Improving the Surface Roughness of a CVD Coated Silicon Carbide Disk By Performing Ductile Regime Single Point Diamond Turning

Deepak Ravindra  
(Department of Mechanical & Aeronautical Engineering)  
&  
John Patten  
(Department of Manufacturing Engineering)

Manufacturing Research Center
Presentation Overview

- Introduction
- Research Background
- Preliminary Machining on CVD-SiC
- Final Machining on CVD-SiC
- Past, Ongoing & Upcoming work
Ductile Regime Machining of Ceramics

• Plastic flow of material in the form of severely sheared machining chips occur

• Possible due to High Pressure Phase Transformation (HPPT) or direct amorphization

• Plastic deformation caused from highly localized contact pressure and shear stresses.

• High pressure (metallic) phase could be used to improve manufacturing processes and ductile response during machining.
Ductile Regime Machining of Ceramics

- DBT is calculated based on material properties
- Depth exceeding critical depth will result in brittle machining
- Micro-cracks / surface damage depth, $y_c$ should not extend beyond the cut surface plane

Model proposed by Blake & Scattergood
Critical Depth of Cut ($d_c$)

- Griffith fracture propagation criteria:
  $$d_c \sim 0.15 \cdot \frac{E}{H} \cdot \left(\frac{K_c}{H}\right)^2$$

where:
- $0.15$ = estimated constant of proportionality
- $E$ = elastic modulus
- $H$ = hardness
- $K_c$ = fracture toughness
Why Use Silicon Carbide?

- Extreme hardness (~27GPa for 3-C β Polycrystalline CVD coated)
- High wear resistance
- High thermal conductivity
- High Temperature Operation
- Wide energy bandgap
- High electric field breakdown strength
- High maximum current density
- High saturated electron drift velocity
Project Goals

• Improve surface finish (surface roughness) via ductile mode machining

• Increase material removal rate (MRR) by altering:
  – Feed
  – Depth of Cut
  – Cutting Speed

• Minimize diamond tool wear

• Minimize/Eliminate sub-surface damage

*Establish machining parameters to meet all three criteria's (project goals)
Concept of improving surface roughness

1. Initial surface with a rough SiC surface.
2. Diamond tool cutting along the direction to improve the surface roughness.
3. Final surface with improved roughness after the cutting process.
Improving the Surface Roughness of a CVD-SiC by Performing Ductile Regime SPDT

• 6” disk from POCO Graphite Inc. was used (3-C, β Polycrystalline)

• Mirror finish surface required

• To be used as optic mirrors in an Airborne Laser (ABL) device

• CVD coated SiC is preferred because:
  – High Purity (>99.9995%)
  – High Density (99.9%)
  – Homogeneity
  – Chemical & Oxidation Resistance
  – Good Cleanability & Polishability
  – Good Thermal & Dimensional Stability
Experimental Procedure

- Initial matrix designed (with varying depths of cuts and feeds)
- Preliminary machining on 6” CVD-SiC (as-received)
- Final experimental matrix is designed based on preliminary machining results
- Final machining on 6” CVD-SiC
Experimental Setup for SPDT
SPDT of SiC
Preliminary Machining Results (surface roughness & feed correlation)

- Ra improved from 1.16µm to 83nm
- Feed is more dominant than depth of cut when improving surface roughness
- Feed is reduced when surface roughness does not improve
Preliminary Machining Results \((Rz \text{ for all machining passes})\)

- Rz improved from 8.49µm to 0.51µm
- The Rz value was used to determine the required depth of cut
- The feed and/or depth of cut is reduced when the Rz value does not improve.
Preliminary Machining Results *(Cutting force vs. depth of cut)*

- Depth of cut, feed and surface roughness influence the cutting forces
- Depth of cut is the dominant parameter
Results *(Surface image of 6 passes)*

- Image was taken at 50x magnification
- Surface continuously improved after each pass
- Band between pass 4 & 5 was due to tool chatter
Results *(Surface image comparison)*

- Images comparing the surface before (left) and after (right) SPDT
- Images were taken at a 1000x magnification
- The sharp/uneven peaks on the surface disappeared after the SPDT operation
Preliminary Machining Results (Cutting force vs. tool wear across cutting edge)

- Wear across cutting edge radius is a function of depth of cut
- Wear length and cutting forces increase as depth of cut increases
Choosing Machining Parameters for Final Pass

Surface Roughness (Ra) vs. Feed

Feed (µm/rev)

Ra (nm)

