

Ductile Regime Single Point Diamond Turning of CVD-SiC Resulting in an Improved and Damage-Free Surface

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Presentation Overview

- Introduction
- Research Background
 - Concept of Ductile Regime Machining
- SPDT on CVD-SiC
- Subsurface Damage Analysis (Nondestructive)
 - Laser micro-Raman Spectroscopy
 - Scanning Acoustic Microscopy
- Ongoing & Upcoming work

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

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

Project Goals

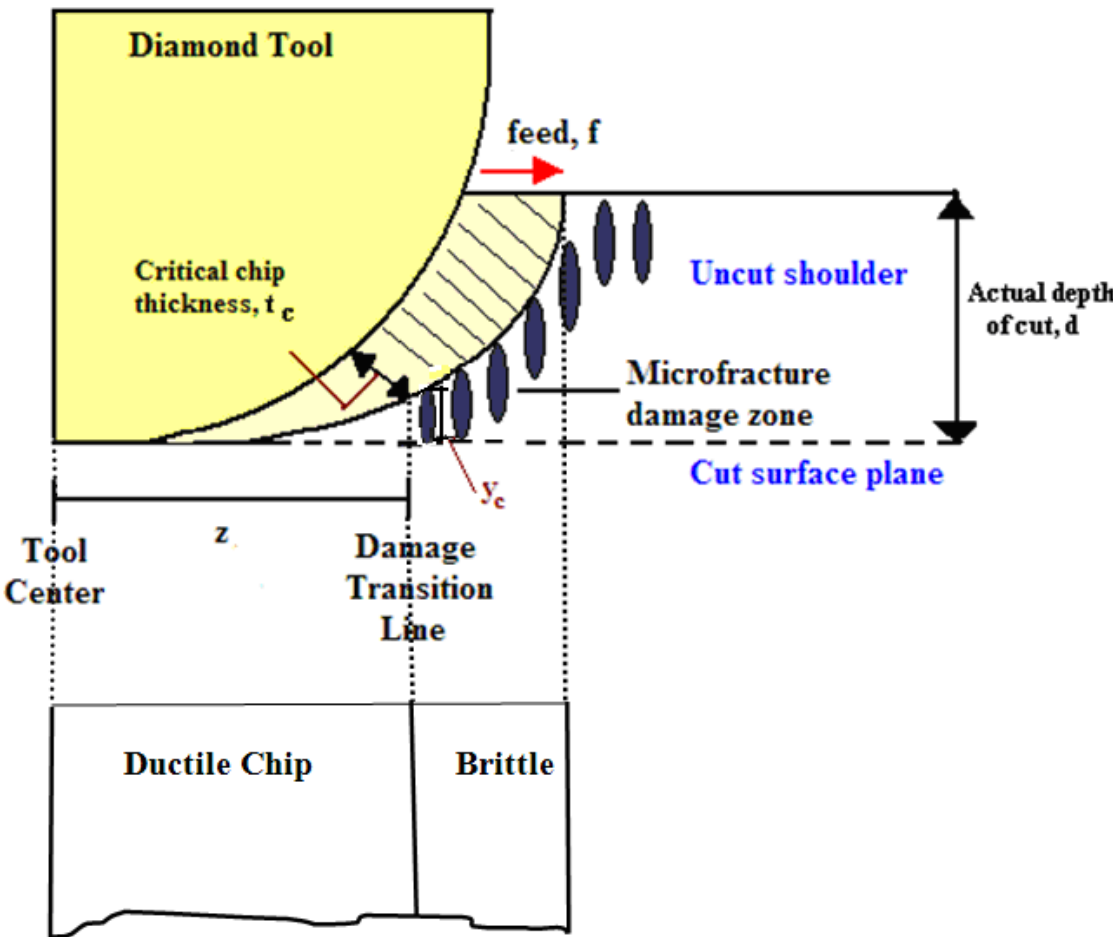
- **Improve surface finish (surface roughness) via ductile mode machining**
- **Increase material removal rate (MRR) by altering:**
 - Feed
 - Depth of Cut
 - Cutting Speed
- **Minimize diamond tool wear**
- **Minimize/Eliminate sub-surface damage**

