

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_2O_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

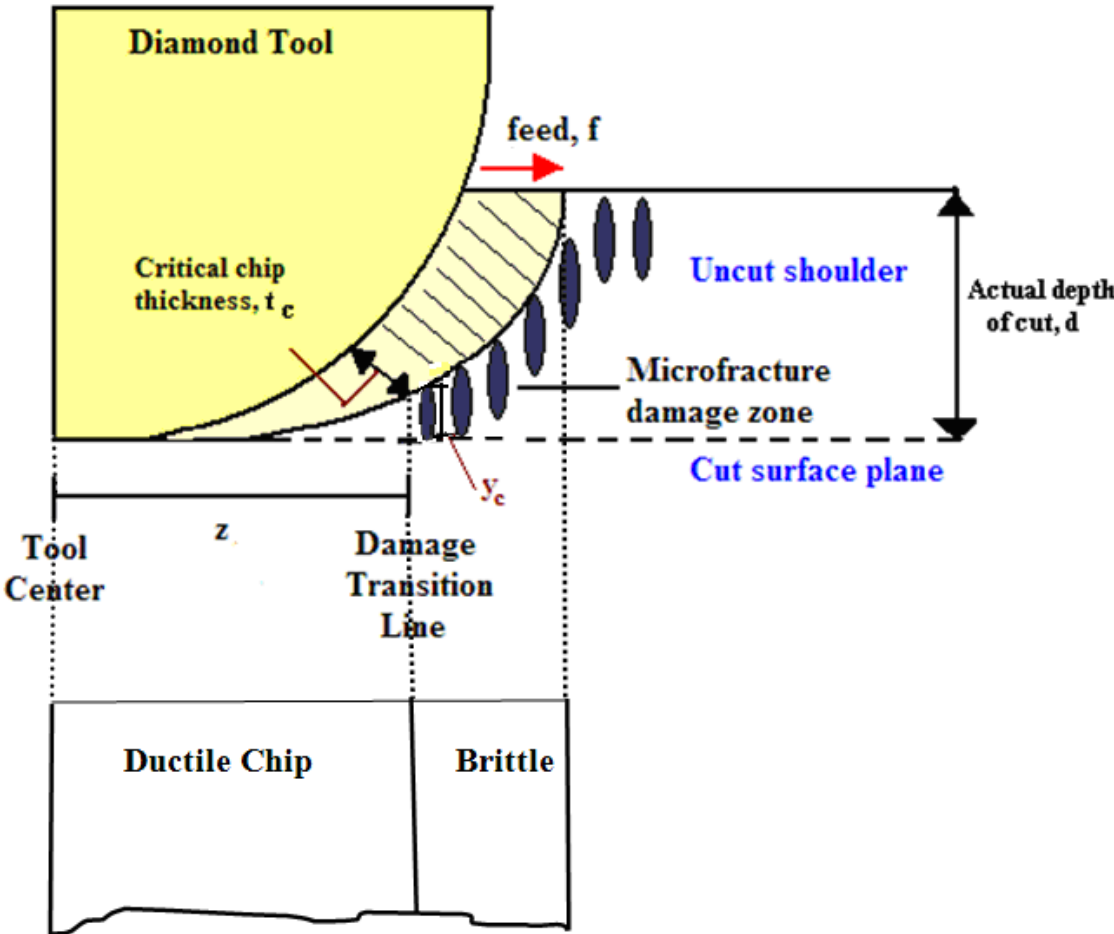
- **Improve surface finish (surface roughness) via ductile mode machining**
- **Increase material removal rate (MRR) by altering:**
 - Feed
 - Depth of Cut
 - Cutting Speed
- **Minimize diamond tool wear**
- **Minimize/Eliminate sub-surface damage**

** 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) $<1\mu\text{m}$

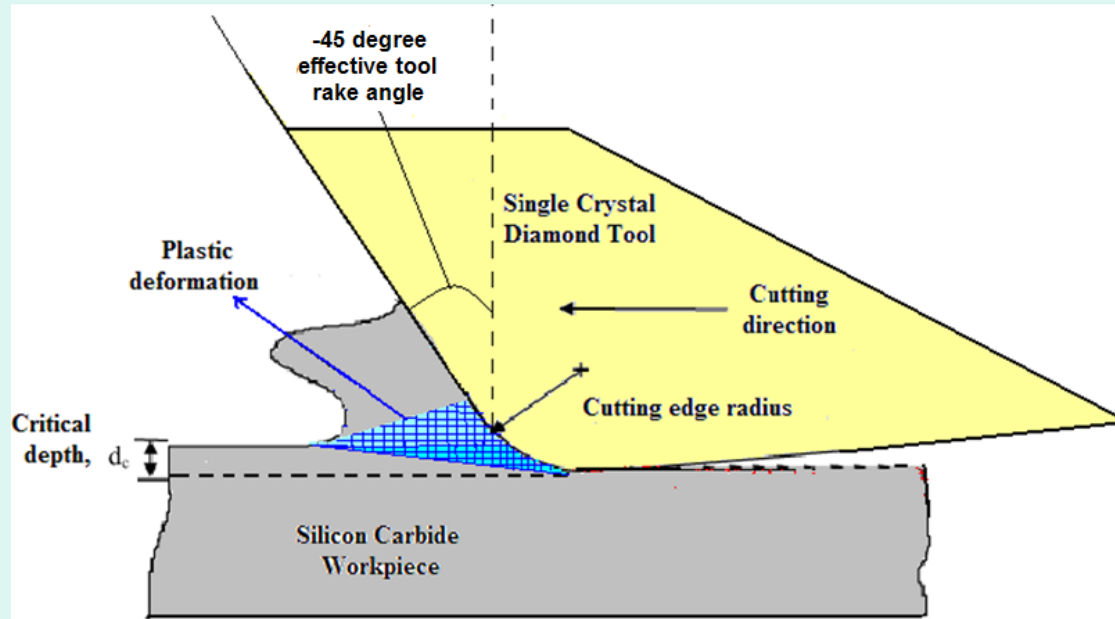
Ductile Regime Machining of Ceramics



Model proposed by Blake & Scattergood

- 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

Critical Depth of Cut (d_c)



- Griffith fracture propagation criteria:

$$d_c \sim 0.15 \cdot (E / H) \cdot (K_c / H)^2$$

where:

