

Ductile regime single point diamond turning of CVD-SiC resulting in an improved and damage-free surface.

Deepak Ravindra* and John Patten**

* Mechanical and Aeronautical Engineering
Western Michigan University
Kalamazoo, MI-49008, USA.

Email: deepak.ravindra@wmich.edu

** Manufacturing Engineering (Director)
Western Michigan University
Kalamazoo, MI-49008, USA.

Email: john.patten@wmich.edu

Abstract

Silicon carbide (SiC) is one of the advanced engineered ceramic 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 or optical properties that benefit the semiconductor, MEMS and optoelectronic industry respectively. Manufacturing this material is extremely challenging due to its high hardness, brittle characteristics and poor machinability. Severe fracture can result when trying to machine hard brittle materials like SiC due to its low fracture toughness. However, from past and current research efforts, it has been proven that ductile regime machining of nominally 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, to be used as optics devices (mirrors), via single point diamond turning (SPDT). Sub-surface damage analysis was carried out on the machined sample using non-destructive methods such as Raman spectroscopy and Scanning Acoustic Microscopy. Surface roughness (Ra) values of less than 88 nm (for CVD coated SiC), without sub surface damage were obtained. In addition to improving the surface roughness of the material, the research also emphasized increasing the material removal rate (MRR) and minimizing the diamond tool wear. Machining parameters that make this manufacturing process more time and cost efficient were also identified.

Keywords: 3C Beta CVD silicon carbide (SiC), subsurface damage, Nanomanufacturing

1.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 (manufactured by POCO Graphite) CVD coating $\approx 250\mu\text{m}$ 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, 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.

The mechanics of material removal in SiC 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 extremely brittle materials such as glasses do not necessarily behave as a brittle material (even at room temperature) especially at the nanometric scale.^{3,4,5} The strength, hardness and fracture toughness of the work piece material are the governing factors that control the extent of brittle fracture.⁶ Some studies include observations of a small amount of plastic deformation in brittle materials during a precision machining operation.⁷

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.⁸ 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.⁹ 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.¹⁰ 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 and shear stress.

2.0 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 1* shows the equipment setup for the 6" CVD coated 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.¹¹

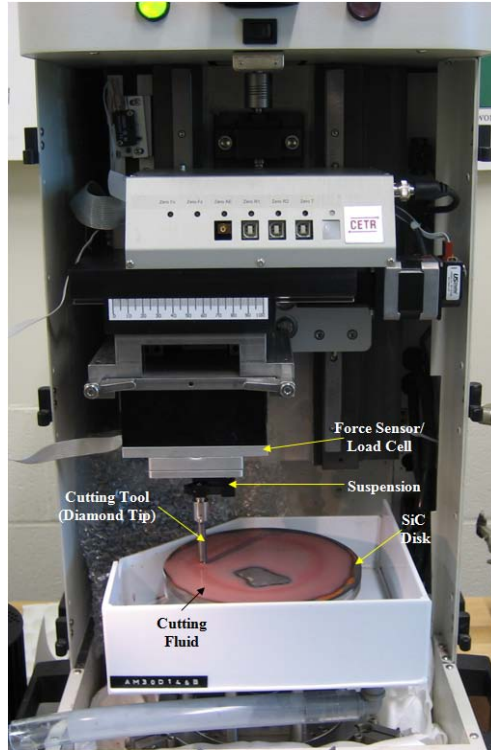


Figure 1: Machining Setup for the 6" CVD coated SiC disk

2.1 Final machining of the 6" CVD coated SiC

The preliminary single point diamond turning experiments were successful in reducing the surface roughness of a CVD coated silicon carbide disk.¹² The Ra was brought down by over one order of magnitude (*from 1158nm to 83nm*). 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) were eliminated to make the actual production process more cost and time efficient.

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

Table 1: Recommended machining parameters for improving surface quality of a CVD coated SiC disk by SPDT.

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 1*.

3.0 Results

3.1 Final machining of a 6” CVD coated SiC

All six machining passes carried out for the final machining experiment were successful. This section discusses the results for the final machining of the 6” CVD-SiC. *Figure 2* shows the surface roughness data for all passes.

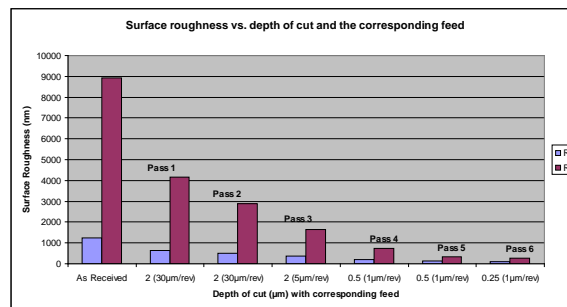


Figure 2: Surface roughness with their corresponding depth of cut and feed in parenthesis.

