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

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## ABSTRACT

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, 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).

## INTRODUCTION

Silicon carbide is used in specialized industries due to its excellent mechanical properties such as extreme hardness, high wear resistance, high thermal conductivity, high electric field breakdown strength and high maximum current density.[1] The fully dense cubic (beta) polycrystalline silicon carbide CVD coating (≈250µm thick) is a potential candidate to be used as mirrors for surveillance, high energy lasers (such as airborne laser), laser radar systems, synchrotron x-ray, vacuum ultraviolet (VUV) telescopes, large astronomical telescopes and weather satellites.[2] 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 silicon carbide is extremely challenging due to its extreme hardness (≈27 GPa) and brittle characteristics. Besides the low fracture toughness of the material, severe tool wear 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.[3] Single point diamond turning (SPDT) was chosen as the material removal method as SPDT offers better accuracy, quicker fabrication time and lower cost when compared to grinding and polishing.[4] Although SiC is naturally 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.[5] The plastic deformation or plastic flow of the material, at the atomic to micro scale, occurs in the form of severely sheared` machining chips caused by highly localized contact pressure. Figure 1 shows a graphical representation of the highly stressed area that result from ductile regime machining.

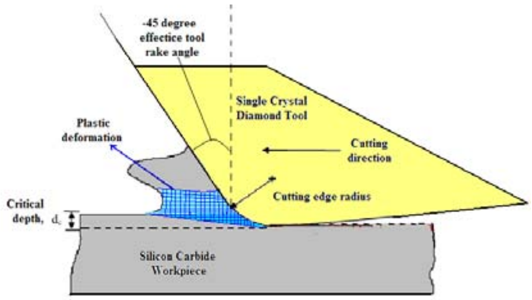


**Figure 1: A ductile cutting model showing the high compressive stress and plastically deformed material behavior in brittle materials.**

A critical depth, $d_c$ is determined before any ductile mode machining operation is carried out. Any depth beyond or exceeding the critical depth, also known as the Ductile to Brittle Transition (DBT) depth, will result in a brittle cut. The primary purpose of this research was to improve the surface roughness of a CVD coated SiC disk by SPDT in the ductile regime. The experimental process and results of this investigation will be discussed in this paper. 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.

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 (Micro-Tribometer by CETR) 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[6] ductile regime machining model (as shown in Figure 2) 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. [7]

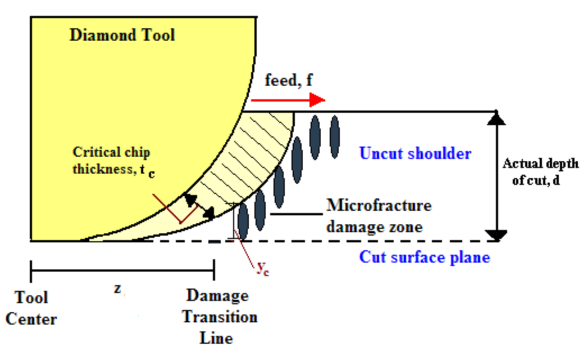


**Figure 2: Model for ductile regime machining.**

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

## EXPERIMENTAL METHOD

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* 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.[8]

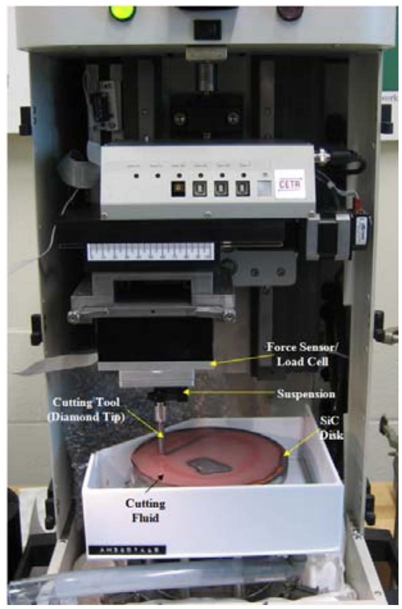


**Figure 3: Machining Setup for the 6" CVD coated SiC disk**

### *Final machining of a 6" CVD coated SiC*

Results from previous experiments which involved scratching and SPDT of CVD SiC, were used as guidelines to establish the experimental plan for an initial set of machining tests. [2,9] Several tests were conducted on polished and as received CVD-SiC to observe the equipment stability, tool condition after machining, thrust force and depth of cut correlation and surface finish of the workpiece after machining.

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 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.

Once reliable data was obtained from the preliminary tests, the machining parameters for the final machining on the 6" SiC disk were determined. Table 1 shows the planned machining parameters for the 6" CVD coated SiC.