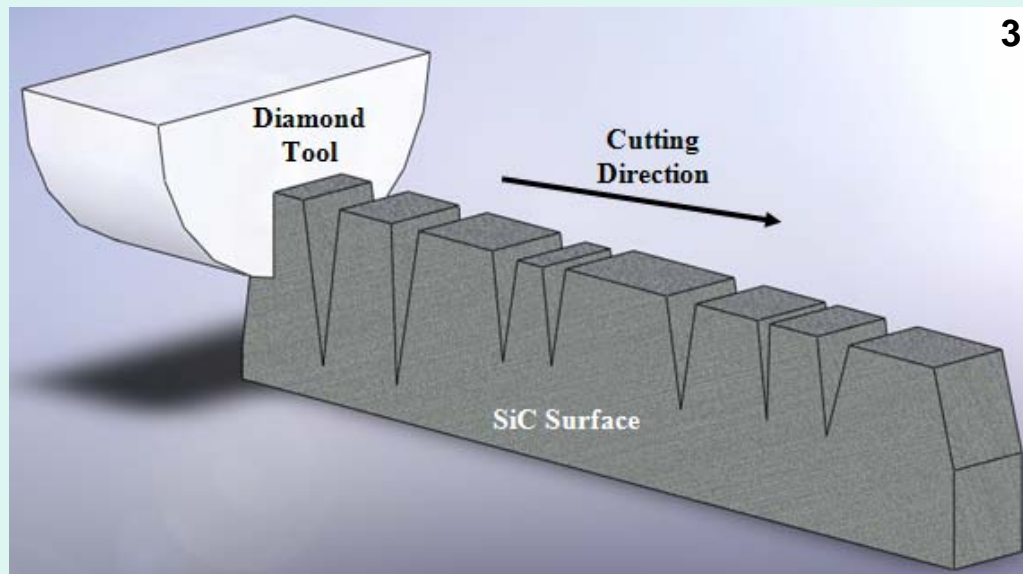
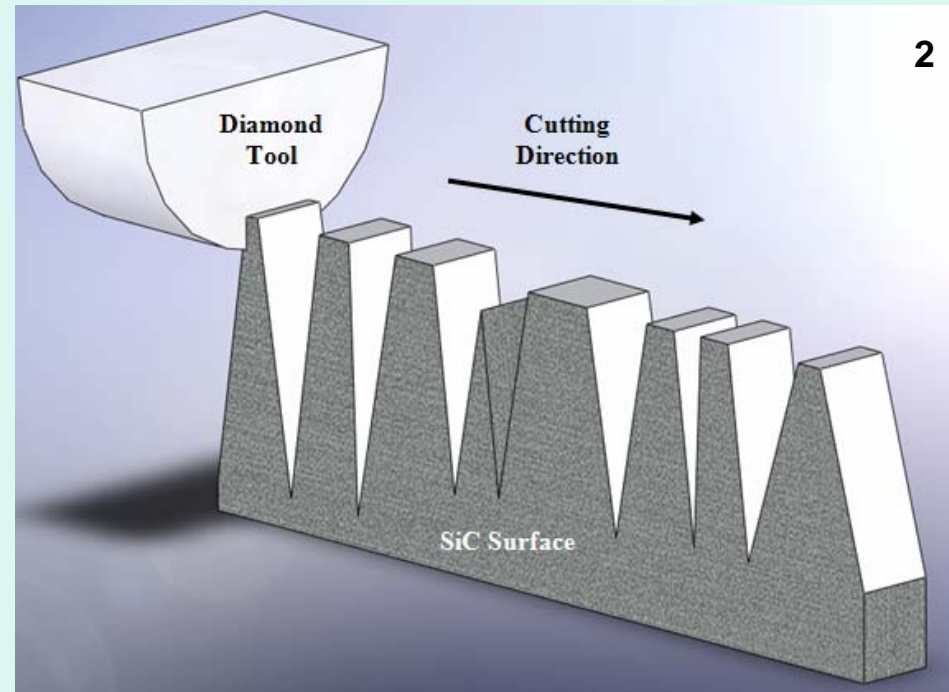
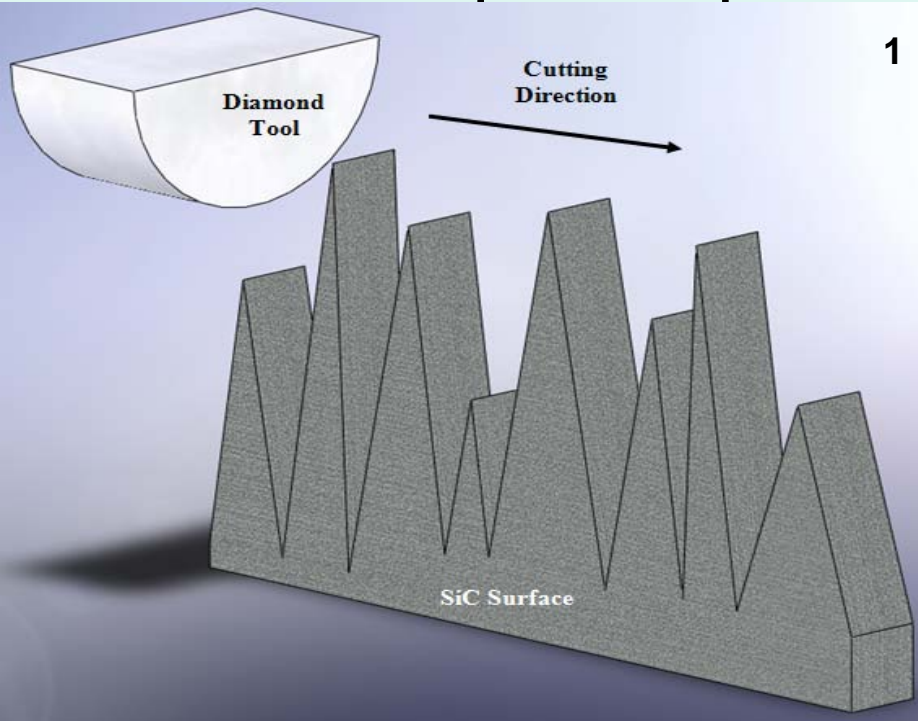
0.15 = estimated constant of proportionality

