80-5)</td>
<td>8560</td>
<td>9.07</td>
<td>273.60</td>
<td>268</td>
<td>2.09</td>
</tr>
<tr>
<td>#6 (500-1)</td>
<td>8559</td>
<td>0.32</td>
<td>156.00</td>
<td>148</td>
<td>5.41</td>
</tr>
<tr>
<td>#7 (Cntrl Avg)</td>
<td>8562/8563</td>
<td>38.09</td>
<td>296.18</td>
<td>288</td>
<td>2.84</td>
</tr>
<tr>
<td>Square (60-1)</td>
<td>8558</td>
<td>505.8</td>
<td>386.25</td>
<td>379</td>
<td>1.91</td>
</tr>
</tbody>
</table>

Both methods provided very similar values where the maximum percentage difference was always below 6%. A sample measurement for both imaging methods is shown in the appendix. Figure 5.17 shows an example of a wear measurement taken using an image from an optical microscope.

Figure 5.12: The measured wear length across the cutting radius vs. the track length covered by the tool.

The width of each bar represents the approximate magnitude of track length the tool had covered during the SPDT operation. The change of widths of the bar chart is done to
dramatize the results and help in visualizing the amount of track length covered by each tool on that particular plateau. The total wear length is proportional to the total track length (tool life) as to be expected.

Figure 5.13: The measured rake and flank wear across the cutting radius vs. the track length covered by the tool.

The width of each bar represents the approximate magnitude of track length the tool had covered during the SPDT operation. The change of widths of the bar chart is done to dramatize the results and help in visualizing the amount of track length covered by each tool on that particular plateau. The total wear length is proportional to the total track length (tool life) as to be expected. In all cases the flank wear exceeds the rake wear.
In general the chart trend suggests that the higher the cutting forces, the shorter the tool life (except for plateau 500-5 as this plateau had a rougher surface to start off with than plateau 500-1). The width of each bar represents the approximate magnitude of track length the tool had covered during the SPDT operation. The change of widths of the bar chart is done to dramatize the results and help in visualizing the amount of track length covered by each tool on that particular plateau.
The wear across the cutting edge radius can be measured from the upper picture (292x magnifications). The Cutting edge radius is also indicated in the above picture. This cutting edge radius is used as a reference line to differentiate the rake and flank wear respectively which is shown in the lower figure (1139x magnification). This tool was used for Plateau #5 (80-5). Figures 5.16 and 5.17 show images obtained from an optical
microscope. These images compare the same tool before and after a SPDT operation. The measured wear length across the cutting edge radius is shown in Figure 5.17.

**Figure 5.16: Image of new 1mm nose radius (-45° rake & 5° clearance) tool.**

The optical image in Figure 5.16 was taken at 200x magnification (Tool # 8563).
Figure 5.17: Image of worn 1mm nose radius (-45° rake & 5° clearance) tool.

The optical image in Figure 5.16 was taken at 200x magnification (Tool # 8563). This tool was used to machine Plateau # 7 (Control regions)
SPDT Carried Out at a 5µm/rev Feed (1µm Depth of Cut)

Surface Finish after SPDT at 5µm/rev feed:

A second set of experiments were carried out on the 2" diameter CVD-SiC disk for some of the plateaus discussed previously. This section details cutting tests performed at a higher feed (5µm/rev) in an attempt to extend the tool life for those plateaus that had minimal tool life (low total cutting length) when machined at a 1µm/rev feed. These plateaus were machined at a 1µm depth of cut with a 5µm/rev feed. The reason the feed was increased (from 1µm/rev to 5µm/rev) was to determine if the tool would cover a longer track length than the previous set of data. This higher feed had been previously demonstrated to provide a ductile mode cutting operation. If a longer track length is achieved, then more valid surface roughness data can obtained as the machined area increases proportionally with the track length. Table 5.7, Figure 5.18, Figure 5.19 and Figure 5.20 compares the as received surface roughness with the roughness after the single point diamond turning (SPDT) operation was carried out. The control average region is the as-received region where no laser ablation was carried out.

Table 5.7: The surface profile of individual plateaus after machining at a feed of 5µm/rev.

<table>
<thead>
<tr>
<th>Plateau</th>
<th>Actual d.o.c. (µm)</th>
<th>Ra(before) (µm)</th>
<th>Ra(after) (µm)</th>
<th>Rz(before) (µm)</th>
<th>Rz(after) (µm)</th>
<th>Rt(before) (µm)</th>
<th>Rt(after) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#4 (500-5)</td>
<td>2.857</td>
<td>4.149</td>
<td>2.032</td>
<td>15.022</td>
<td>4.681</td>
<td>31.248</td>
<td>7.874</td>
</tr>
<tr>
<td>#5 (80-5)</td>
<td>2.248</td>
<td>4.259</td>
<td>2.862</td>
<td>14.957</td>
<td>5.216</td>
<td>30.858</td>
<td>11.261</td>
</tr>
<tr>
<td>#6 (500-1)</td>
<td>2.042</td>
<td>4.352</td>
<td>2.982</td>
<td>16.315</td>
<td>4.326</td>
<td>31.69</td>
<td>14.264</td>
</tr>
</tbody>
</table>

Data in Table 5.7 was obtained from a Mitutoyo surface Profilometer. These values are an average of 3 runs done across the sample in 3 different directions.
The 5µm/rev machining pass has improved the surface roughness (Ra) of each plateau/sample. The results show that the Ra value has dropped by about 50% for all plateaus/sample just after one pass.

Figure 5.19: Chart comparing the as received Rz values with the Rz values obtained after machining at the 5µm/rev feed.
The 5µm/rev machining pass has removed the high peaks of each plateau/sample. The numbers show that the Rz value has dropped by almost 75% for all plateaus/sample after just one pass. This significant drop in Rz values from the 1st pass is consistent with past experiments (Bhattacharya, 2005.)