The results suggest that the surface roughness improved after every machining pass. The trend was consistent with the results obtained in the preliminary machining experiment where the Ra value decreased as the peak-to-valley (Rz) value decreased. The surface roughness (Ra) was reduced from 1.23µm to 88nm in six passes. *Figure 3* shows the cutting force with the corresponding feed and depth of cut for all six passes.

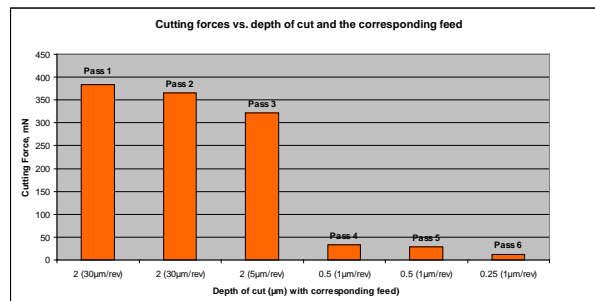


Figure 3: Cutting forces with their corresponding depth of cut and feed in parenthesis.

The cutting force constantly decreased after each pass. The main drop in cutting forces is observed in pass 4 due to the lower depth of cut. Cutting forces are a function of surface roughness (higher cutting forces due to rougher surfaces), depth of cut and feed. However, as seen in Figure 3, the most dominant parameter that influences the cutting force is the depth of cut (deeper cuts yield in higher cutting forces).

The final study done for the final machining was on the tool wear. *Table 2* shows the tool wear data for the respective machining conditions.

Pass	Fx (mN)	Depth of Cut (μm)	Feed	Length across the cutting radius (μm)	Rake Wear μm	Flank Wear μm
1	383.18	2 μm	30 $\mu\text{m}/\text{rev}$	370	6	36
2	364.83	2 μm	30 $\mu\text{m}/\text{rev}$	360	4	29
3	321.67	2 μm	5 $\mu\text{m}/\text{rev}$	343	3	27
4	32.67	500nm	1 $\mu\text{m}/\text{rev}$	220	2	14
5	28.37	500nm	1 $\mu\text{m}/\text{rev}$	218	2	11
6	11.48	250nm	1 $\mu\text{m}/\text{rev}$	155	2	9

Table 2: Tool wear data for the machining passes carried out

A new tool was used for every pass and there were no tool failures reported for either of the machining passes. In general, the tool wear data shows that the wear length across the cutting edge radius is directly proportional to the depth of cut (the deeper the depths of cut, the longer the measured wear across the cutting radius). The rake and flank wear are both a function of surface roughness, depth of cut and feed. In all six passes, the measured flank wear was more than the measured rake wear due to the larger contact area between the flank face of the tool and the workpiece.

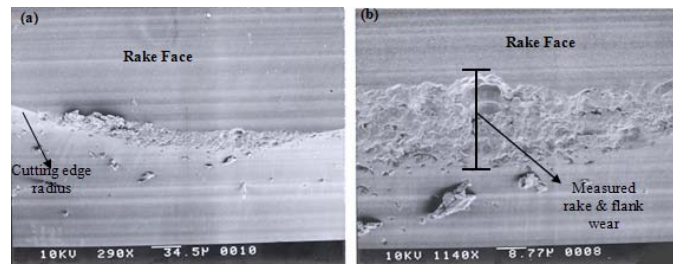


Figure 4 (a) & (b): SEM images of the cutting edge of the diamond tool after machining.

Figure 4(a) was taken at 290x and *Figure 4 (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 2 μm with a 30 $\mu\text{m}/\text{rev}$ feed. The large measured wear on the tool is due to the initial rough surface of the disk.

4.0 Subsurface Damage Analysis

Since SiC undergoes an extremely high pressure phase transformation during machining, it is possible that subsurface damage occurs in this brittle material without any indication of surface damage. Two different non destructive techniques were used to investigate the subsurface damage of the machined SiC; laser micro-Raman spectroscopy and scanning acoustic microscopy (SAcM).

4.1 Laser micro-Raman Spectroscopy

Laser Raman spectroscopy is a well known non destructive characterization technique often used for semiconductors. A 633nm wavelength He-Ne laser was used to study the sub-surface of the machined. The main purpose of the Raman spectroscopy in this study is to attempt to detect the amorphous layer beneath the machined surface.