** Establish machining parameters to meet all criteria's (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.

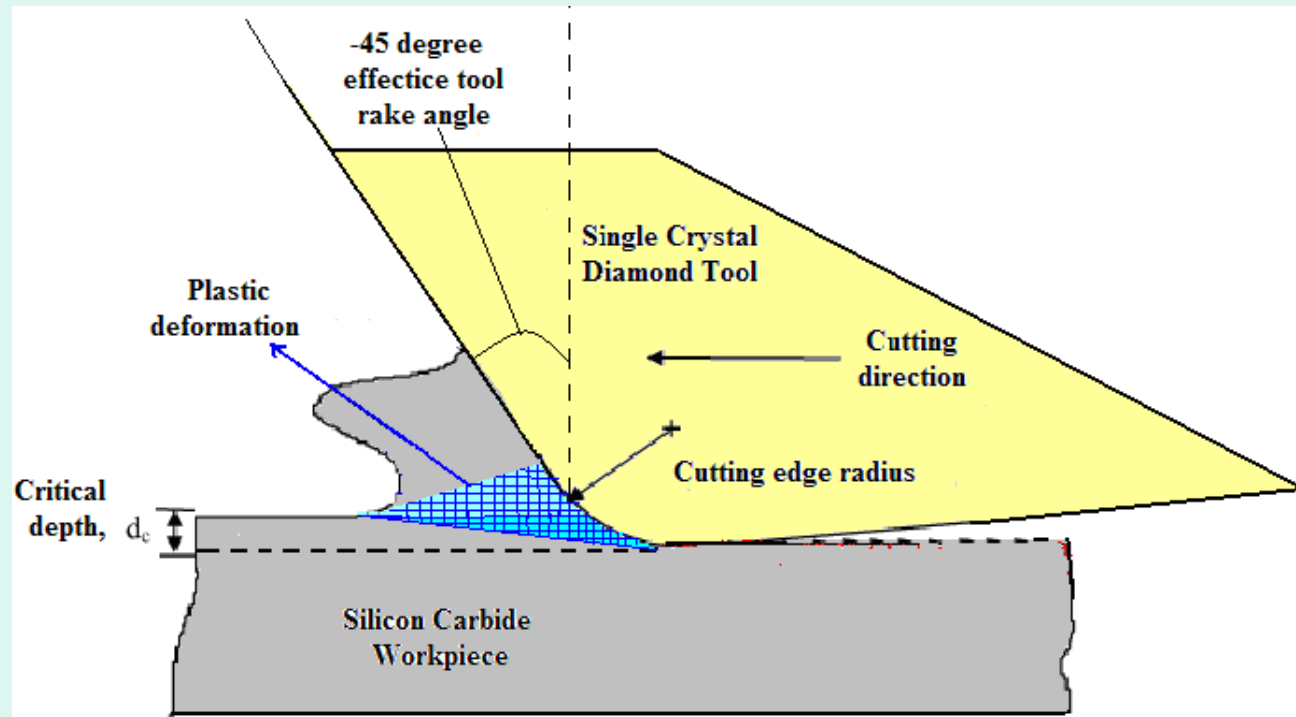
Ductile Regime Machining of Ceramics



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:

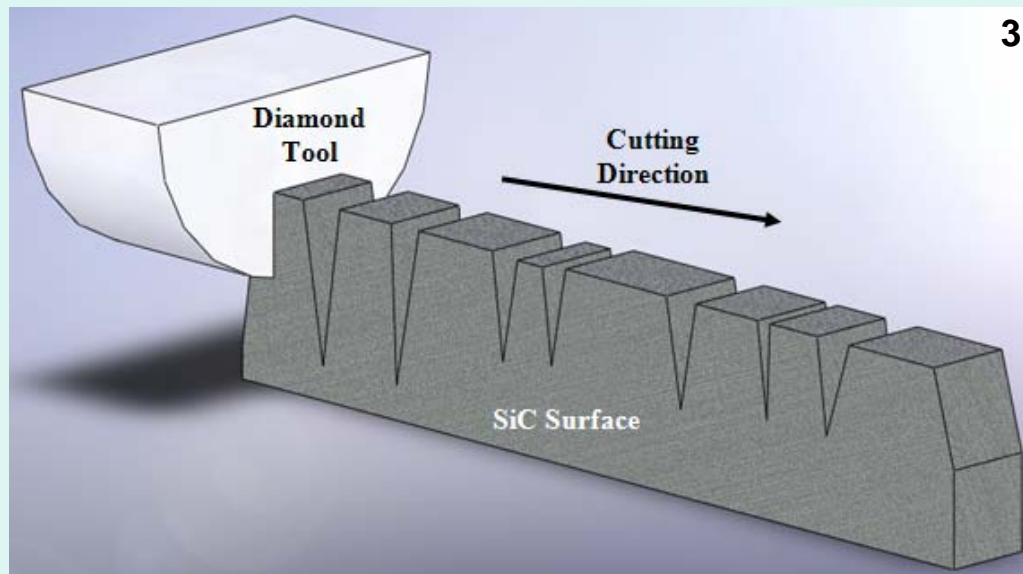
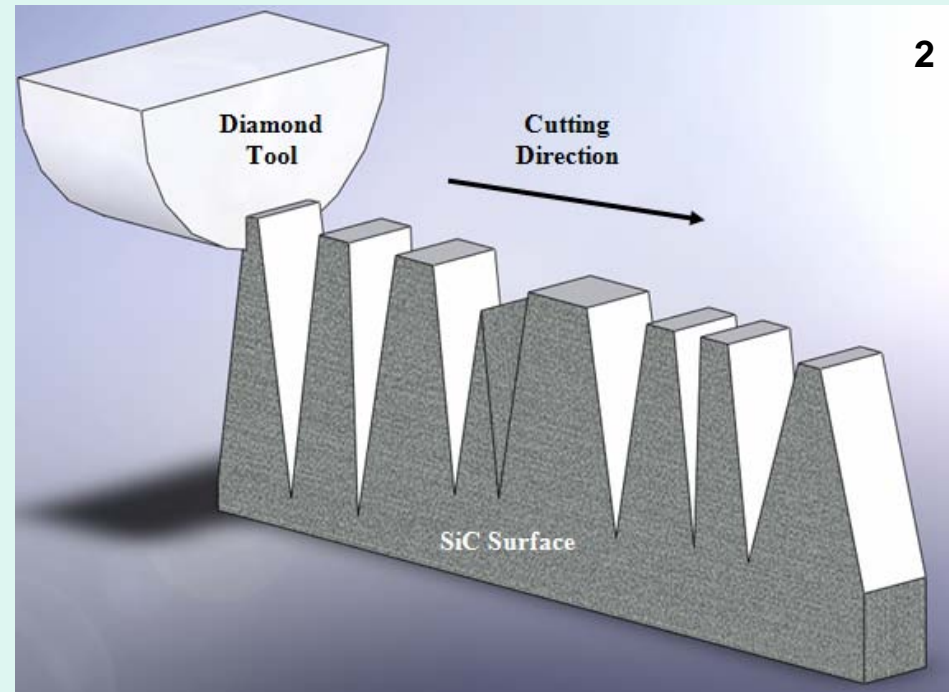
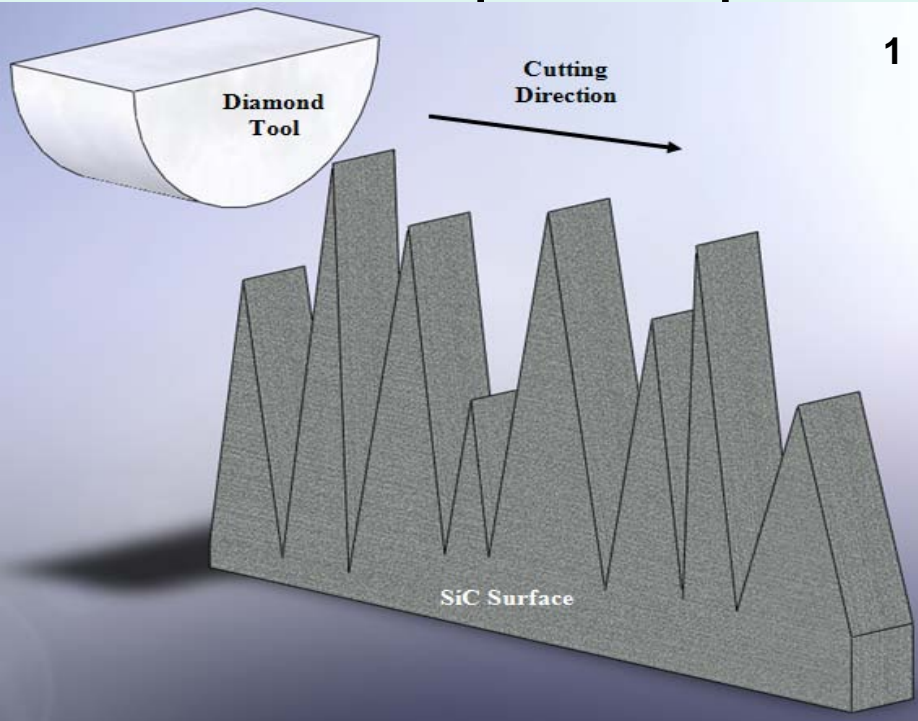
0.15 = estimated constant of proportionality