Figure 5.20: Chart showing the change in the Rz after the SPDT was carried out.

![Change in peak-to-valley values, Rz (5µm feed rate)](chart)

In general the final Rz values decreased by about 75% after the SPDT operation and the final Rz value is dependent on the as received Rz value before the SPDT operation (i.e. the lower the as received Rz value, the lower the final Rz value).

Force Data Obtained from the SPDT at 5µm/rev feed:

The cutting forces were obtained for every machining experiment and recorded in Table 5.8. The cutting forces were then plotted for every machining experiment and recorded in Figure 5.21. Once again as mentioned for the previous set of experiments, cutting forces can vary due to several reasons such as surface roughness of the work
piece and the initial tool positioning. In general, the lower the force the better the overall performance.

Table 5.8: Table of the force data for the 5µm/rev feed experiments.

<table>
<thead>
<tr>
<th>Plateau</th>
<th>Track Length (m)</th>
<th>*Fz (Thrust Force)mN</th>
<th>**Fx (Cutting Force)mN</th>
<th>***COF</th>
</tr>
</thead>
<tbody>
<tr>
<td>#4 (500-5)</td>
<td>11.688</td>
<td>321.8</td>
<td>30.25</td>
<td>0.09</td>
</tr>
<tr>
<td>#5 (80-5)</td>
<td>21.270</td>
<td>321.8</td>
<td>31.39</td>
<td>0.10</td>
</tr>
<tr>
<td>#6 (500-1)</td>
<td>23.124</td>
<td>321.8</td>
<td>21.54</td>
<td>0.07</td>
</tr>
<tr>
<td>Square (Cntrl. Avg)</td>
<td>616.983</td>
<td>321.8</td>
<td>11.24</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Note:

*The thrust force (Fz) is set by the operator to achieve a 1µm depth of cut.

**The cutting force (Fx) is obtained from the force sensor during the cutting operation.

***The coefficient of friction (COF) is just a calculated ratio of (Fx/Fz).

Figure 5.21: Chart showing the average of the cutting force recorded along the entire length of cut.

Cutting forces can vary due to a couple of reasons such as surface roughness and initial tool positioning, but in general the lower the force the better the overall performance.
Tool Wear from the SPDT at 5µm/rev feed:

A similar tool wear study was conducted as for the previous set of data. Once again all new tools were used for every plateau/sample machining test, and tool wear data is determined individually for each experiment for further analysis. The general pattern in the data suggest that the tool wear is a function of track length covered (longer track length results in more tool wear as shown in Figure 5.22 & 5.23), and cutting force (larger cutting forces yield a greater tool wear as shown in Figure 5.24). This pattern is similar and consistent to the initial set of data collected at the 1µm/rev feed.

Table 5.9: Table of the measured tool wear after machining each plateau/sample.

<table>
<thead>
<tr>
<th>Plateaus/Sample</th>
<th>Tool #</th>
<th>Track Length (m)</th>
<th>Total time (mins)</th>
<th>Length across cutting radius (µm)</th>
<th>Rake Wear (µm)</th>
<th>Flank Wear (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#4 (500-5)</td>
<td>8560</td>
<td>11.688</td>
<td>6.59</td>
<td>158.2</td>
<td>7.42</td>
<td>15.86</td>
</tr>
<tr>
<td>#5 (80-5)</td>
<td>8559</td>
<td>21.270</td>
<td>5.38</td>
<td>156.2</td>
<td>7.26</td>
<td>15.23</td>
</tr>
<tr>
<td>#6 (500-1)</td>
<td>8561</td>
<td>23.124</td>
<td>15.73</td>
<td>182.6</td>
<td>8.21</td>
<td>16.23</td>
</tr>
<tr>
<td>Square (Cntrl. Avg)</td>
<td>8563</td>
<td>616.983</td>
<td>95.55</td>
<td>312.4</td>
<td>11.26</td>
<td>22.44</td>
</tr>
</tbody>
</table>

The wear was measured from images obtained from a Scanning Electron Microscope (SEM). A sample tool measurement obtained from a SEM image is shown in Figure 5.15.

Table 5.10: Wear length measured across the cutting edge radius using two different microscopes; SEM and Optical.

<table>
<thead>
<tr>
<th>Plateaus/Sample</th>
<th>Tool #</th>
<th>Track Length (m)</th>
<th>Length across cutting radius (µm) (SEM)</th>
<th>Length across cutting radius (µm) (Optical)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>#4 (500-5)</td>
<td>8560</td>
<td>11.688</td>
<td>158.2</td>
<td>152</td>
<td>4.08</td>
</tr>
<tr>
<td>#5 (80-5)</td>
<td>8559</td>
<td>21.270</td>
<td>156.2</td>
<td>149</td>
<td>4.83</td>
</tr>
<tr>
<td>#6 (500-1)</td>
<td>8561</td>
<td>23.124</td>
<td>182.6</td>
<td>176</td>
<td>3.75</td>
</tr>
<tr>
<td>Square (Cntrl. Avg)</td>
<td>8563</td>
<td>616.983</td>
<td>312.4</td>
<td>302</td>
<td>3.44</td>
</tr>
</tbody>
</table>
Both imaging methods provided us with very similar values where the maximum percentage difference was always below 6%.

**Figure 5.22:** Plot showing the measured wear length across the cutting radius vs. the tool track length.

The width of each bar represents the approximate magnitude of track length the tool had covered during the SPDT operation. The change of widths of the bar chart is done to dramatize the results and help in visualizing the amount of track length covered by each tool on that particular plateau. The total wear length is roughly proportional to the total track length (tool life) as to be expected.
Figure 5.23: Plot showing the measured rake and flank wear across the cutting radius vs. the tool track length.