As Received 2µm

Pass #1 30 30

Pass #2 30 30

Pass #3 30 30

Pass #4 30 30

Pass #5 30 30

Pass #6 2µm 2µm

Pass #7 2µm 2µm

Pass #8 2µm 2µm

Pass #9 2µm 2µm

Pass #10 2µm 2µm

Pass #11 0.5µm 0.5µm

Pass #12 0.5µm 0.5µm

Pass #13 0.5µm 0.5µm

Pass #14 0.5µm 0.5µm

Pass #15 0.25µm 0.25µm

Pass #16 0.25µm 0.25µm

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### Final Machining Parameters

<table>
<thead>
<tr>
<th>Pass #</th>
<th>Depth of Cut</th>
<th>Feed (µm/rev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2µm</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>2µm</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>2µm</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>500nm</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>500nm</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>250nm</td>
<td>1</td>
</tr>
</tbody>
</table>

- Recommended machining parameters for commercial manufacturing of CVD-SiC
- The actual depths are usual about 50% of the programmed depths of cuts (due to elasticity)
- Best surface finish is achieved from the lowest feed
Results for final machining (surface roughness)

Surface roughness vs. depth of cut and the corresponding feed

- Ra improved from 1.23µm to 88nm in six passes
- Rz improved from 8.9µm to 0.27µm
- Workpiece in general had lesser run-out due to flatter back
Results for final machining (cutting forces)

- Larger depths of cuts result in larger cutting forces
- Forces can also increase due to rough surfaces, machining debris, tool vibration, workpiece run-out, etc
- Cutting fluid helps several problems such as machining debris
Results (SEM images of tool wear)

- Tool was used for pass 1 (2µm depth & 30µm/rev feed)
- SEM images are used to measure tool wear
  - Wear length across cutting edge
  - Rake wear
  - Flank wear
Results (6” disk before & after SPDT)
## Ductile Machining vs. Brittle Machining

<table>
<thead>
<tr>
<th>Ductile</th>
<th>Brittle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well defined &amp; straight edges</td>
<td>Jagged edges &amp; chipped material</td>
</tr>
<tr>
<td>Controlled material removal process</td>
<td>Hard to control as microcracks extend below the machined surface</td>
</tr>
<tr>
<td>Final depth of cut can be predicted below the DBT depth</td>
<td>No direct control of the resultant depth beyond the DBT depth</td>
</tr>
<tr>
<td>Good surface finish and mechanical properties</td>
<td>Poor surface finish and could end in a catastrophic failure at times</td>
</tr>
</tbody>
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Other projects accomplished

- **Ductile to Brittle Transition (DBT) of single crystal 4H SiC**
  - Nanometric cuts are performed on wafer
  - Cuts were imaged using AFM

- **Developing a hybrid laser-SPDT machining process for smoothing ceramics**
  - CVD-SiC is laser ablated with various parameters
  - SPDT is carried out on the ablated plateaus
  - Best combination is chosen based on smoothest surface achieved, longest tool life and minimum cutting forces obtained.

- **SPDT of Quartz (Spectrosil 2000)**
  - Establish machining parameters to SPDT a 14” piece

- **Subsurface damage analysis on all SPDT work pieces**
  - Scanning acoustic microscopy (ORNL)
  - Raman spectroscopy (WMU)
  - No subsurface damage was identified

- **Ductile to Brittle Transition depth of AlTiC**
  - Scratch tests using variable loads
  - Cuts were imaged using AFM, while light Interferometer & profilometer
Use of final SiC & Quartz disk

- To be used as ABL device nose cover
- Mirror finish surface required for the above use
- Image courtesy of Boeing Corporation

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Ongoing Work

- Micro Laser Assisted Machining (µLAM) on single crystal SiC
  - Study the effect of heating (from laser)/softening of material and combining it with SPDT

- Identifying crystal orientation & preferred machining direction (if any) for CVD-SiC
  - X-ray Diffraction and Orientation Imaging Microscopy (OIM) to identify crystal orientation
  - Scratch tests on single crystal SiC wafers to observe ductile to brittle transition (DBT)

- SPDT of Spinel
  - Establishing the DBT of the material
  - Developing machining parameters
  - Attempting to improve the surface roughness via ductile regime machining
Future Developments

• Transmission Electron Microscopy on SiC & quartz machined chips

• Experiment other tool & machining parameters (i.e. rake angle, tool nose radius, depth of cut and feed)

• Attempt to design a more efficient/accurate ductile machining model

• Experiment on simultaneously machining brittle materials with the assistance of thermal softening (laser).

• Analyzing Acoustic Emission signal to identify fracture of the material
Thank you