E = elastic modulus

H = hardness

K_c = fracture toughness

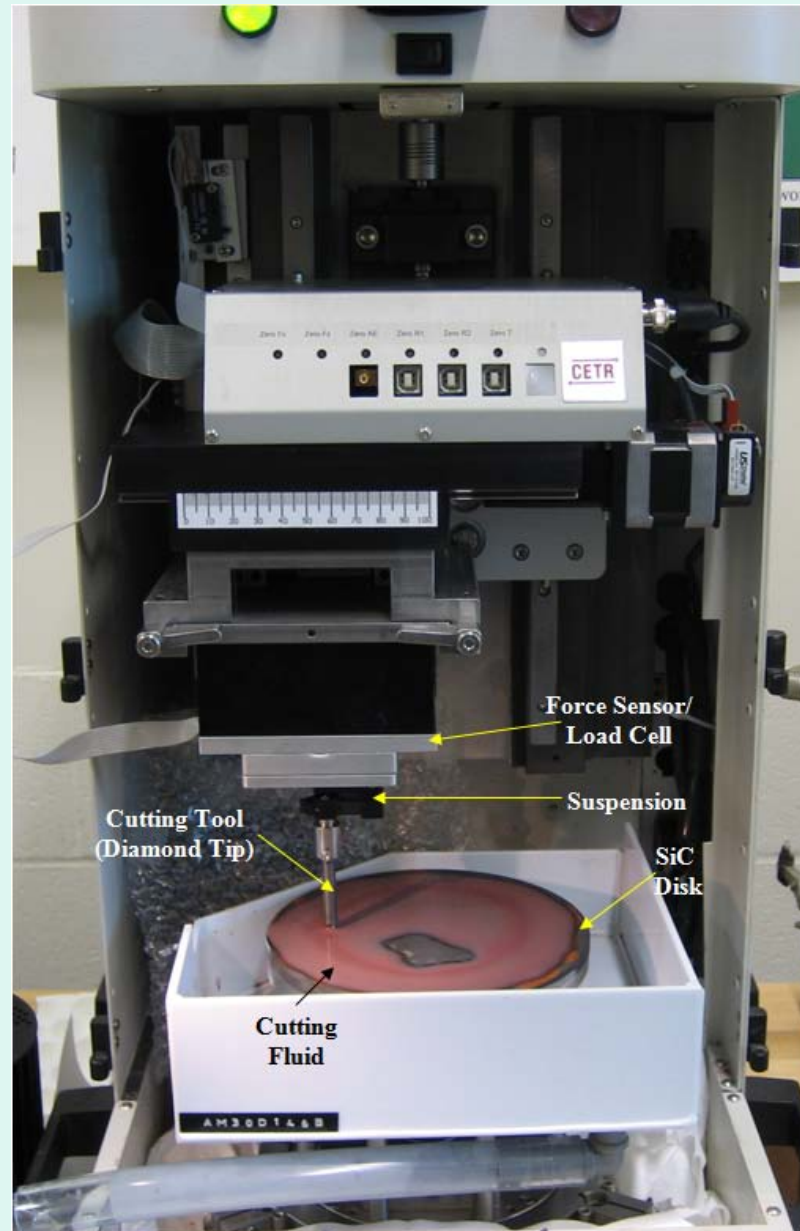
Concept of improving surface roughness



Experimental Procedure

- Preliminary 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