E = elastic modulus

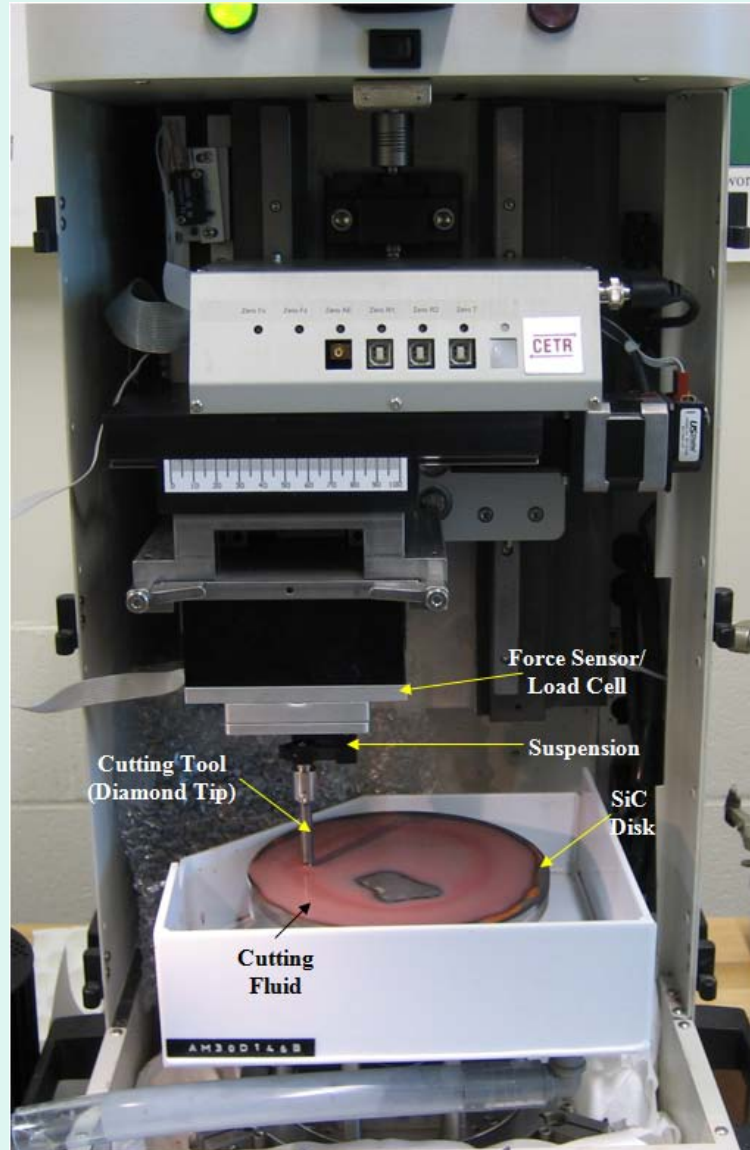
H = hardness

K_c = fracture toughness

Concept of improving surface roughness



Single Point Diamond Turning of CVD-SiC



SPDT of SiC

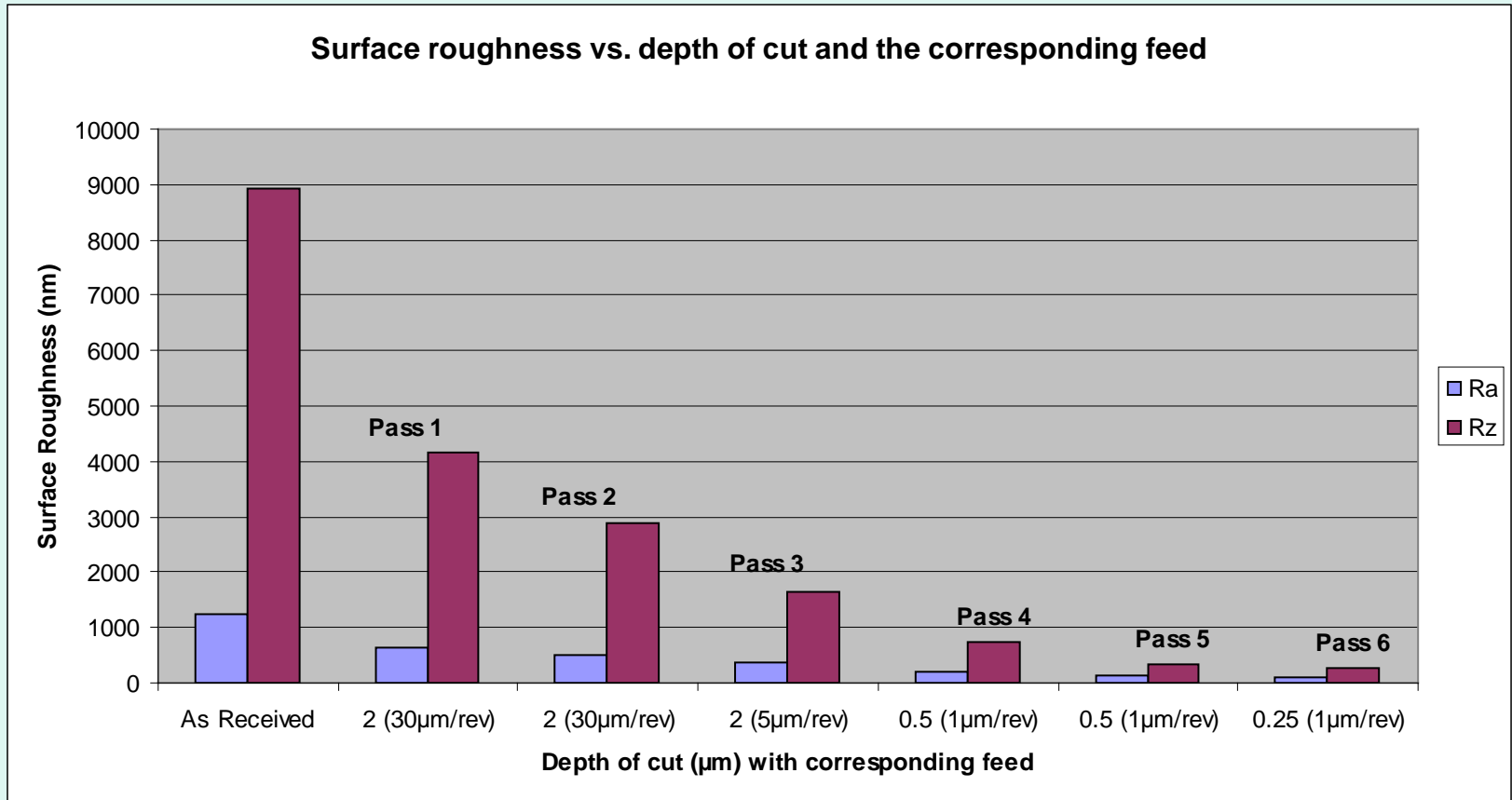


Machining Parameters

Pass #	Depth of Cut	Feed ($\mu\text{m}/\text{rev}$)
1	2 μm	30
2	2 μm	30
3	2 μm	5
4	500nm	1
5	500nm	1
6	250nm	1

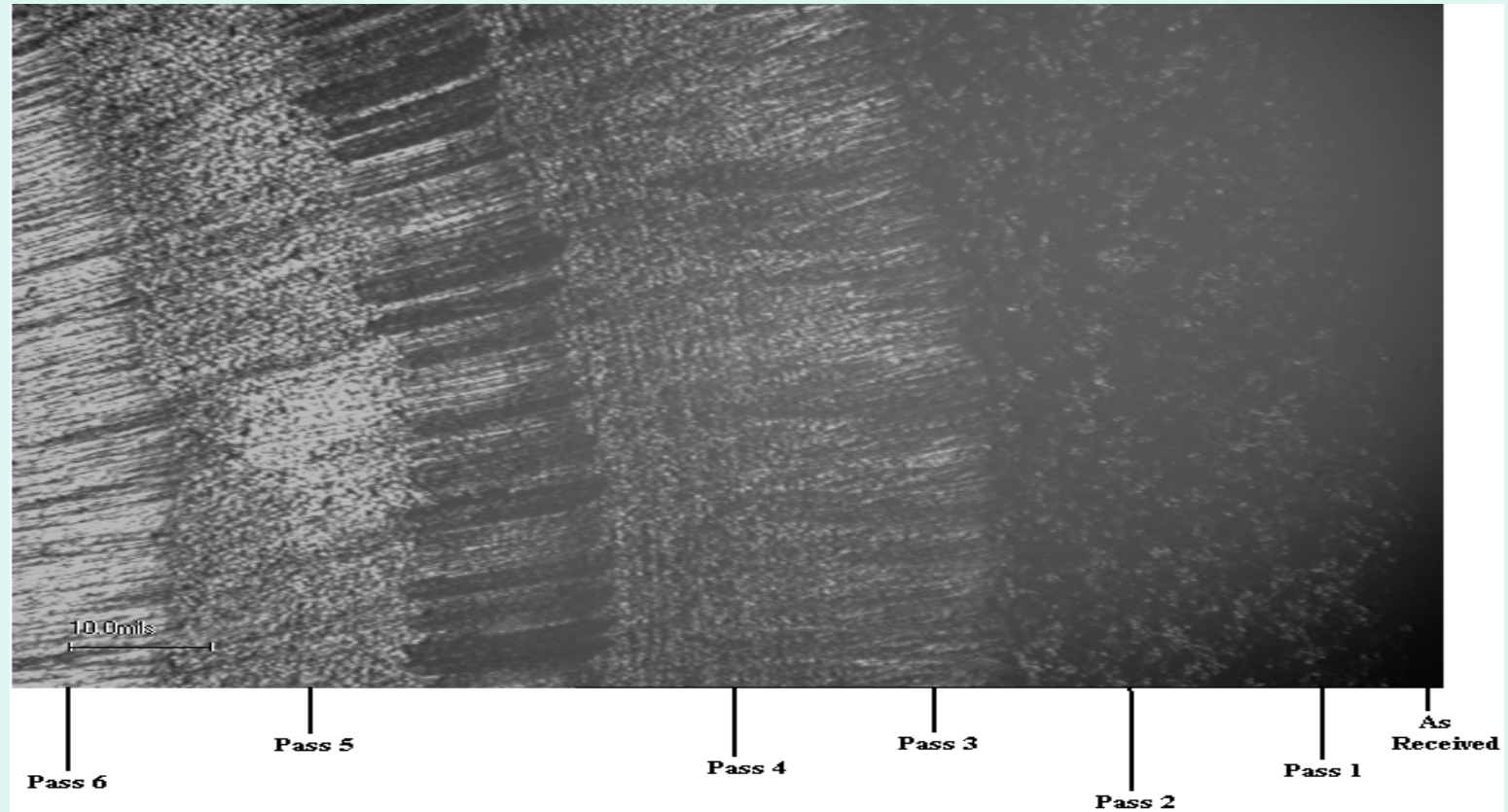
- The actual depths are usual about 50% of the programmed depths of cuts (due to elasticity)
- Best surface finish is achieved from the lowest feed (with a low depth of cut)

Results for final machining (surface roughness)



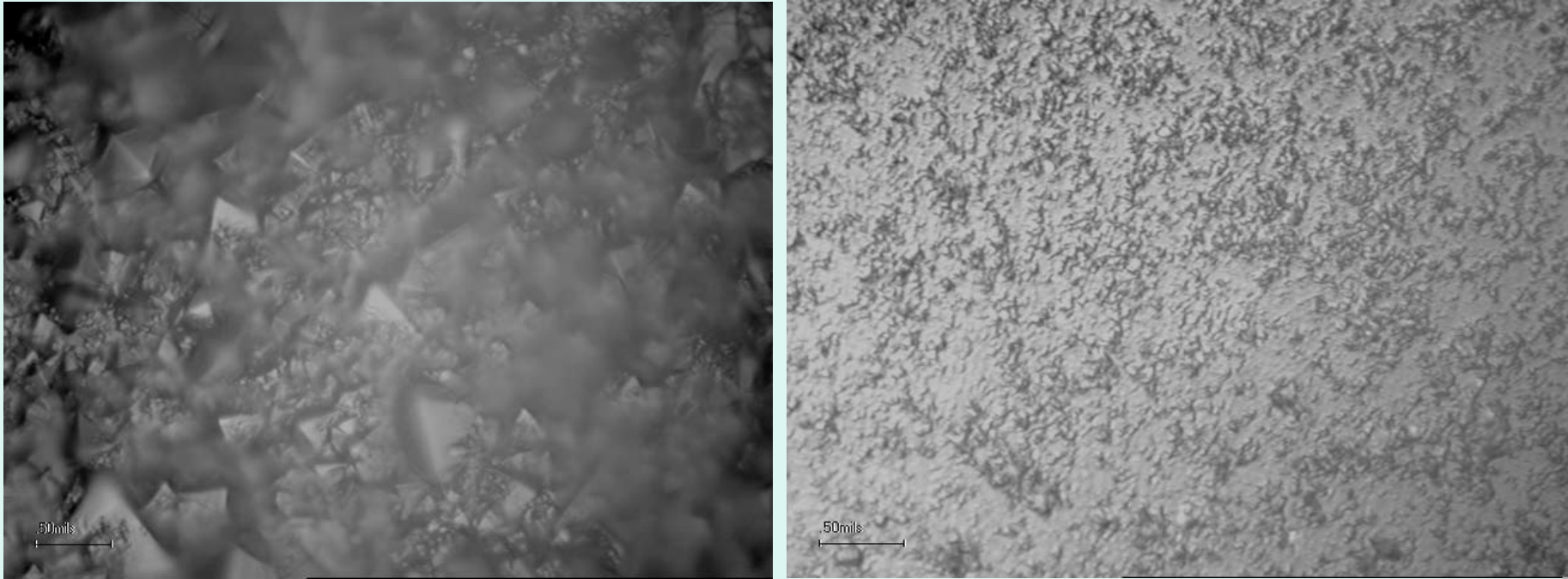
- Ra improved from 1.25μm to 85nm in 6 passes
- Rz improved from 9.0μm to 250nm
- Target Ra (Ra<100nm) achieved in 6 passes