The width of each bar represents the approximate magnitude of track length the tool had covered during the SPDT operation. The change of widths of the bar chart is done to dramatize the results and help in visualizing the amount of track length covered by each tool on that particular plateau/sample. The total wear length is proportional to the total track length (tool life) as to be expected.
In general the chart trend suggests that the higher the cutting forces are, the shorter the tool life is. The width of each bar represents the approximate magnitude of track length the tool had covered during the SPDT operation. The change of widths of the bar chart is done to dramatize the results and help in visualizing the amount of track length covered by each tool on that particular plateau/sample.
Figure 5.25: Images of a worn tool taken at three different magnifications.
The magnification for the images in Figure 5.25 are 42.2x (top), 422x (center) and 1050x (bottom). This tool was used for the square Plateau (80-1). Generally, a higher feed results in less tool wear due to the shorter track length covered by the tool. This means that the tool wear obtained from the 5µm/rev feed experiments are smaller compared to the tool wear obtained from the 1µm/rev feed experiments.

Comparing Results from Both Feeds (1µm/rev & 5µm/rev):

The data comparing 3 plateaus; #4 (500-5), #5 (80-5) and #6 (500-1) was analyzed. The reason these three plateaus were chosen was because they are common plateaus machined under both feeds (1µm/rev and 5µm/rev). The surface roughness data (Figure 5.26 and 5.27) suggest that the lower feed rate (1µm/rev) yields in a slightly better surface finish, as expected. As per the tool wear data (Figure 5.28), the tools lasted longer for the 5µm/rev feed compared to the 1µm/rev feed, as expected.

**Figure 5.26: Chart comparing the as received Ra values with the Ra values obtained after the 1µm/rev and 5µm/rev feed experiments.**
The data suggest that the lower feed rate (1µm/rev) yields a slightly better surface finish, as expected.

Figure 5.27: Chart comparing the as received Rz values with the Rz obtained after the 1µm/rev and 5µm/rev feed experiments.

The data suggest that the lower feed rate (1µm/rev) yields a slightly better surface finish, as expected.
Figure 5.28: Chart showing the duration (track length) a single tool lasted for two different feed rates on three common plateaus.

In general, the tools lasted much longer for the 5µm/rev feed rate compared to the 1µm/rev feed, as expected.

Experimental Data Summary

Finally, all data was summarized (track length, cutting forces & surface roughness) in one chart to visualize the ideal machining conditions with respect to the plateaus/sample (as shown in Figure 5.29). The results suggest that the combination of laser machining of (60-1) followed by SPDT performed the best, resulting in the lowest surface roughness values, longest track length and/or lowest cutting forces.
The y-axis is a ratio between the track length covered by the tool and the cutting forces obtained from that particular pass (ideally longer track lengths and lower cutting forces that yield in larger ratios are preferred). The x-axis represents the final surface roughness value (Ra) after carrying out the single point diamond turning (SPDT) operation. From the chart above, it can be summarized that all the data points that fall in quadrant #1 (upper right) is most preferred as these result in low surface roughness values (note the surface roughness is plotted from high to low values going from left to right, to create the upper right quadrant as the best or preferred region), longer tool track lengths and low cutting forces. On the other hand, all data points that fall in quadrant #4 are least preferred as these results in high surface roughness values, short track lengths and/or high cutting forces. The results suggest that the combination of laser machining of (60-1)
followed by SPDT performed the best, yielding the lowest surface roughness values, longest track length and/or lowest cutting forces.

All of the processing parameters that fall in the upper right quad, represent x-1 laser machining and 1µm/rev SPDT conditions, this combination of the hybrid machining appears to produce the best results. All of the processing parameters that fall in the upper left quadrant (#3) were machined at the higher feed rate, 5µm/rev, which consistently provided longer tool life, but higher surface roughness. This result is as expected, i.e. the trade off between tool life and surface finish, and is consistent with previous work.

The chart does not contain all of the data, as some processing conditions did not produce sufficient tool life (track length) to provide measurable data. These data would fall in the lower left quadrant (#4), which represents the least efficient machining conditions. Data in quads 2 and 3 represent a trade off between tool life (track length/force) and surface roughness respectively. Overall, the material laser processed with the 60-1 conditions and then SPDT performed the best and is the candidate for future research, testing and evaluation.

Conclusion

In conclusion, the material laser processed with the 60-1 conditions and then SPDT performed the best and is the candidate for future research, testing and evaluation. Besides this sample, the 80-1 and 160-1 also performed well and was placed in quadrant #1 (Figure 5.26), which explains that these samples also yielded longer track lengths, lower cutting forces and lower surface roughness. This suggests that samples produced with burst mode 1 are preferred for this experiment (except 500-1 as it had a higher
surface roughness to start off with), and that the overall hybrid process improved as the laser ablation duration (pulse repetition frequency) decreased from the highest of 500 to lowest of 60 (for the burst mode 1 samples, a similar trend also occurred for the burst mode "5" samples, however there were only two data points, 500 and 80). The samples/plateaus produced with burst mode 5 did not perform as well as the burst mode “1” plateaus as it resulted in high surface roughness and/or high cutting forces and/or shorter track length.
CHAPTER 6

MACHINING AND IMPROVING THE SURFACE ROUGHNESS OF A QUARTZ DISK (FUSED SILICA) BY PERFORMING DUCTILE REGIME SINGLE POINT DIAMOND TURNING

Introduction

The mechanics of material removal in glass (Quartz) can be classified in two categories: brittle fracture and plastic deformation. Good optical quality surfaces can be achieved by removing the material in a ductile manner. The work of past researchers suggests that glasses do not necessarily behave as a brittle material (even at room temperature) at the nanometric scale. The strength, hardness and fracture toughness of the work piece material are the governing factors that control the extent of brittle fracture. Some studies include detailed observations of a small amount of plastic deformation in glasses (Quartz) during a precision machining operation.