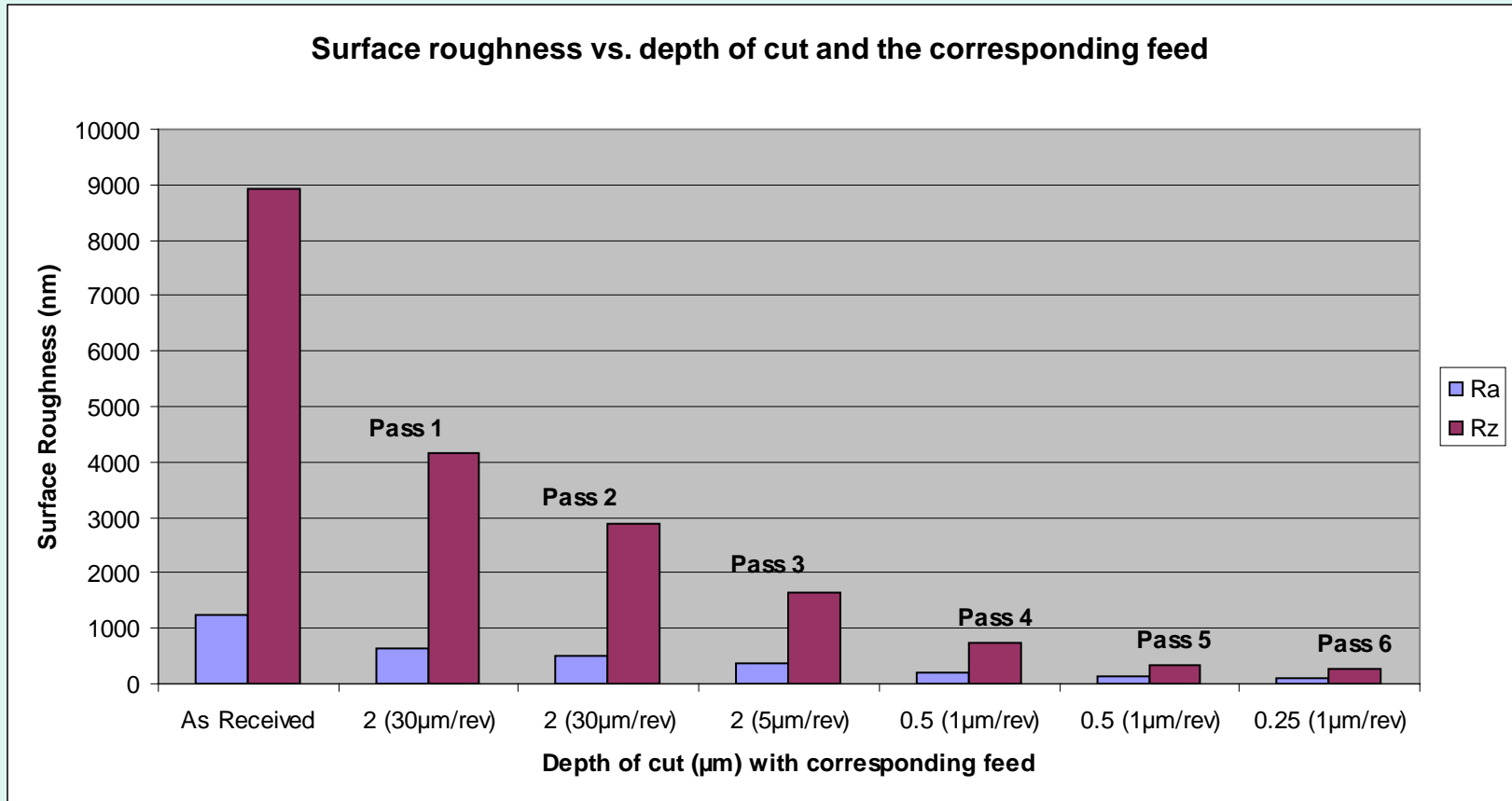


Final Machining Parameters

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

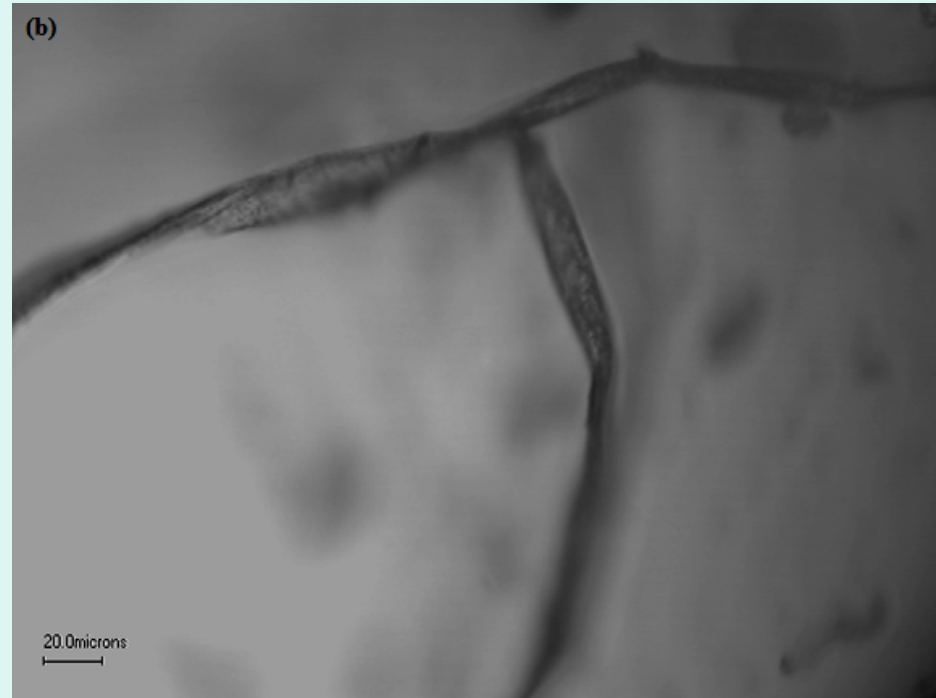
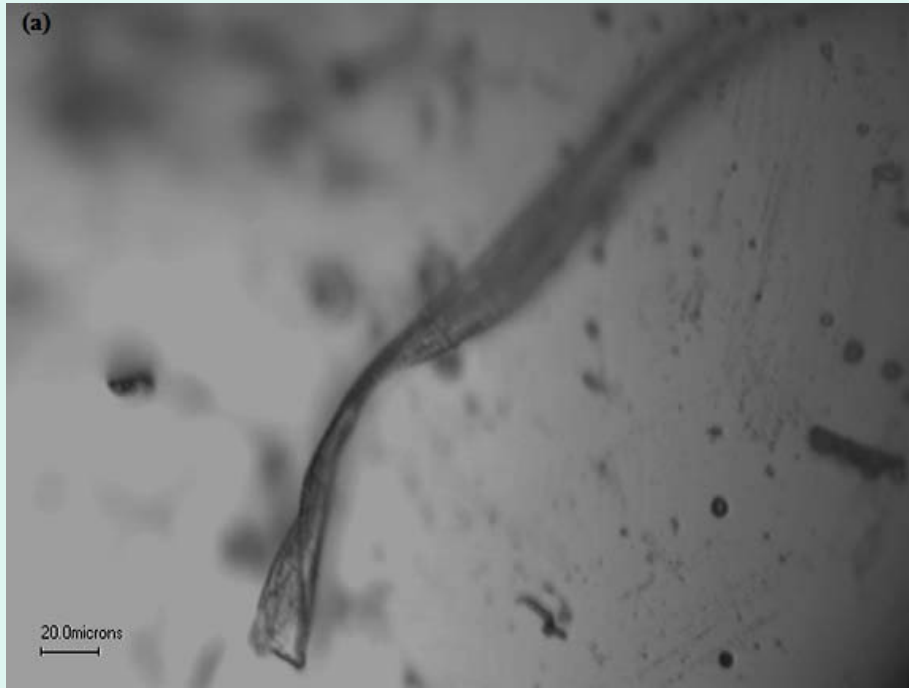
- Recommended machining parameters for commercial manufacturing of CVD-SiC
- The actual depths are usual about 50% of the programmed depths of cuts (due to elasticity)
- Best surface finish is achieved from the lowest feed