Results *(Surface image of 6 passes)*



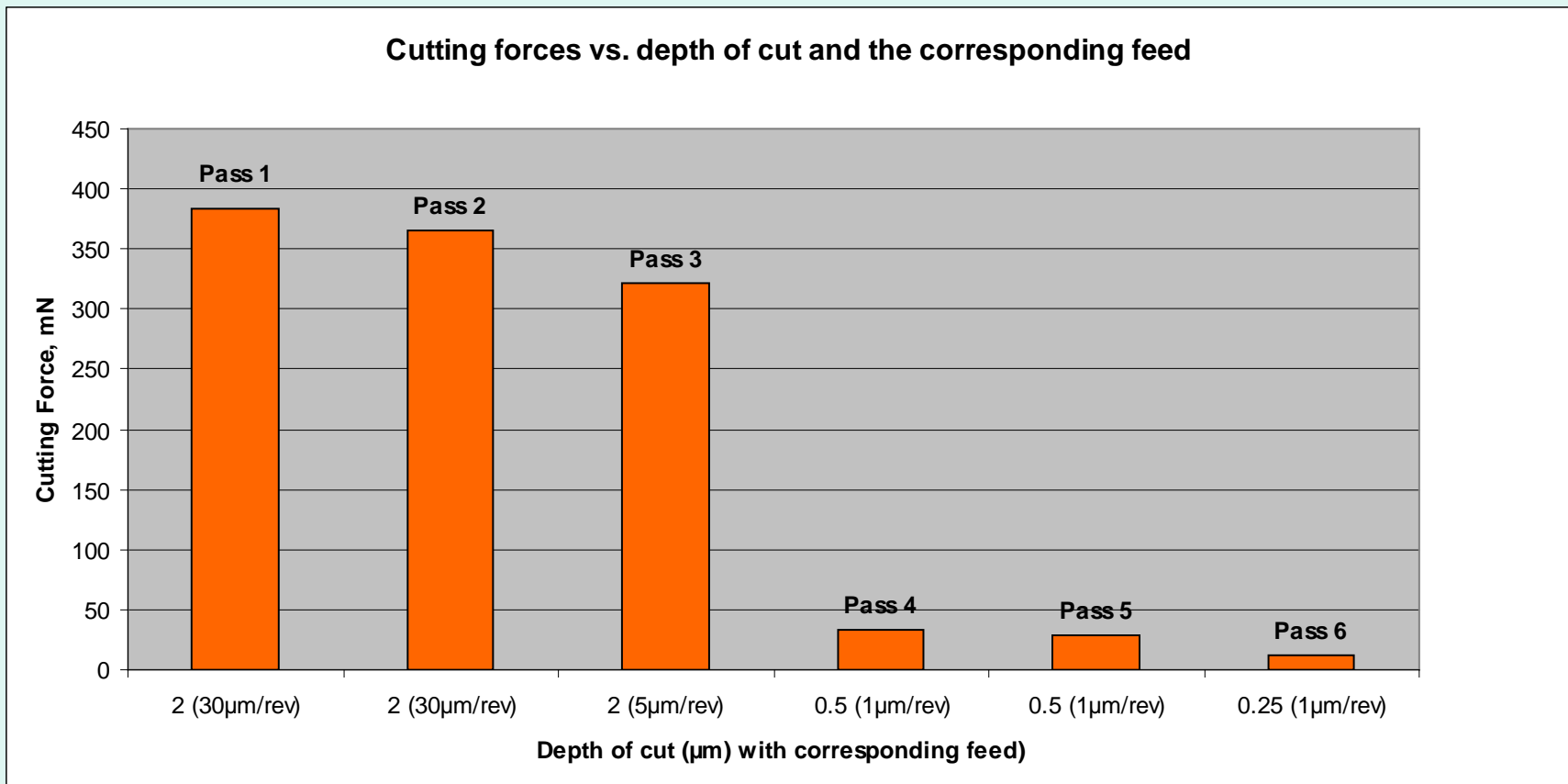
- Image was taken at 50x magnification
- Surface continuously improved after each pass
- Band between pass 4 & 5 was due to tool chatter

Results *(Surface image comparison)*



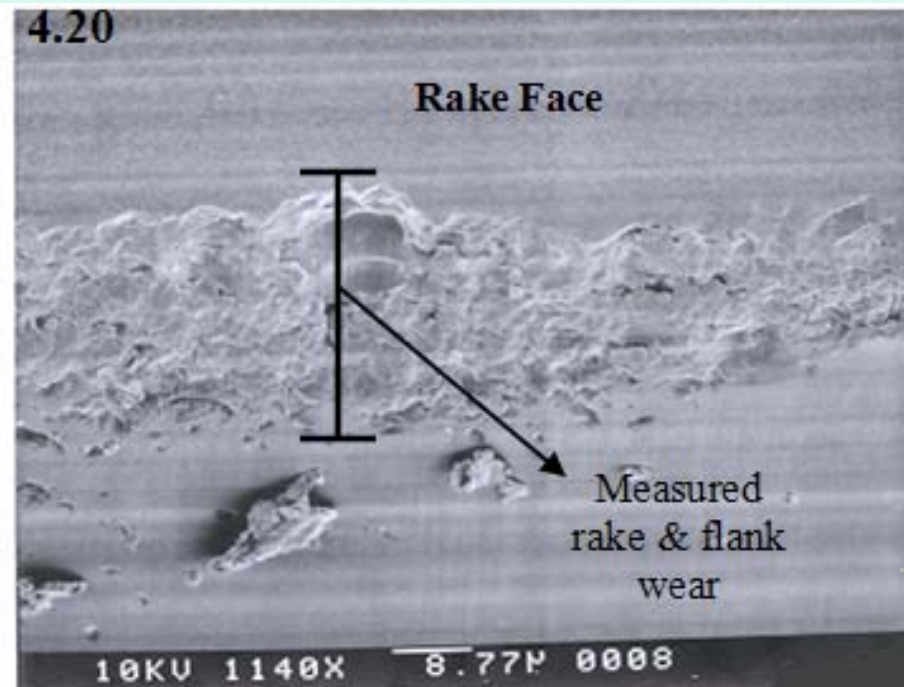
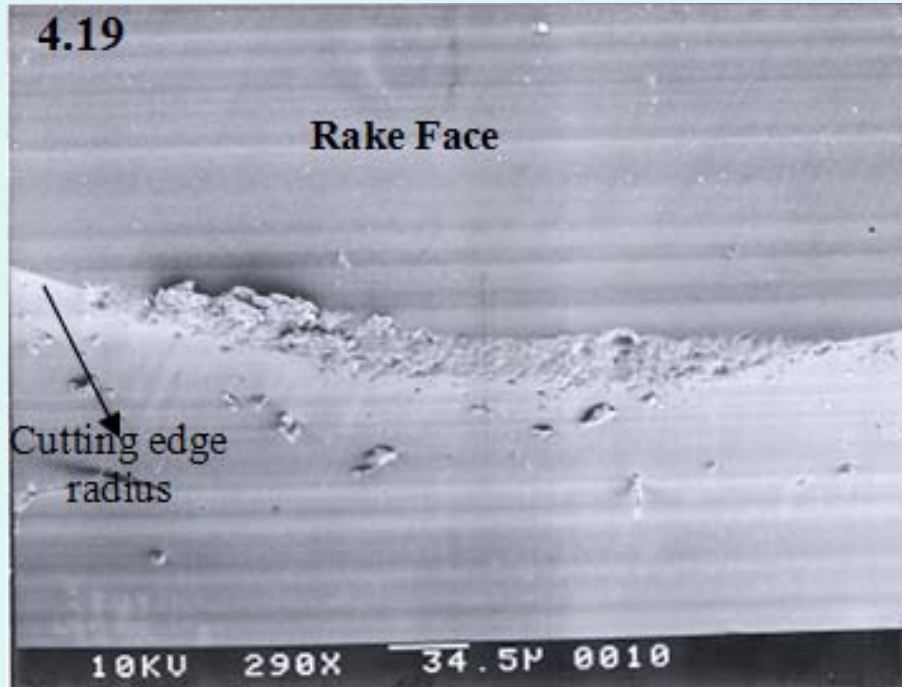
- Images comparing the surface before (left) and after (right) SPDT
- Images were taken at a 1000x magnification
- The sharp/uneven peaks on the surface disappeared after the SPDT operation

