SPDT Effects on Surface Quality & Subsurface Damage in Ceramics

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Presentation Overview

• Brief intro on ceramics

• Research Background
  – Research Goals
  – Concept of Ductile Regime Machining

• Single Point Diamond Turning Experiments
  – CVD-SiC
  – Quartz (Fused Silica)

• Subsurface Damage Analysis (Nondestructive Techniques)
  – Laser Raman Spectroscopy
  – Scanning Acoustic Microscopy

• Ongoing & Upcoming work
Ceramics worked on:

• Silicon Carbide
  – 4H Single Crystal
  – 6H Single Crystal
  – 3C Polycrystalline (CVD)

• Quartz (Fused Silica)

• Spinel (MgAl\textsubscript{2}O\textsubscript{4})

• AlTiC

• Sapphire (synthetic)

• AlON
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

• Note: Extreme brittle characteristics due to low fracture toughness
Why Use Quartz?

- High hardness (~9.8GPa)
- Large supply (most abundant non-metallic mineral on earth)
- Good optical properties (optical range from 180nm to 2000nm)
- Synthetic fused silica can be manufactured using an environmentally friendly process

Note: Extreme brittle characteristics due to low fracture toughness
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 criteria (project goals)*
Ductile Regime Machining

• 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.

• DBT of materials (Quartz and SiC) <1μm
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:
  $$d_c \sim 0.15 \cdot (E / H) \cdot (K_c / H)^2$$

where:
0.15 = estimated constant of proportionality
E = elastic modulus
H = hardness
$K_c$ = fracture toughness
Concept of improving surface roughness
Single Point Diamond Turning of CVD-SiC
SPDT of SiC
Machining Parameters

<table>
<thead>
<tr>
<th>Pass #</th>
<th>Depth of Cut</th>
<th>Feed (µm/rev)</th>
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<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>

- 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 (with a low depth of cut)
Results for final machining (surface roughness)

- Ra improved from 1.25µm to 85nm in 6 passes
- Rz improved from 9.0µm to 250nm
- Target Ra (Ra<100nm) achieved in 6 passes
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
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 (3mm nose radius)
  - Rake wear (-45 degrees rake angle)
  - Flank wear (5 degrees clearance angle)
Results (6” disk before & after SPDT)
Single Point Diamond Turning of Quartz (Spectrosil 2000)
Results *(surface roughness)*

- A total of two passes were carried out to achieve the targeted Ra (achieved Ra~40nm).
- A feed of 1µm/rev was used for both passes.

![Surface Roughness After SPDT](image)

- As Received
  - Surface Roughness (Ra): 1200 nm
  - Surface Roughness (Rz): 1300 nm
- Pass 1 (1µm)
  - Surface Roughness (Ra): 800 nm
  - Surface Roughness (Rz): 900 nm
- Pass 2 (500nm)
  - Surface Roughness (Ra): 300 nm
  - Surface Roughness (Rz): 400 nm
Results *(Quartz surface images)*

- Images comparing the surface after Pass 1 and 2 were carried out.
- No signs of brittle machining – surface & subsurface can be imaged to a certain degree as Quartz is transparent.
Ductile Chips from a Brittle Material

- Continuous plastically deformed chips indicate ductile mode machining.
- Both images were taken at a 400x magnification.
Subsurface Damage Analysis

• CVD SiC
  – Raman Spectroscopy
  – Scanning Acoustic Microscopy

• Quartz (Fused Silica)
  – Optical Microscopy
  – Scanning Acoustic Microscopy
Raman Spectroscopy - SiC

- 633nm wavelength He-Ne laser

- Amorphous broadening is observed along with the smaller crystalline peaks in the machined region
Scanning Acoustic Microscopy

- Scientific Instruments (KSI) SAM2000 (ORNL)
- Uses focused sound to image an object
- High-frequency acoustic waves (60MHz to 2.0GHz)
Typical Image of Scanning Acoustic Microscopy - SiC

- Images show no signs of subsurface cracks or damage
- Features seen are pits and voids that existed in the as received material and not from SPDT
Typical Image of Scanning Acoustic Microscopy - Quartz

- Features seen are normal surface features and feedmarks
- No signs of fracture beneath the machined surface
Research Conclusion

• SPDT is an effective method to improve surface finish of ceramics via ductile mode machining

• SPDT also enables a larger depth of cut in a machining pass

• SPDT did not cause any surface or subsurface damage in the material

• Raman spectroscopy & SAM are effective NDT to investigate subsurface damage
Future/Ongoing 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

• Micro Laser Assisted Machining (µLAM) on SiC
  – Study the effect of heating (from laser)/softening of material and combining it with SPDT
  – Minimize diamond tool wear as hardness of material is reduced
Potential use of SiC & Quartz disks

- Quartz to be used as ABL device nose cover
- Mirror finish surface required for the above use
- Image courtesy of Boeing Corporation
Thank you
<table>
<thead>
<tr>
<th>Common Name</th>
<th>4H-SiC Wafer</th>
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<tbody>
<tr>
<td>Moms Hardness</td>
<td>~9</td>
<td>Value</td>
<td>Units</td>
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<tr>
<td>Crystal Structure</td>
<td>Hexagonal</td>
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<tr>
<td>Energy Bandgap</td>
<td>3.26</td>
<td>eV</td>
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<tr>
<td>Electric Field</td>
<td>2E6</td>
<td>V/cm</td>
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<tr>
<td>Breakdown</td>
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<tr>
<td>Thermal Conductivity</td>
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<td>W/(cm.K)</td>
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<tr>
<td>Melting Temperature</td>
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<td>°C</td>
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<tr>
<td>Electron Drift</td>
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<td>Velocity</td>
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**Table A1: Material properties of 4H-SiC wafer**

<table>
<thead>
<tr>
<th>Common Name</th>
<th>CVD-SiC (SuperSiC-2)</th>
<th>Value</th>
<th>Units</th>
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<tbody>
<tr>
<td>Hardness, H</td>
<td>27</td>
<td>GPa</td>
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<tr>
<td>Young's Modulus</td>
<td>466</td>
<td>GPa</td>
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<tr>
<td>Density</td>
<td>3.18E6</td>
<td>g/cc</td>
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<tr>
<td>Fracture Toughness, K_c</td>
<td>3E6</td>
<td>Pa.m^0.5</td>
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<tr>
<td>Thermal Conductivity</td>
<td>129</td>
<td>W/(m.K)</td>
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<tr>
<td>Melting Temperature</td>
<td>2500</td>
<td>°C</td>
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<tr>
<td>Poisson's Ratio</td>
<td>0.26</td>
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**Table A2: Material properties of 3C (β) CVD-SiC**

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Quartz(Spectrosil 2000)</th>
<th>Value</th>
<th>Units</th>
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<tr>
<td>Hardness, H</td>
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<td>GPa</td>
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<tr>
<td>Young's Modulus</td>
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<td>GPa</td>
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<tr>
<td>Density</td>
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<td>Fracture Toughness, K_c</td>
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<td>Pa.m^0.5</td>
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<td>Thermal Conductivity</td>
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<td>Melting Temperature</td>
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<td>Poisson's Ratio</td>
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<tr>
<td>Specific Heat Capacity</td>
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<td>Refractive Index</td>
<td>1.4585</td>
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**Table A3: Material properties of Quartz**
Measured feed marks

Cutting direction

30μm