**Table 1: Machining parameters for the 6" CVD coated SiC**

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

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

### *Final machining of a 6" CVD coated SiC*

Based on the results from all the test experiments, the final machining was carried out. The results for the final machining experiment are discussed in this section. 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, 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, 5 and 6).

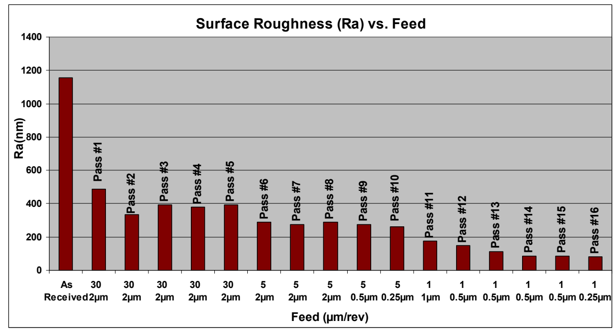


**Figure 4: Surface roughness values as a function of feed for all the machining passes carried out on the final machining experiment.**

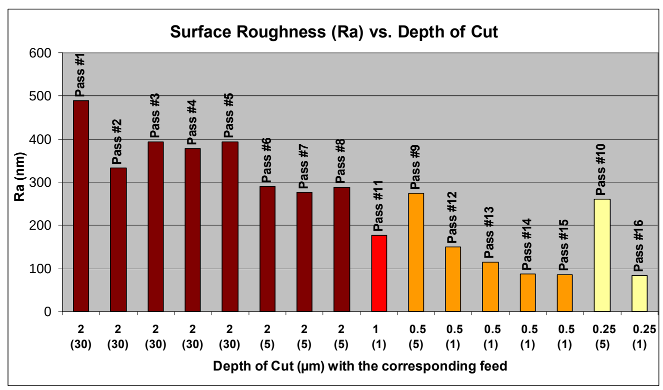


**Figure 5: Surface roughness values as a function of the depth of cut for all the machining passes carried out on the final machining experiment.**

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 and 5 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 11 where the significant drops in Ra happen when the feed rate is reduced. This trend is not observed in Figure 5 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 5, 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. In Figure 6, 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.

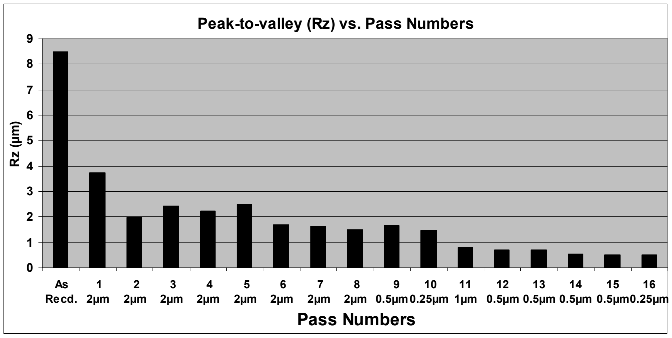


**Figure 6: Peak-to-valley values for all machining passes and their corresponding programmed depths of cuts.**

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. 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.

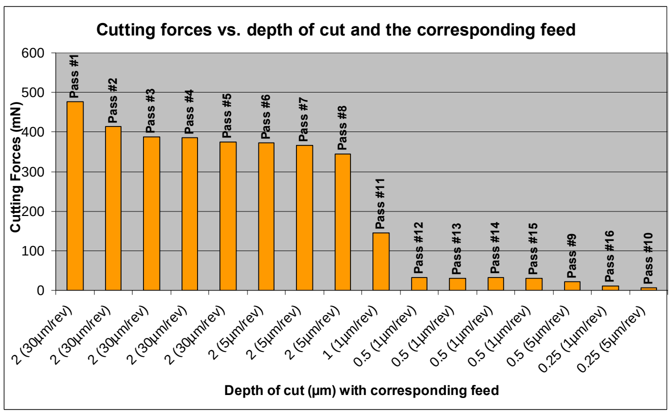


**Figure 7: Cutting forces for various passes carried out for the final machining experiment with their corresponding depth of cut and feed in parenthesis.**

The deeper cuts (2µm) have higher forces compared to the 1µm 500nm, and 250nm depths of cut as shown in Figure 7. 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).