Quartz, also known as silicon dioxide (SiO₂), is the most abundant nonmetallic mineral on earth. There are several forms of quartz such as quartz crystals, natural fused silica (amorphous form of SiO₂) and synthetic fused silica (polycrystalline). For this project, a synthesized fused silica (Spectrosil 2000) was used. Spectrosil 2000 is an ultra pure synthetic fused silica manufactured by Saint-Gobain Quartz PLC. This quartz material has a wide optical range from 180nm in the deep ultra violet transmission through to 2000nm in the infrared (IR). This material possesses a chemical purity of 99.999% and is manufactured using an environmentally friendly process, which results in
a material that is both chlorine-free and bubble-free. A 6” diameter round disk was obtained in order to carry out the SPDT experiments.

The main goal of this experiment is to establish a production-level process condition for quartz mirror fabrication via ductile mode machining. A 6” diameter Spectrosil 2000 round disk (0.250” thick) was used to carry out the experiments. The very first task was to see if this material can be diamond turned at all with the current setup for SPDT (similar to setup used for the 6” TWS CVD-SiC). If ductile mode machining is possible, then SPDT of quartz will be attempted to improve the surface roughness (Ra < 50nm) and monitor the tool wear. These results obtained will be used to predict machining and tool wear data for a 14” diameter round quartz disk which will be used as part of a nose cover for a high power Airborne Laser (ABL) device (the machining of the 14” diameter disk will not be carried out at Western Michigan University).  

Experimentation Process

Single Point Diamond Turning Setup

The equipment used to carry out all of the SPDT experiments was The Micro-Tribometer (UMT) from the Center for Tribology Research Inc. (CETR). This equipment was developed to perform comprehensive micro-mechanical tests of coatings and materials at the micro scale. Figure 6.1 below shows the SPDT setup for the 6” Spectrosil 2000 disk (the similar setup was used for both the preparatory machining and final machining experiments). A single crystal diamond tool with a 3mm nose radius,
degree rake angle and 5 degree clearance angle was used for the cutting tests (tools were custom made by Chardon Tool, Inc.).

Figure 6.1: Image shows the SPDT setup for the Spectrosil 2000 workpiece.

Note from Figure 6.1 that the tool length had been shortened (from 2” to 0.78”) to minimize tool vibration. A high pH (~ 10.5) cutting fluid (MASTERMET 2 Colloidal Silica Suspension) was used for the final machining experiment. This cutting fluid (obtained from Buehler, Inc.) contains fine, noncrystallizing (0.02μm) SiO₂ particles in an aqueous base that is suitable for polishing and machining quartz/glass.⁵⁸
The purpose of the preparatory experiment was to determine if ductile machining on the quartz disk was possible (the scratching test results from the research work of Battacharya (2005) were used as a guideline). The as-received surface roughness measurement was carried out using a Mitutoyo surface profilometer. The Ra (Roughness Average), Rz (Average Peak-to-Valley of the Profile) and Rt (Maximum Height of the Profile) values were recorded. Preliminary calculations were carried out to correlate the feed, depth of cut and applied thrust force based on the Blake and Scattergood model\textsuperscript{36}. Scratching tests results done on a similar type of material (Infrasil 302) carried out at Western Michigan University (Bhattacharya, 2005) was also used as a guideline. One of the key concerns for this machining process was to make sure that the applied thrust force was constant (minimal standard deviation) throughout the entire cutting operation in order to achieve a uniform cut. Several factors could contribute to an unstable cutting operation such as work piece runout, tool vibration and even debris along the tool path. Tool vibration is often caused by large sample runouts. The runout of the work piece was adjusted (total runout was less than 500nm) using shims and the tool length was reduced, to minimize vibration, to obtain a uniform and stable cut.

A 1\textmu m depth of cut with a 1\textmu m/rev feed SPDT operation was attempted. Several trials were carried out in order to test for work piece runout, tool vibration, force stability, tool wear, thrust force and depth of cut correlation and surface conditions after machining. The quartz disk and diamond tool were analyzed after the tests were carried out. Chips from the machining operation were collected and analyzed to study the
material removal behavior. These preparatory tests were done dry, without a cutting fluid. The results of this step are reported in section 6.3

*Final Machining* - *SPDT on Spectrosil 2000*

After the preparatory/preliminary tests were carried out and analyzed, the final machining on the Spectrosil 2000 was conducted (preparatory results showed ductile mode machining conditions were achieved). A total of two passes were carried out in order to achieve the target surface roughness (Ra < 50nm). The first pass was done at a 1µm programmed depth of cut with a 1µm/rev feed and the second pass was done at a 500 nm programmed depth of cut with a 1µm/rev feed. The 1µm depth of cut was carried out as it showed ductile mode material removal behavior in the preparatory tests. A low feed (1µm/rev) was chosen to minimize brittle fracture and to help with improving the surface roughness.

The surface roughness was measured after each pass in order to finalize the machining conditions for the following pass (in this case the surface was analyzed after Pass 1 to decide the machining conditions for Pass 2). The diamond cutting tool was imaged and the tool wear was measured and recorded. Cutting force (Fx) data was extracted in order to correlate it with the measured tool wear and resultant surface roughness. All of the final machining was done under wet conditions using the MASTERMET 2 Colloidal Silica Suspension from Buehler Inc.
Results and Discussion

Preparatory Experiment Process - SPDT Trials on Spectrosil 2000

Several short cuts (60-100μm total width) were done towards the outer diameter of the 6” quartz disk in order to test for force stability, tool vibration and ductile mode machining. The test cuts were promising and ductile mode machining was identified by looking at the work piece surface after machining and collecting the quartz chips from the experiment.