Results for final machining (surface roughness)



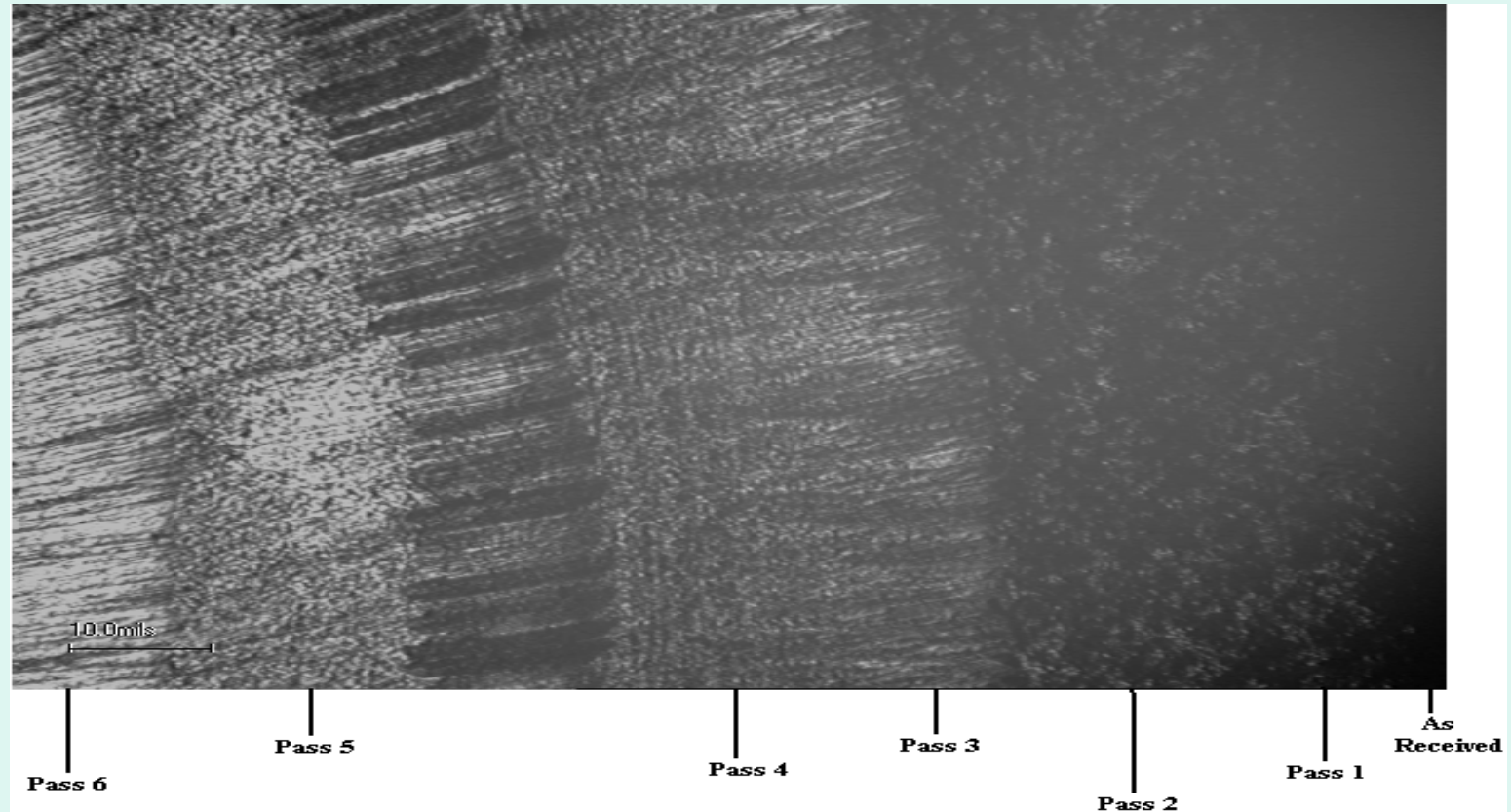
- Ra improved from 1.23μm to 88nm in six passes
- Rz improved from 8.9μm to 0.27μm
- Workpiece in general had lesser run-out due to flatter back