Results for final machining (cutting forces)



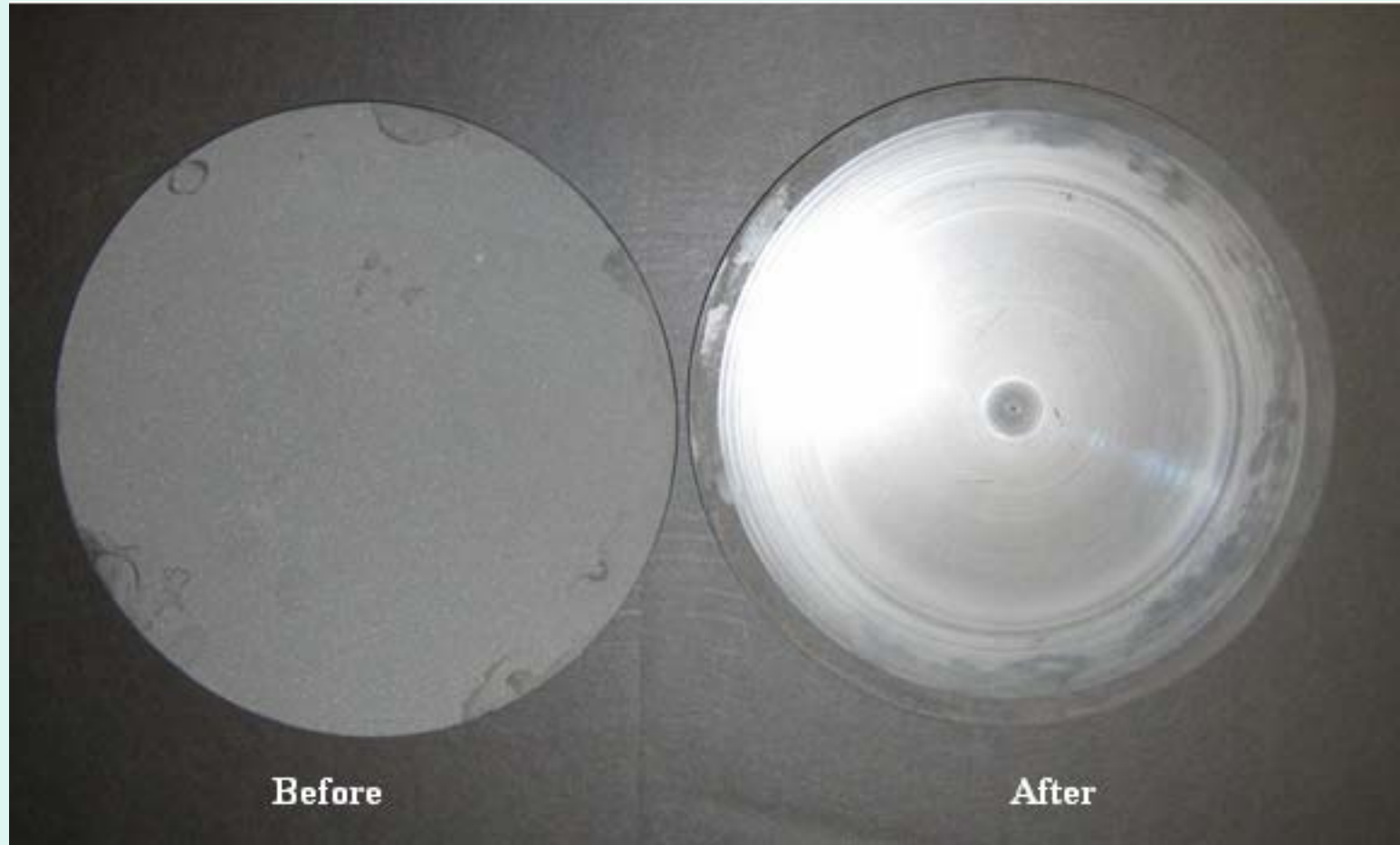
- Larger depths of cuts result in larger cutting forces
- Forces can also increase due to rough surfaces, machining debris, tool vibration, workpiece run-out, etc
- Cutting fluid helps several problems such as machining debris

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)

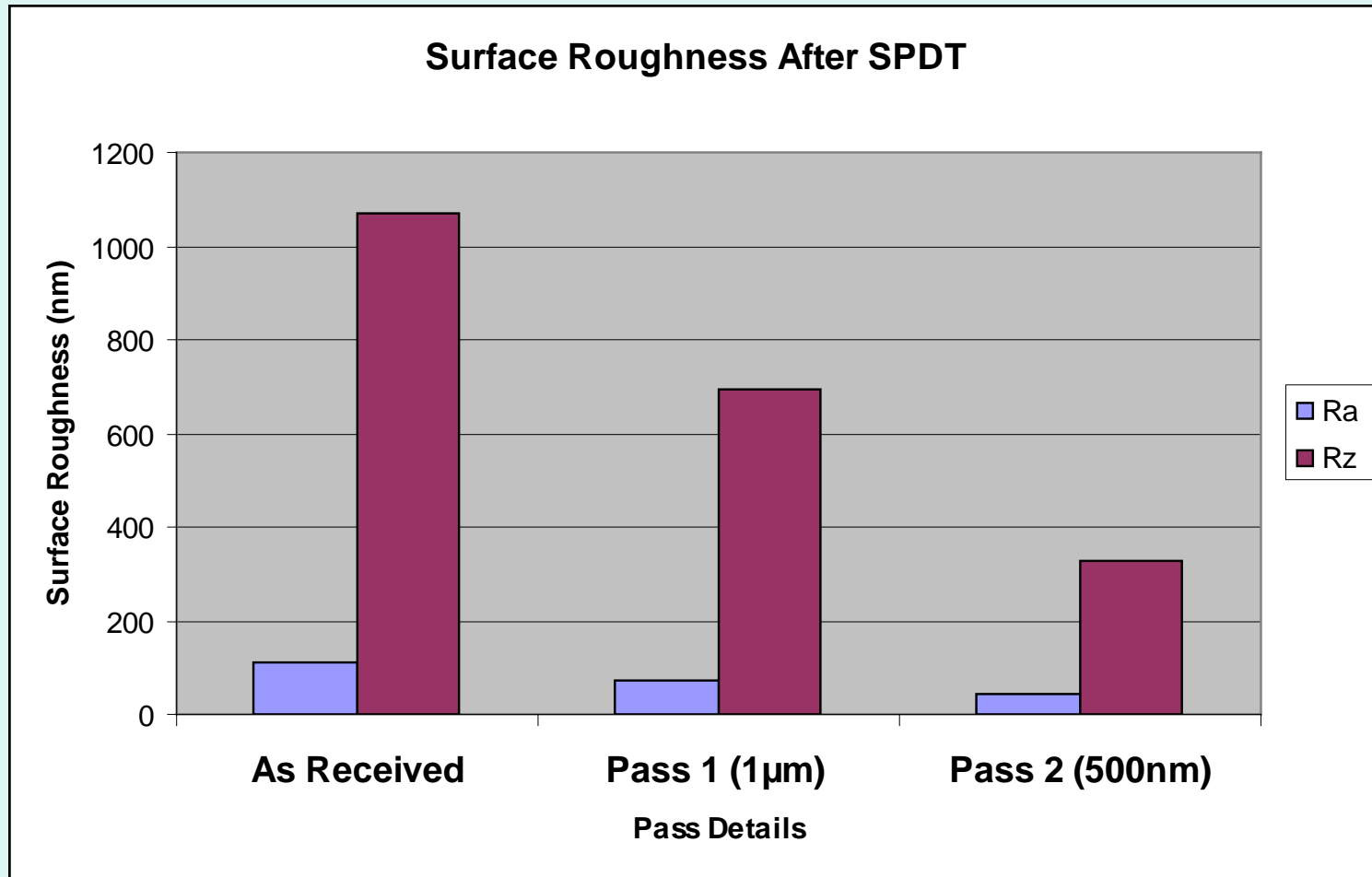
Results *(6" disk before & after SPDT)*



Single Point Diamond Turning of Quartz (Spectrosil 2000)