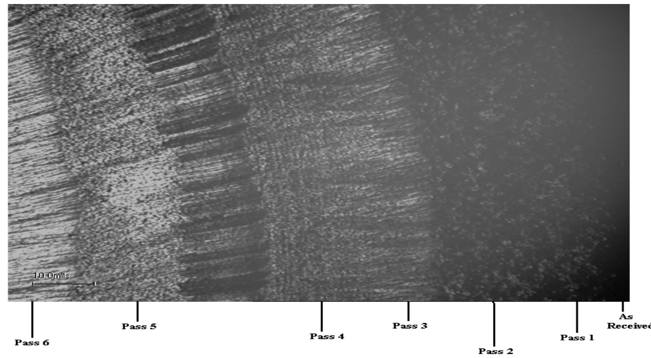


**Figure 8: An optical image of various passes taken under a microscope at 50x magnification. The region between Pass 4 and 5 was a result of tool chatter (the experiment was aborted as soon as tool vibration was detected).**

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 8). Figure 8 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.

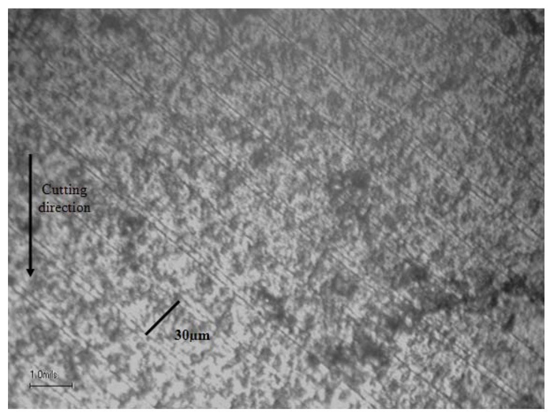


**Figure 9: An optical microscope image showing the feedmarks (30µm) on the workpiece surface Image was taken at a magnification of 400x.**

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 9. 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).

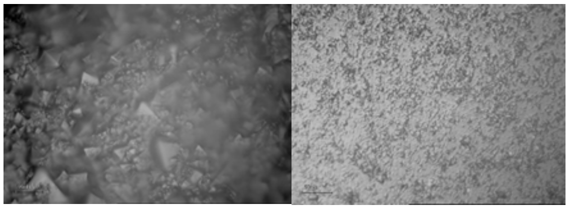

**Figure 10: Optical images comparing the surface finish of the as received workpiece (left) and the surface after pass 11 (right). This image was taken at 1000x magnification.**

From Figure 10, 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.

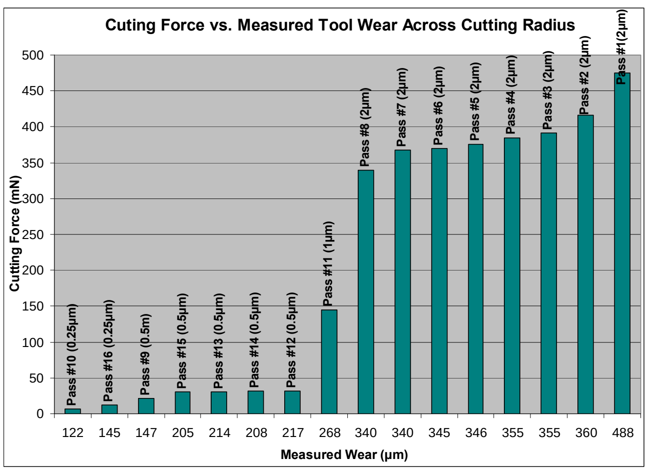


**Figure 11: The cutting force as a function of the horizontal wear length measured across the tool cutting edge radius (refer to figure 13). The corresponding pass numbers and depth of cuts are indicated in parentheses**

The horizontal wear measured (shown in Figure 11) 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%.

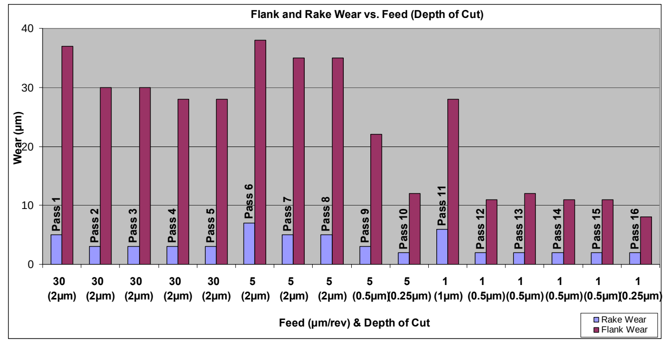


**Figure 12: Measured rake and flank wear at the cutting edge for various feed rates and their corresponding depths of cuts indicated in parentheses.**

The rake and flank wear is a function of both feed and depth of cut, but from Figure 12 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 12 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.