Figure 6.2: Machined surface of the quartz disk showing no signs of brittle fracture.

The image shown in Figure 6.2 was obtained from an optical microscope at 200x.
Figure 6.3: Image showing the surface of the machined region.

Figure 6.3 shows that multiple cuts were carried out in the shown field of view. No cracks or brittle characteristics were observed at a 400x magnification. The surface images of the machined region may not seem as clear as the quartz piece is transparent and therefore a significant amount of light from the microscope shines through it and creates multiple reflections and obscures the image of the surface.

The quartz chips were collected from the cutting operation and examined under the microscope. The images below suggest the occurrence of ductile mode machining, as the chips are continuous and plastically deformed.
These continuous plastic chips suggest ductile mode machining. The optical microscope images above were captured at a 400x magnification.

The final observation of the preparatory experiment was to measure the tool wear. Figures 6.6 and 6.7 show the cutting edge radius of the tool seen under an optical microscope. From these Figures there is no visible wear and the cutting edge radius is
still well defined. The debris seen on the tool tip in the images are from the cutting operation (debris are on the surface) and is not a sign of worn diamond tip. Since the test results were promising, the final machining experiment was setup and carried out. The surface roughness and cutting forces were not a major concern at this point as the main goal was to determine if the material can be machined in the ductile-regime using SPDT (also a surface roughness measurement will not be valid as the machine controls were constantly being changed to find the optimum setting).

**Final Machining- SPDT on Spectrosil 2000**

A total of two passes were required in order to achieve the desired surface roughness (Ra <50nm). The results in Figure 6.8 suggest that the surface roughness consistently improved after each pass.

*Figure 6.8: Chart comparing the as-received surface roughness with Passes 1 and 2.*
The data in Figure 6.8 indicates that the surface roughness (in terms of Ra and Rz) had improved after both machining passes. After pass 2, the final surface roughness was measured to be 41nm (Ra) which is lower than the targeted Ra value. The depth of cut was decreased (from 1µm to 500nm) for the second pass as the peak-to-valley value was much lower than the as received surface (in general the program depth of cut is approximately equal to the Rz value). Also, a deeper cut could worsen the surface by causing more valleys (feed marks or grooves) on the workpiece surface.

Table 6.1: Table of the parameters used to machine the Spectrosil 2000.

<table>
<thead>
<tr>
<th>Programmed Depth of Cut</th>
<th>Actual Depth of Cut</th>
<th>Feed</th>
<th>Thrust Force (Fz)</th>
<th>Fz (s)</th>
<th>Cutting Force (Fx)</th>
<th>Fx (s)</th>
<th>Force Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1µm</td>
<td>651nm</td>
<td>1µm/rev</td>
<td>115mN</td>
<td>1.99mN</td>
<td>13.17mN</td>
<td>0.65mN</td>
<td>0.11</td>
</tr>
<tr>
<td>500nm</td>
<td>363nm</td>
<td>1µm/rev</td>
<td>50.25mN</td>
<td>2.61mN</td>
<td>5.65mN</td>
<td>0.38mN</td>
<td>0.11</td>
</tr>
</tbody>
</table>

The thrust (Fz) force was an input value used to obtain the required depth of cut and the cutting force (Fx) was an output value measured during the turning operation. Fz(s) is the std dev of the thrust force. Force ratio is (Fx/Fz). The data in Table 6.1 above indicates that the forces (both thrust and cutting) were stable throughout the entire machining operation resulting in a standard deviation of less than 7% (Fz(s)). As mentioned in the previous section, it is important to obtain stable forces in order to produce a uniform cut. The force ratio (Fx/Fz) for both cuts were consistent (0.11), indicating uniformity in both cuts/passes. The second pass had lower cutting forces due to a lower depth of cut and a smoother surface to start off with (in general smaller forces are preferred). The actual depth of cut for both passes were less than the programmed depth of cut due to the elastic properties of the material (this elasticity effect was expected and is consistent with the work done on the 6” CVD-Sic; Chapter 4). The surface roughness
data and surface images (Figure 6.9 & 6.10) suggest that material was removed in the ductile mode even at the 651 nm depth of cut (actual measured depth of cut). This conclusion is reasonable as past researchers have indicated pure ductile material removal below a depth of cut of 1 µm.\textsuperscript{59} Q.L. Zhao et al. Also stated in their research that for any cuts from 1 µm to 3.5 µm, the starting of brittle material removal is observed as micro-cracks form on the surface.

**Figure 6.9: The optical microscope image shows the feed marks of the machined region (left) after Pass 1.**

The unmachined region (right) in Figure 6.9 has no marks. This image was taken at a 400x magnification.
Figure 6.10: Image showing very light feed marks on the machined region (left side of image) after Pass 2.

The unmachined region in Figure 6.10 (right side) has no feed marks. This image was taken at a 1000x magnification. Comparing Figures 6.9 and 6.10 it is obvious that the resultant surface obtained after pass 2 is better than the machined surface after pass 1. This complements the surface roughness data obtained after each pass, as shown in Table 6.1. The feed marks caused in pass 1 have almost been removed after pass 2, resulting in a much smoother surface.

The final analysis done in this project was to attempt to measure the tool wear. A total of two diamond tools were used, as a new tool was used for each pass. Both tools lasted the entire machining experiment (approximately 6” diameter) and the SEM images suggest that there was no catastrophic tool wear.
Table 6.2: Tool wear data of the 3mm nose radius diamond tool after the machining operation.