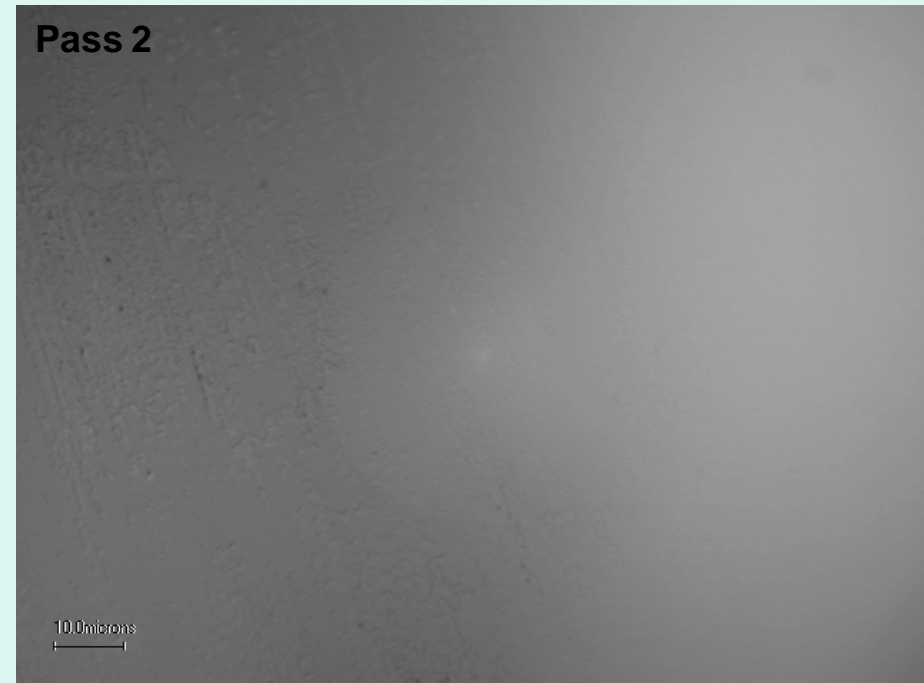
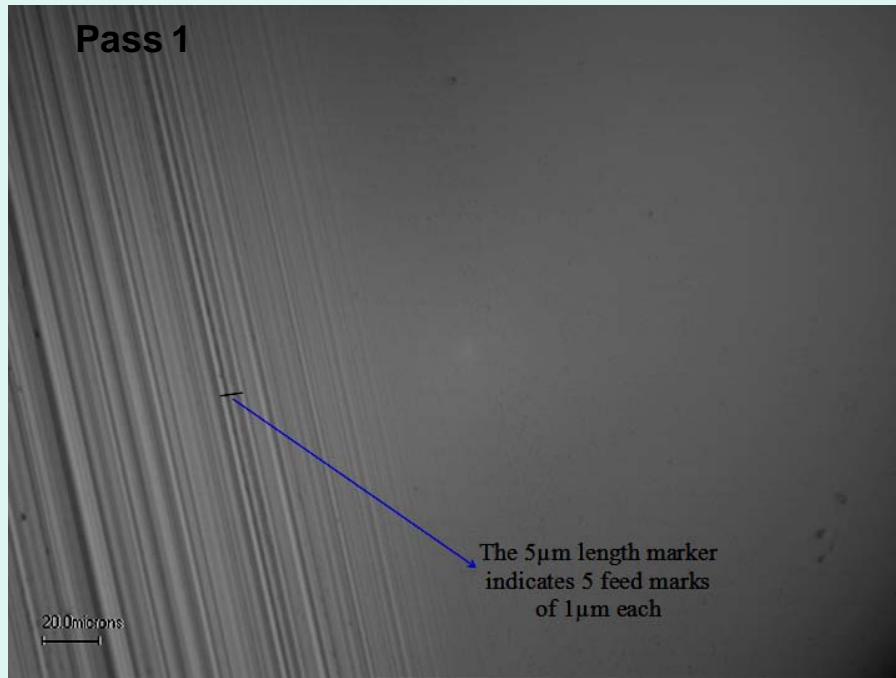


Results (*surface roughness*)



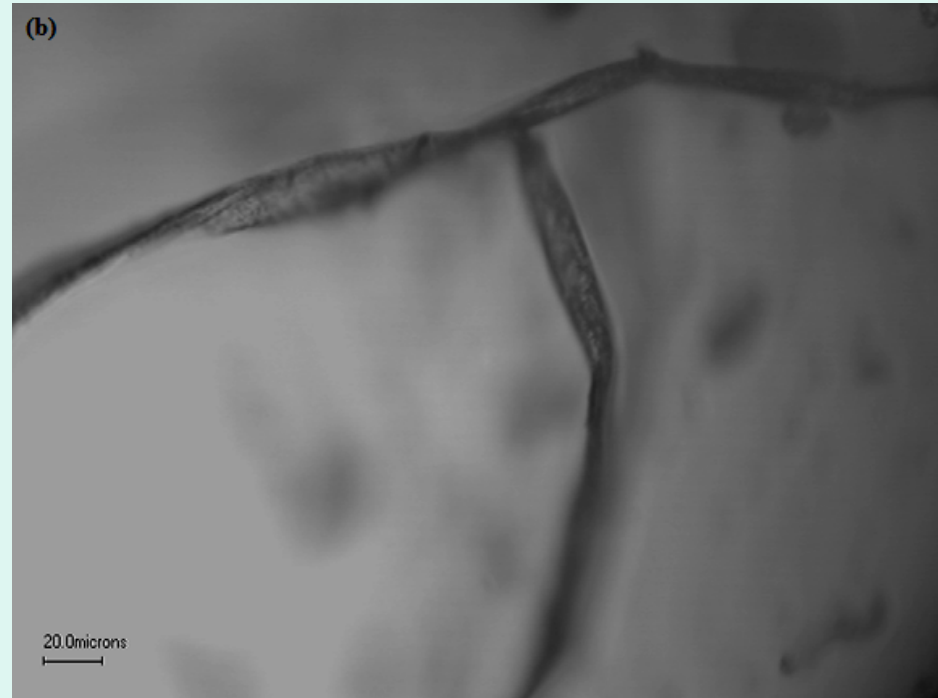
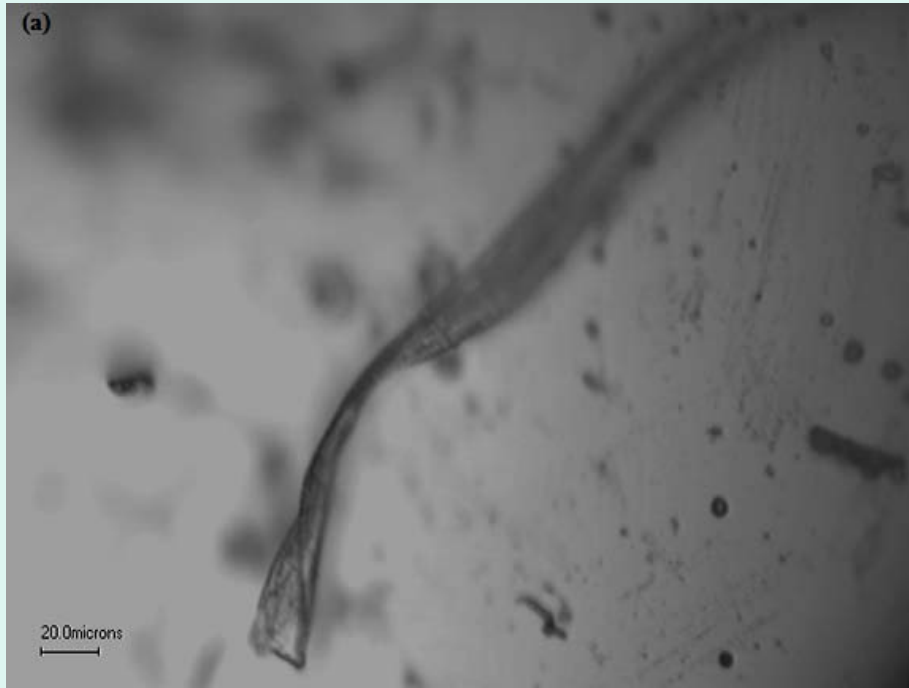
- A total of two passes were carried out to achieve the targeted Ra (achieved Ra~40nm)
- A feed of 1µm/rev was used for both passes