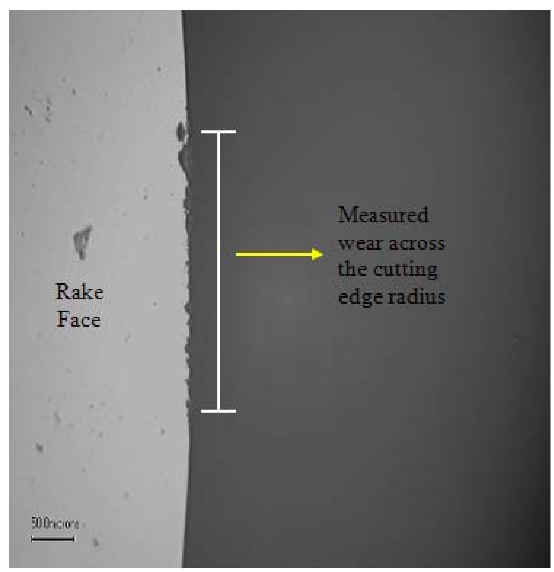


**Figure 13: An image of a flattened tool tip taken under an optical microscope at 200x.**

The wear length across the cutting radius can be measured from Figure 13 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.

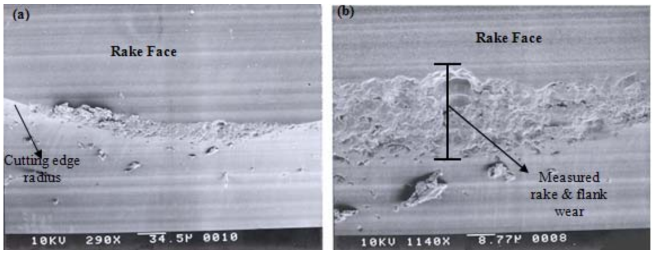


**Figure 14 (a) & (b): SEM images of the cutting edge of the diamond tool after machining.**

Figure 14(a) was taken at 290x and Figure 14 (b) was taken at 1140x. This tool was used in for Pass #1 (also know as the roughing pass) where the programmed depth of cut was 2µm with a 30µm/rev feed. The large measured wear on the tool is due to the initial rough surface of the disk.

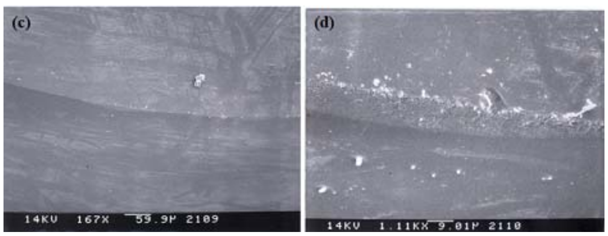


**Figure 14 (c) & (d): SEM images of the cutting edge radius of the diamond tool after machining (Pass #16; 250nm depth of cut with a 1µm/rev feed).**

Comparing Figures 14(a) & (b) with (c) & (d), we see that the wear observed in images (c) and (d) 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 14(a) is taken at 290x magnification in order to measure the entire horizontal wear across the cutting edge. Figure 14(b) 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.

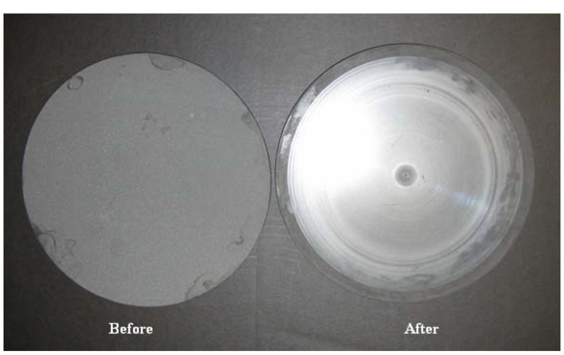


**Figure 15: The figure above compares the 6" CVD-SiC before SPDT was carried out (left) and after the SPDT operation was carried out (right).**

Note that the machined disk is more reflective, indicating a better surface finish (lower Ra) than the as received disk (illustrated in Figure 15). 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 1158nm to 83nm*)*. 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 2: Recommended machining parameters for improving surface quality of a CVD coated SiC disk by single point diamond turning.**

| Pass # | Actual Depth of Cut | Feed (µm/rev) |
|---|---|---|
| 1 | 1.3µm | 30 |
| 2 | 1.2µm | 30 |
| 3 | 845nm | 5 |
| 4 | 255nm | 1 |
| 5 | 210nm | 1 |
| 6 | 160nm | 1 |

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 2. The best surface finish was obtained with the lowest feed rate attempted (1µm/rev) but initially a higher feed rate was used (30µm/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 12), but the resultant surface finish is improved (refer to Figure 4). 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 2.

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