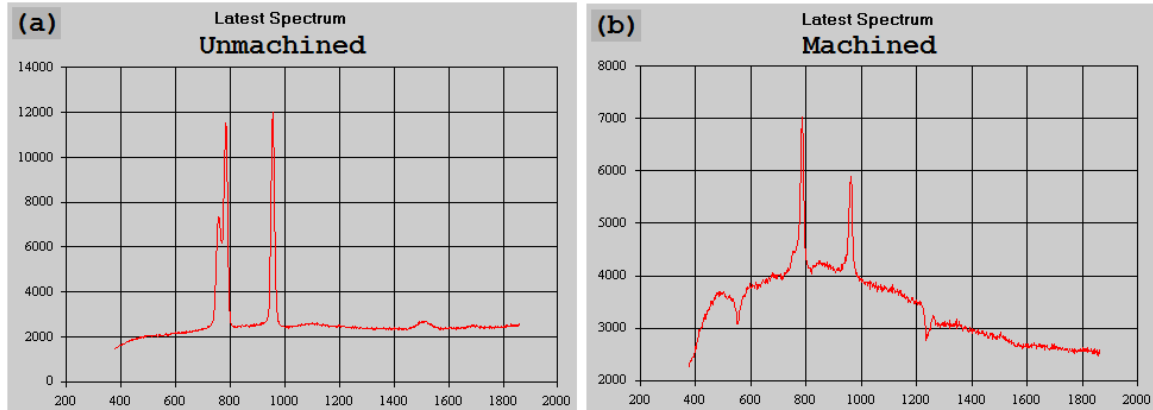


Figure 5: micro-Raman laser spectrum of the unmachined SiC (a) and the machined SiC (b) surfaces.

In *Figure 5(a)*, the spectrum shows the crystalline peaks of the unmachined SiC sample. Comparing these peaks with *Figure 5 (b)*, it is seen that a combination of the crystalline peaks (sharp peaks) and amorphous peaks (broadband peaks) are formed in the machined surface. The amorphous layer is a good indication of a ductile material removal process. In general, the thickness of the amorphous layer increases as the depth of cut is increased.

4.2 Scanning Acoustic Microscopy (SAcM)

SAcM is widely used in non-destructive evaluation (NDE) of materials as its high-frequency acoustic waves (60MHz to 2.0GHz), enables the waves to travel beneath the surface revealing surface topography, subsurface features and material properties.¹³ The Kramer Scientific Instruments (KSI) SAM2000 scanning acoustic microscope at the Oak Ridge National Labs (ORNL) was used for this study. The main purpose SAcM was carried out was to investigate subsurface cracks and fracture after SPDT if any.

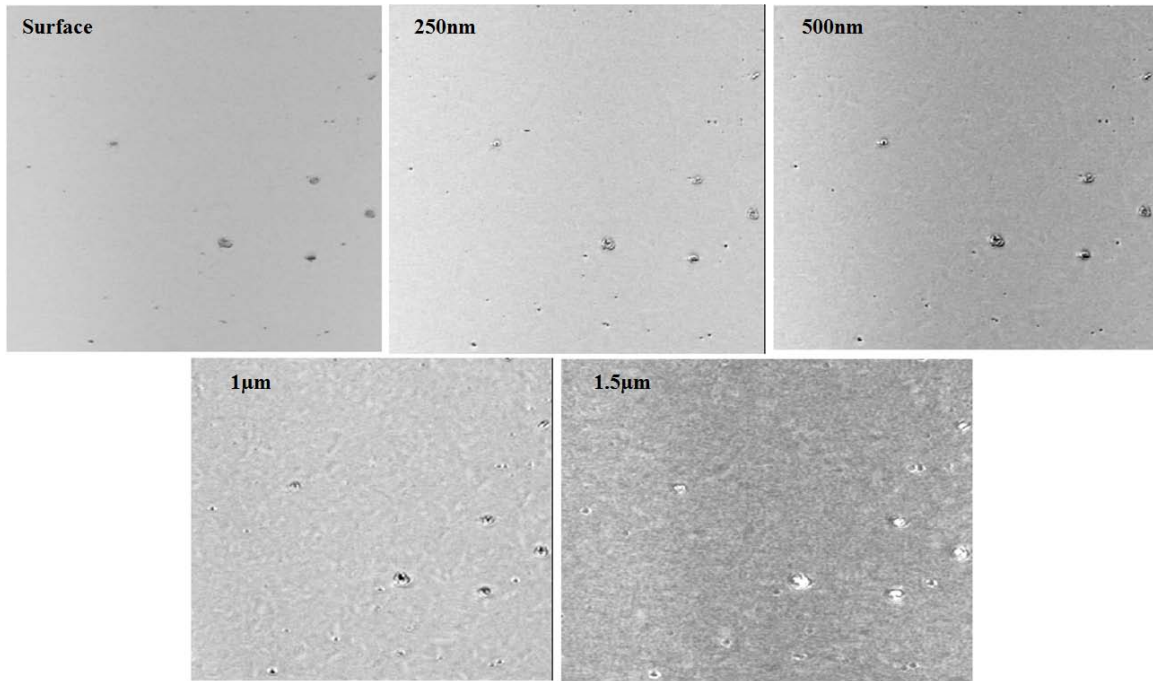


Figure 6: A sequence of images of the machined SiC sample (first image shows the surface and the numbers on the top left of each image represents the scanned depth beneath the machined surface).