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

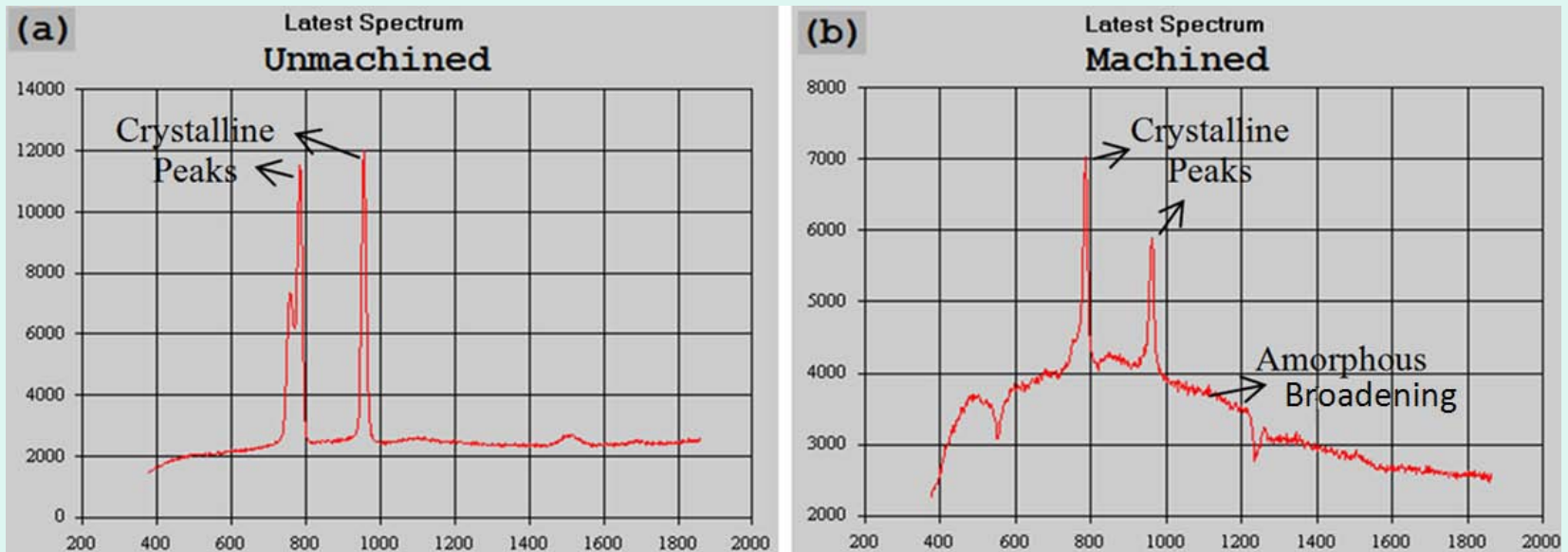
Subsurface Damage Analysis

- CVD SiC
 - Raman Spectroscopy
 - Scanning Acoustic Microscopy

- Quartz (Fused Silica)
 - Optical Microscopy
 - Scanning Acoustic Microscopy

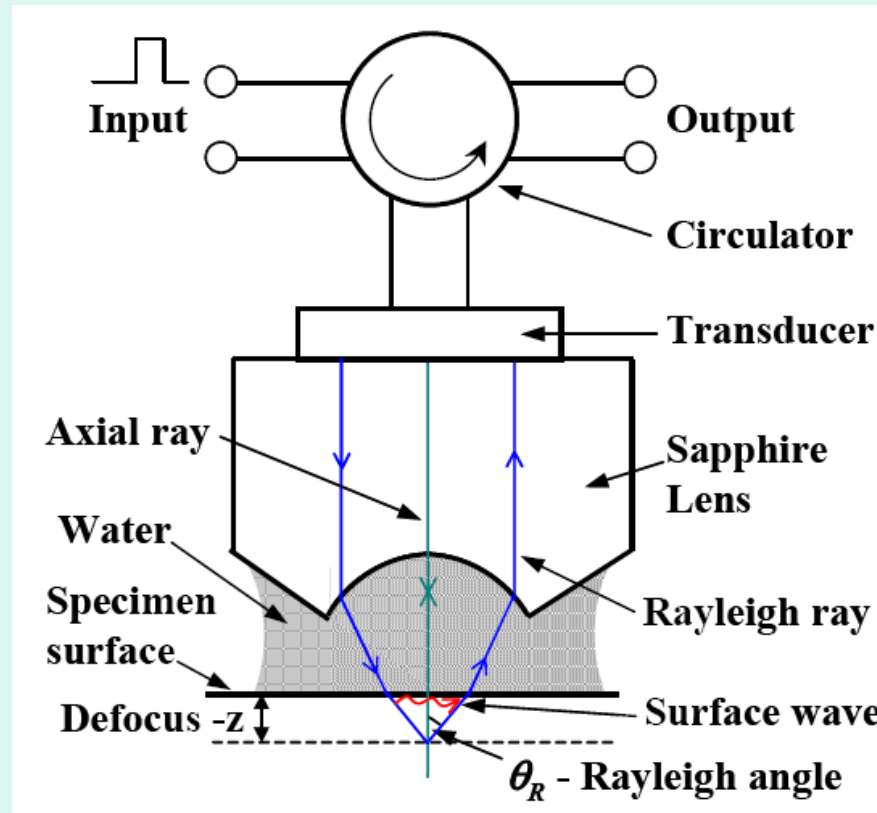
Raman Spectroscopy - SiC

- 633nm wavelength He-Ne laser



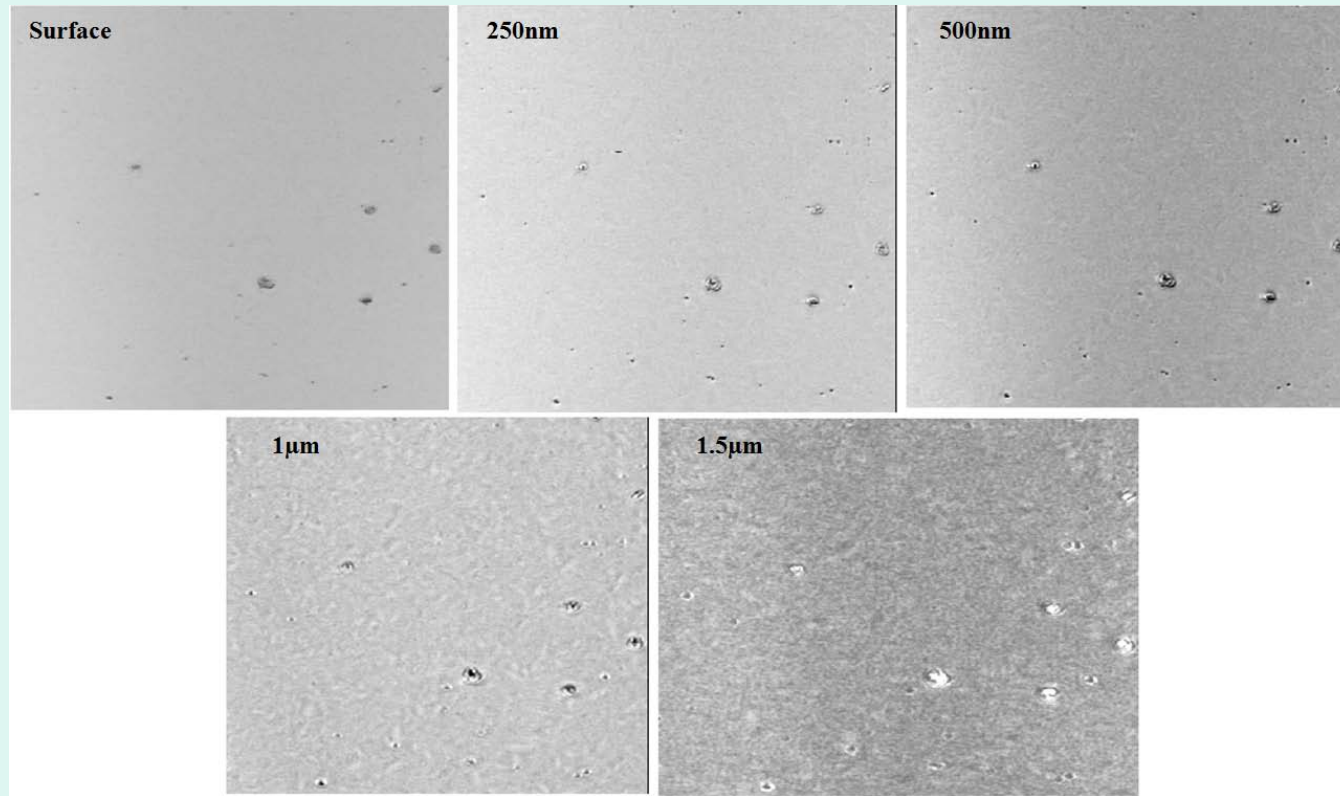
- Amorphous broadening is observed along with the smaller crystalline peaks in the machined region