<table>
<thead>
<tr>
<th>Pass #</th>
<th>Measured wear length across cutting edge radius</th>
<th>Rake Wear</th>
<th>Flank Wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>113 µm</td>
<td>1 µm</td>
<td>3 µm</td>
</tr>
<tr>
<td>2</td>
<td>106 µm</td>
<td>Not observed</td>
<td>Not observed</td>
</tr>
</tbody>
</table>

Both tools held up for the entire machining operation. The values reported in the above table were obtained from the SEM images. *Table 6.2* above shows the measured wear of the tools after the machining experiment obtained from the SEM images at different magnifications. Minor rake and flank wear was measured for the tool used for pass 1 (1 µm program depth of cut), where as no wear was visible for the tool used for pass 2 (500 nm program depth of cut). The measured wear length across the cutting edge radius corresponds to the contact length between the tool tip (radius) and the work piece.

*Figure 6.11*: The SEM image shows slight wear measured at the tool cutting edge radius (311x). *Figure 6.12*: The SEM image shows slight wear measured at the tool cutting edge radius (311x).

The 331x magnification (*Figure 6.11*) was used to measure the wear length across the cutting edge radius (113µm). This tool was used for pass 1 which was the 1µm depth of cut. The 1040x magnification (*Figure 6.12*) was used to measure the rake (1µm) and flank (3µm) wear at the cutting edge radius.
Figure 6.13: The optical microscope image shows the worn region of the tool tip taken at 400x.

The wear length across the cutting edge radius measured to be about 110µm using the optical microscope images; this compares favorable to the measurement (113 µm) from the SEM image shown in Figure 6.11. This tool was used for pass 1 where the programmed depth of cut was 1µm.

Figure 6.14: The SEM image above shows no visible wear at the cutting edge radius (415x).
Figure 6.15: The SEM image above shows no visible wear at the cutting edge radius (1040x).

The 415x magnification was used to measure the wear length across the cutting edge radius (106µm). This can be observed towards the right hand side of the Figure 6.14.
Note that the large debris seen in both figures was not picked up from the machining operation. This debris is on the surface and not chipped diamond. This tool was used for pass 2 which was the 500nm depth of cut. The 1040x (Figure 6.15) magnification was used to attempt to find any rake and flank wear at the cutting edge radius (no wear was visible). Once again the large debris seen in the figure is on the surface and not chipped diamond.

Conclusion

The results show that ductile mode machining (using SPDT) is possible for the Spectrosil 2000 quartz material. The surface roughness of the Spectrosil 2000 had been reduced from 110nm (Ra), as received condition (surface prepared by grinding) to 41nm (Ra) in two machining passes. From the surface images, it is evident that there were no signs of brittle fracture and the surface was successfully improved with each pass. The tools held up for both passes and only slight wear was observed off the tool used in pass 1 whereas no rake and flank wear was observed off the tool used for pass 2. This is a result of lower cutting forces (shallower depth of cut) and a smoother surface to start off with in pass 2 (as a result of pass 1). These machining parameters will be recommended for a final 14” quartz disk (to be done by a commercial partner later in the project) in order to achieve a surface roughness of less than 50nm (Ra). From the existing tool wear pattern, it is predicted that a single tool will be able to hold up for an entire pass. Table 6.3 below shows the machining parameters suggested for the final 14” quartz disk machining.
Table 6.3: Recommended machining parameters for a 14” diameter quartz disk.

<table>
<thead>
<tr>
<th>Pass #</th>
<th>Actual Depth of Cut</th>
<th>Feed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>650nm</td>
<td>1μm/rev</td>
</tr>
<tr>
<td>2</td>
<td>350nm</td>
<td>1μm/rev</td>
</tr>
</tbody>
</table>

Note that these parameters are recommended assuming similar surface conditions as the 6” Spectrosil 2000 used in this project.
Concluding Remarks

It is important to understand the fracture toughness and corresponding material limits (fracture tolerance) in ceramics when attempting to machine them. Ceramics (i.e., SiC and quartz) are extremely brittle materials but can be successfully machined at the nano/micro scales. The results of this research confirmed that brittle materials (i.e. SiC and quartz) can be machined in the “ductile regime.”

It is also vital to establish ductile regime machining conditions for finishing and smoothing ceramics, as brittle mode behavior results in pitting, micro-cracks and uncontrolled subsurface damage. One of the first steps in attempting ductile mode machining is to establish/determine a critical depth of cut or the Ductile to Brittle Transition (DBT) of the material. The DBT of a material can be determined by performing cuts at the nano to micro scale on the material surface, which has been previously smoothed (generally by polishing) so as to be able to more readily determine the onset of fracture. One of the methodologies of determining the DBT of a single-crystal 4H-SiC wafer is demonstrated in this research (refer to Chapter 3). The DBT was determined by performing nanometric cuts and then analyzing those cuts using an AFM. Scratching tests with varying loads can also be performed on brittle materials (as done in the master’s thesis of Bhattacharya) to determine the DBT; however the diamond geometry may be different (from the machining process) and must be properly
evaluated. The results from the scratching tests were used as guidelines for the SPDT projects in this research. The Blake and Scattergood\textsuperscript{36} cutting model was used to determine the calculated critical depth of cut as a function of tool geometry and feed.

The first Single point diamond turning (SPDT) project (refer to Chapter 4) was carried out on the 6” CVD-SiC disk in an attempt to improve its surface roughness. SPDT was proven to be successful in smoothing CVD-SiC (Ra for SiC was reduced from 1158nm to 83nm) to enhance its optical properties so as to be used as an optical mirror in an Airborne Laser (ABL) device. Several passes were carried out to achieve a final surface roughness (Ra) of 83nm. Multiple machining passes are required because of the maximum depth of cut limitation (for each pass) that cannot exceed the critical depth of cut (550 nm for CVD SiC and 120 nm for Quartz) in order to achieve ductile-regime machining. All of the diamond tools held up (no tool failure) but tool wear was measured and reported for all machining passes.