The acoustic microscopy images show now signs of subsurface cracks or damage. The surface features seen in the images in *Figure 6* are pits and voids that existed in the as received material and were not caused by the SPDT operation.

5.0 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 1.23µm to 88nm*). 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).

A total of 6 passes have been suggested and successfully carried out 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 machining experiment. 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, but the resultant surface finish is improved. 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*. Both subsurface damage techniques showed complimenting results where no signs of brittle material removal was detected. SPDT was successful in improving the surface of SiC without causing surface and subsurface damage. *Figure 7* compares the CVD-SiC surface before and after the machining is carried out. 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)

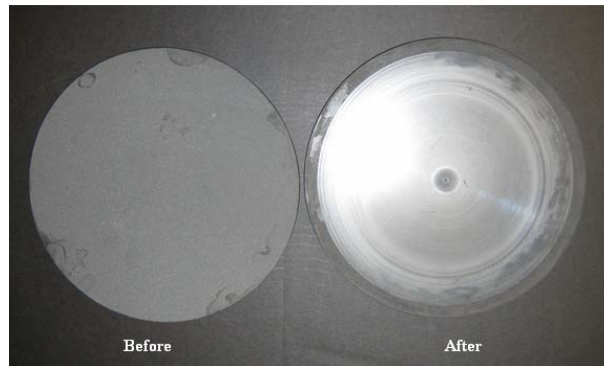


Figure 7: The figure above compares the 6” CVD-SiC before SPDT was carried out (left) and after the SPDT operation was carried out (right).

6.0 References

- ¹ Deepak Ravindra, John Patten and Makoto Tano, 2007, “Ductile to Brittle Transition in a Single Crystal 4H SiC by Performing Nanometric Machining”, ISAAT 2007 Precision Grinding and Abrasive Technology at SME International Grinding conference, Advances in Abrasive Technology, X, pp 459-465.
- ² Biswarup Bhattacharya, 2005, “Ductile Regime Nano-Machining of Polycrystalline Silicon Carbide”, Masters Theses, Western Michigan University.
- ³ Y. Ishida, G. Ogawa, 1962, Japanese Journal of Mechanical Engineering Laboratory, .v8, (1), pp.15-30.
- ⁴ D.M. Marsh, 1964, “Plastic Flow and Fracture of Glass”, Proc. R. A, v282, pp.33-43
- ⁵ F.M. Ernsberger, 1968, “Glasses Under Point Loading”, Journal of the American Ceramic Society , v51, pp.545-547
- ⁶ R. Komanduri, 1996, “On Material Removal Mechanisms in Finishing of Advanced Ceramics and Glasses “, Annals of the CIRP (College International pour la Recherche en Productique), v45, p.509.
- ⁷ M.A. Moore, F.S. King, 1980, “Abrasive wear of brittle solids “, Wear, v60, pp.123-130
- ⁸ Chunhe Zhang, Teruko Kato, Wei Li and Hitoshi Ohmori, 2000, “A Comparative Study: Surface Characteristics of CVD-SiC Ground with Cast Iron Bond Diamond Wheel”, International Journal of Machine Tools and Manufacture, Vol 40, pp 527-537
- ⁹ FZ Fang, XD Liu, LC Lee, 2003, “Micro-machining of Optical Glasses- A Review of Diamond- Cutting Glasses”, Indian Academy of Sciences, Vol 28, Part 5.
- ¹⁰ John A. Patten, W. Gao and K.Yasuto, 2005, Ductile Regime Nanomachining of Single-Crystal Silicon Carbide, ASME, v127, pp 522- 532.
- ¹¹ http://www.buehler.com/productinfo/consumables/pdfs/FINAL_POLISHING.pdf
- ¹² Deepak Ravindra and John Patten, “Improving the Surface Roughness of a CVD Coated Silicon Carbide Disk by Performing Ductile Regime Single Point Diamond Turning”, Proceedings of the 2008 International Manufacturing Science and Engineering Conference.
- ¹³ Jun Qu, Peter Blau, Albert Shih, Samuel McSpadden, George Pharr and Jae-il Jang, 2004, “Scanning Acoustic Microscopy for Non-Destructive Evaluation of Subsurface Characteristics”.