Scanning Acoustic Microscopy



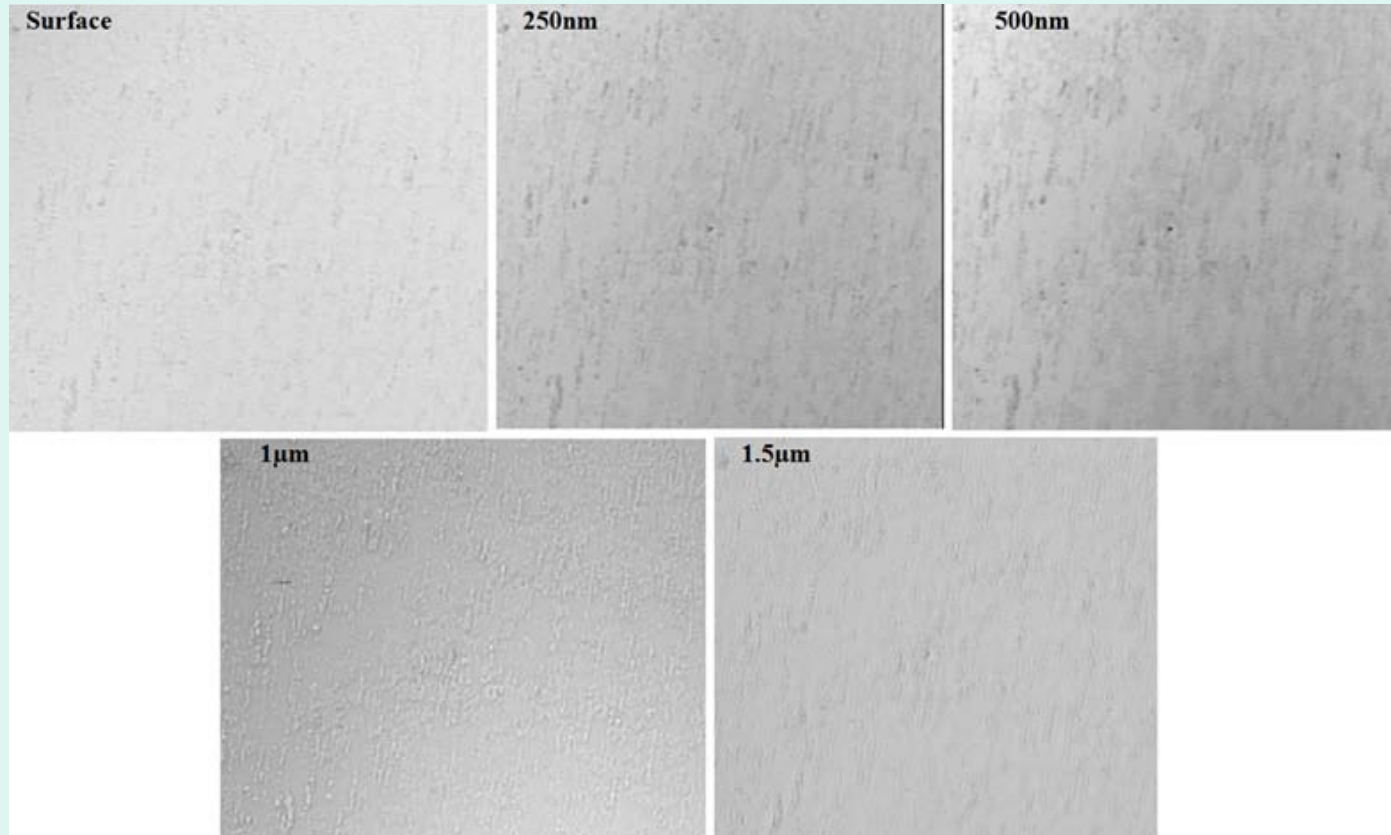
- Scientific Instruments (KSI) SAM2000 (ORNL)
- Uses focused sound to image an object
- High-frequency acoustic waves (60MHz to 2.0GHz)

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 (μ LAM) 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

Common Name	4H-SiC Wafer	
	Value	Units
Moms Hardness	~9	-
Crystal Structure	Hexagonal	-
Energy Bandgap	3.26	eV
Electric Field Breakdown	2E6	V/cm
Thermal Conductivity	3.4	W/(cm.K)
Melting Temperature	1700	°C
Electron Drift Velocity	2E7	cm/sec

Table A1: Material properties of 4H-SiC wafer

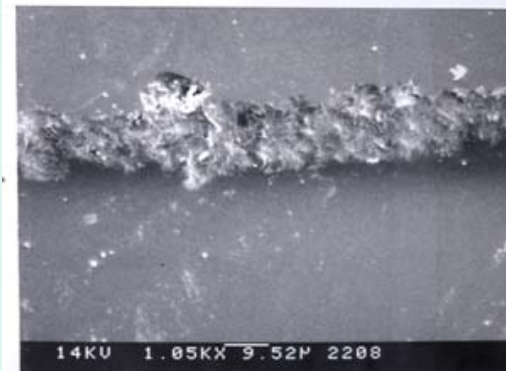
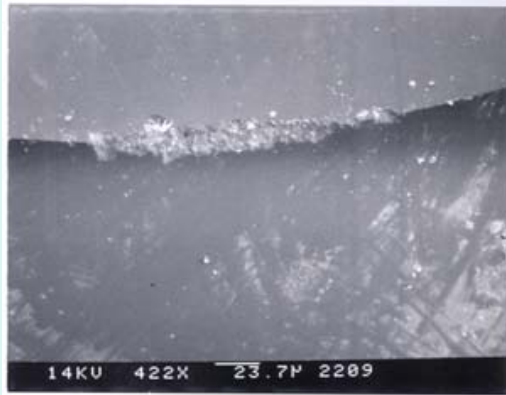
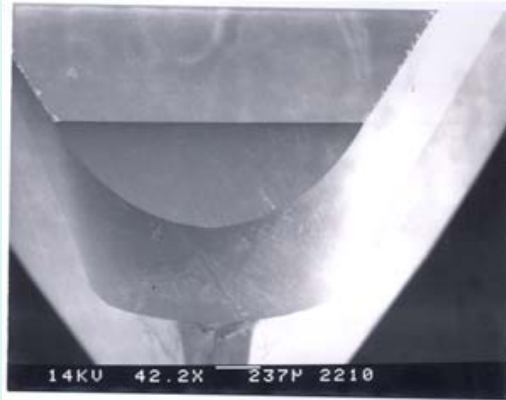
Common Name	CVD-SiC (SuperSiC-2)	
	Value	Units
Hardness, H	27	GPa
Young's Modulus	466	GPa
Density	3.18E6	g/cc
Fracture Toughness, K_{Ic}	3E6	Pa.m ^{0.5}
Thermal Conductivity	129	W/(m.K)
Melting Temperature	2500	°C
Poisson's Ratio	0.26	

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

Common Name	Quartz(Spectrosil 2000)	
	Value	Units
Hardness, H	9.8	GPa
Young's Modulus	73	GPa
Density	2.21	g/cm ³
Fracture Toughness, K_{Ic}	4E6	Pa.m ^{0.5}
Thermal Conductivity	1.38	W/(m.K)
Melting Temperature	1700	°C
Poisson's Ratio	0.17	-
Specific Heat Capacity	728	J/(kg.K)
Refractive Index	1.4585	-

Table A3: Material properties of Quartz

SEM of tool



Measured feed marks