In general, there are several parameters that can be adjusted in order to increase the material removal rate (MRR). However, in precision engineering applications such as precision machining, there are often trade-offs when increasing the MRR. An increase in feed can reduce the total machining time (increase material removal rate) and also reduce tool wear; however, a higher feed rate also results in higher surface roughness. For the SPDT experiments performed on the 6” CVD-SiC, a higher feed was used for the initial/roughing passes. The feeds and depth of cuts were decreased as the workpiece surface continued to improve (smoother surface and lower surface roughness). The trade off at lower feeds is that the measured tool wear is much more than at higher feeds due to
the longer track length covered by the tool at lower feeds the MRR is also less but the resultant surface finish is better compared to higher feeds.

There are various precision machining processes that are used to improve the surface finish of ceramics such as grinding, lapping, turning, polishing and laser ablating. In most cases, a combination of several techniques is used to obtain the surface finish and level of accuracy required. A combination of laser ablation and single point diamond turning of CVD-SiC was successfully performed in this research (refer to Chapter 5). This combination of both machining techniques worked well for specific laser ablation and machining parameters (these parameters are discussed in detail in Chapter 5). The laser process reduced the major peaks and valleys (improved the surface roughness) of the as-received surface. This resulted in a smoother surface and less tool wear after SPDT. The combination of methods can be used in order to achieve nanometric level surface finish/accuracy. For example, a fairly rough CVD-SiC disk can initially be laser ablated or ground, then diamond turned and finally polished to obtain a mirror finish surface.

The final study carried out in this research was to perform SPDT on a 6” quartz disk (Spectrosil 2000). The results form this experiment (refer to Chapter 6) confirmed that quartz (fused silica) can be machined under ductile conditions. The target surface roughness of less than 50nm was met with a total of two machining passes (Ra was reduced from 110nm to 41nm for the 6” Spectrosil 2000 quartz disk). Besides improving the surface roughness of the quartz disk, a tool wear analysis for both passes were carried out in order to predict tool life for SPDT a 14” disk (as part of the a nose cone for an ABL device). The tool wear data suggested that a single tool can be used for the entire
pass (one tool per pass) given similar surface conditions as the 6” quartz disk used in this project.

Results from this research also suggests that tool wear is a function of cutting force (generally lower forces result in less tool wear and better surface finish), depth of cut (the deeper the cut, the greater the cutting force and the larger the measured tool wear), surface roughness (the rougher the surface, the greater the wear), cutting speed (generally tool wear is less when machining closer to the center of the disk due to the lower cutting speed which is a function of the workpiece radius) and equipment stability (i.e., spindle vibration and workpiece runout). It is vital to eliminate tool chatter as it affects productivity, surface finish, and tool life. Cutting fluids, (CMP slurries were used in the research reported in this thesis) are used to reduce tool wear by minimizing the frictional force. Although theoretically it is almost impossible for a layer of cutting fluid to remain at the cutting edge (due to the extremely high pressure generated at the cutting edge radius), it is believed that the slurry helps to remove the machining debris/chips from the cutting region and chemically reacts and changes (perhaps chemically softening the surface which would reduce the cutting force and friction) the workpiece surface during the machining process.

Future Developments

Subsurface damage analysis will be carried out on all machined samples discussed in this thesis. Preliminary Raman spectroscopy was carried out on the 6” CVD-SiC and there were no signs of sub surface damage revealed (such as new or altered crystalline structure or phase changes). This work will be augmented with scanning
acoustic microscopy in order to determine subsurface damage of the machined regions for the SiC and Quartz samples. X-ray diffraction will also be performed to determine the crystal orientation (of the as received CVD SiC) and surface topography of the material. This information will then be used to determine if the observed DBT of CVD SiC is somehow related to a preferred machining direction with respect to the crystal structure/orientation, i.e. the material was much less brittle than expected (quote the actual numbers here), this result may be due to the preferential crystal orientation of the CVD SiC grains. The observation of the phase change (i.e. from crystalline (before machining) to amorphous (after machining) on the workpiece surfaces will be carried out using the Raman backscattering spectroscopy, x-ray diffraction and TEM (of machined chips). If these techniques are successful, it could then provide valuable insight on subsurface damage (if any) of single point diamond turned of ceramics. Finally, a Transmission Electron Microscopy (TEM) analysis will be carried out on the Quartz machining chips, similar to what has been done on SiC chips (Patten, Gao, 2005). This will help to confirm the ductile mode machining conditions, identify any phase transformations (i.e. polycrystalline or amorphous) and the material composition.

Several other tool and process parameters will be explored in the future in order to optimize the SPDT operation for a particular material (i.e. SiC and quartz) and process conditions (i.e. surface roughness). Tool parameters such as different tool manufactures, rake angles, edge and nose radius will be evaluated to determine if there is any preferred tool geometry to achieve mirror finish surfaces, and reduce tool wear when machining ceramics using SPDT. In the past, it has been reported that the tool nose radius plays a significant role in the surface finish of the workpiece (larger nose radius yields a better
surface finish). Process parameters such as cutting speeds, feeds and depths of cuts will be further evaluated to find the most efficient machining parameter combination to improve the quality, cost and time efficiency of this manufacturing process. An investigation on laser assisted machining of ceramics will be attempted (Lei Dong 2006). This technique will be carried out in an attempt to soften the material during SPDT to minimize tool wear and improve the surface roughness.

Other material conditions such as crystal structure (single crystal 3C-SiC), crystallographic plane and orientation effects of 4H and 6H, and orientation effects of CVD-SiC (relative to DBT) will be studied. These studies will perhaps help researchers understand the reason CVD-SiC does not appear to be as brittle as it is claimed to be (quote the DBT conditions). Finally, other cutting fluids (different manufacturers, chemistry and slurry particles) will be investigated to determine if the surface can be further softened chemically to reduce friction forces and reduce tool wear while cutting.
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58 http://www.buehler.com/productinfo/consumables/pdfs/FINAL_POLISHING.pdf


Appendix A

Material Properties of Single Crystal 4H-SiC, Polycrystalline CVD-SiC and Quartz
<table>
<thead>
<tr>
<th>Common Name</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mom's Hardness</td>
<td>~9</td>
<td>-</td>
</tr>
<tr>
<td>Crystal Structure</td>
<td>Hexagonal</td>
<td>-</td>
</tr>
<tr>
<td>Energy Bandgap</td>
<td>3.26</td>
<td>eV</td>
</tr>
<tr>
<td>Electric Field</td>
<td>2E6</td>
<td>V/cm</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>3.4</td>
<td>W/(cm.K)</td>
</tr>
<tr>
<td>Melting Temperature</td>
<td>1700</td>
<td>oC</td>
</tr>
<tr>
<td>Electron Drift Velocity</td>
<td>2E7</td>
<td>cm/sec</td>
</tr>
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</table>

Table A1: Material Properties of 4H-SiC wafer

<table>
<thead>
<tr>
<th>Common Name</th>
<th>CVD-SiC (SuperSiC-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, H</td>
<td>27</td>
</tr>
<tr>
<td>Young's Modulus</td>
<td>466</td>
</tr>
<tr>
<td>Density</td>
<td>3.18E6</td>
</tr>
<tr>
<td>Fracture Toughness, Kc</td>
<td>3E6</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>129</td>
</tr>
<tr>
<td>Melting Temperature</td>
<td>2500</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table A2: Material Properties of 3C (β) CVD-SiC

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Quartz(Spectrosil 2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, H</td>
<td>9.8</td>
</tr>
<tr>
<td>Young's Modulus</td>
<td>73</td>
</tr>
<tr>
<td>Density</td>
<td>2.21</td>
</tr>
<tr>
<td>Fracture Toughness, Kc</td>
<td>4E6</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>1.38</td>
</tr>
<tr>
<td>Melting Temperature</td>
<td>1700</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.17</td>
</tr>
<tr>
<td>Specific Heat Capacity</td>
<td>728</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.4585</td>
</tr>
</tbody>
</table>

Table A3: Material Properties of Quartz
Appendix B

Ductile to Brittle Transition
Depth Calculations
Based on Equation 2.4, the critical depth of a material can be calculated using the relation:

\[ dc \sim 0.15 \cdot \left(\frac{E}{H}\right) \cdot \left(\frac{K_c}{H}\right)^2 \]

where:

- \( dc \) = critical depth of cut
- \( E \) = elastic modulus
- \( H \) = hardness
- \( K_c \) = fracture toughness

Substituting the material properties from Appendix A into the above equation, the critical depth of the material can be calculated.

Sample critical depth calculation for CVD-SiC

\[ E = 466 \text{ GPa} \]
\[ H = 27 \text{ GPa} \]
\[ K_c = 3 \times 10^6 \text{ Pa.m}^{0.5} \]

Substituting the values:

\[ dc \sim 0.15 \cdot \left(\frac{(466 \times 10^9)}{(27 \times 10^9)}\right) \cdot \left(\frac{(3 \times 10^6)}{(27 \times 10^9)}\right)^2 \]

\[ dc = 3.8673 \times 10^{-8} \text{ m or 38.672 nm} \]
Sample critical depth calculation for Quartz (Spectrosil 2000)

\[ d_c \sim 0.15 \cdot \left( \frac{E}{H} \right) \cdot \left( \frac{K_c}{H} \right)^2 \]

\[ E = 73 \text{ GPa} \]
\[ H = 9.8 \text{ GPa} \]
\[ K_c = 4 \times 10^6 \text{ Pa.m}^{0.5} \]

Substituting the values:

\[ d_c \sim 0.15 \cdot \left( \frac{73 \times 10^9}{98 \times 10^8} \right) \cdot \left( \frac{4 \times 10^6}{98 \times 10^8} \right)^2 \]

\[ d_c = 1.785 \times 10^{-7} \text{ m} \text{ or } 178.50 \text{ nm} \]
Appendix C

Height and Feed Profile of Machined Region
Figure C1: An optical microscope image taken at 1000x showing the machined surface of SiC.

The feed marks at this point are visible and can be measured. In this case the feed marks measured corresponded with the programmed feed rate (1µm/rev). The rough area seen around the feed marks are above the smooth (where the feed marks are obvious) area. The feed marks and profile height was picked up by the surface profilometer.
Figure C2: The 1µm/rev measured feed marks.

These feed marks were measured (measurement seen on the x-axis) on the surface of the workpiece using a surface Profilometer. These feed marks are also seen in Figure C1.

Figure C2: The high spots measured on the SiC surface.

The height measured is approximately 145nm which is shown on the y-axis of Figure C2. This confirms that the rough areas seen in Figure C1 are higher than the smoother areas (where the feed marks can be seen).
Appendix D

6" CVD-SiC Surface Images
Figure D1: Machined surface of CVD-SiC

Figure D1 compares the machined surface after pass 11 (right) and pass 12 (left) at a 400x magnification. The image shows a more reflective (indicating a smoother surface) surface after pass 12 was carried out on the 6” CVD-SiC.

Figure D2: Smooth machined surface of CVD-SiC

The image (1000x magnification) above shows a smooth and reflective surface after the final machining pass was carried out on the CVD-SiC (Ra = 83nm).
Appendix E

Feed Marks Measurement on
Surface Profilometer
Figure E1: 1µm/rev feed marks measured on CVD-SiC using a surface profilometer.

Figure E2: 5µm/rev feed marks measured on CVD-SiC using a surface profilometer.