Ductile Chips from a Brittle Material



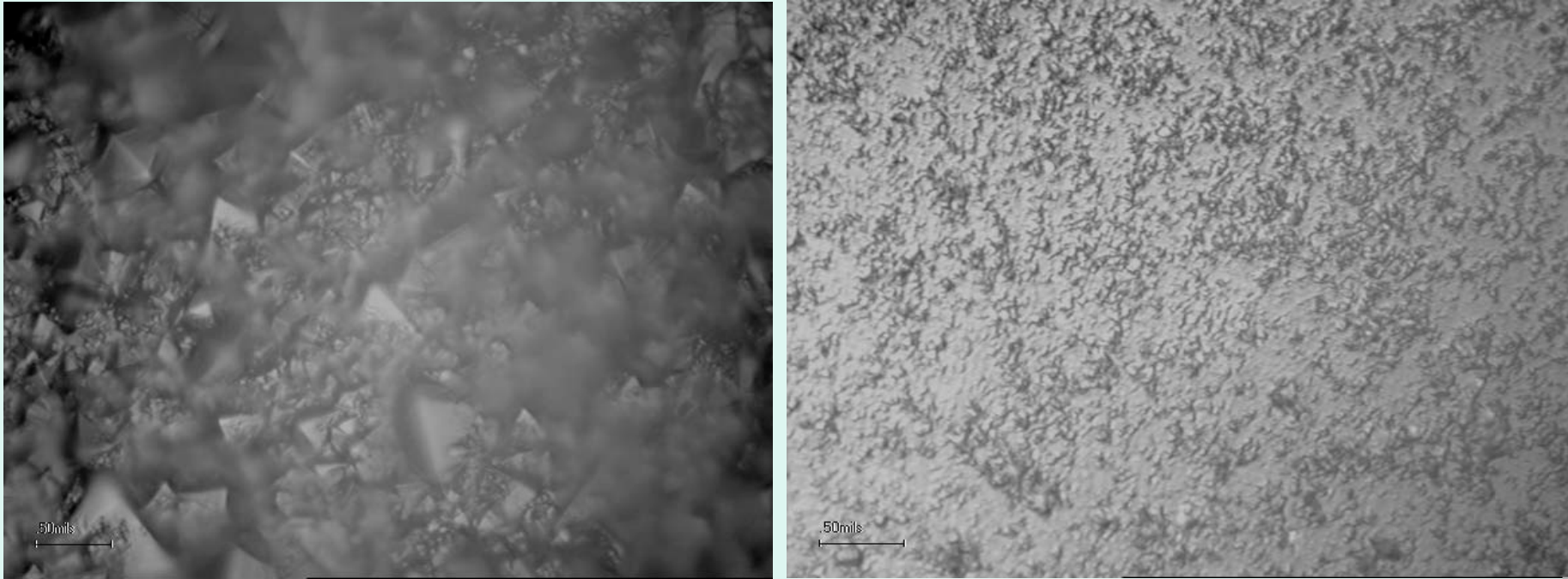
- Continuous plastically deformed chips indicate ductile mode machining.
- Both images were taken at a 400x magnification

Results *(Surface image of 6 passes)*



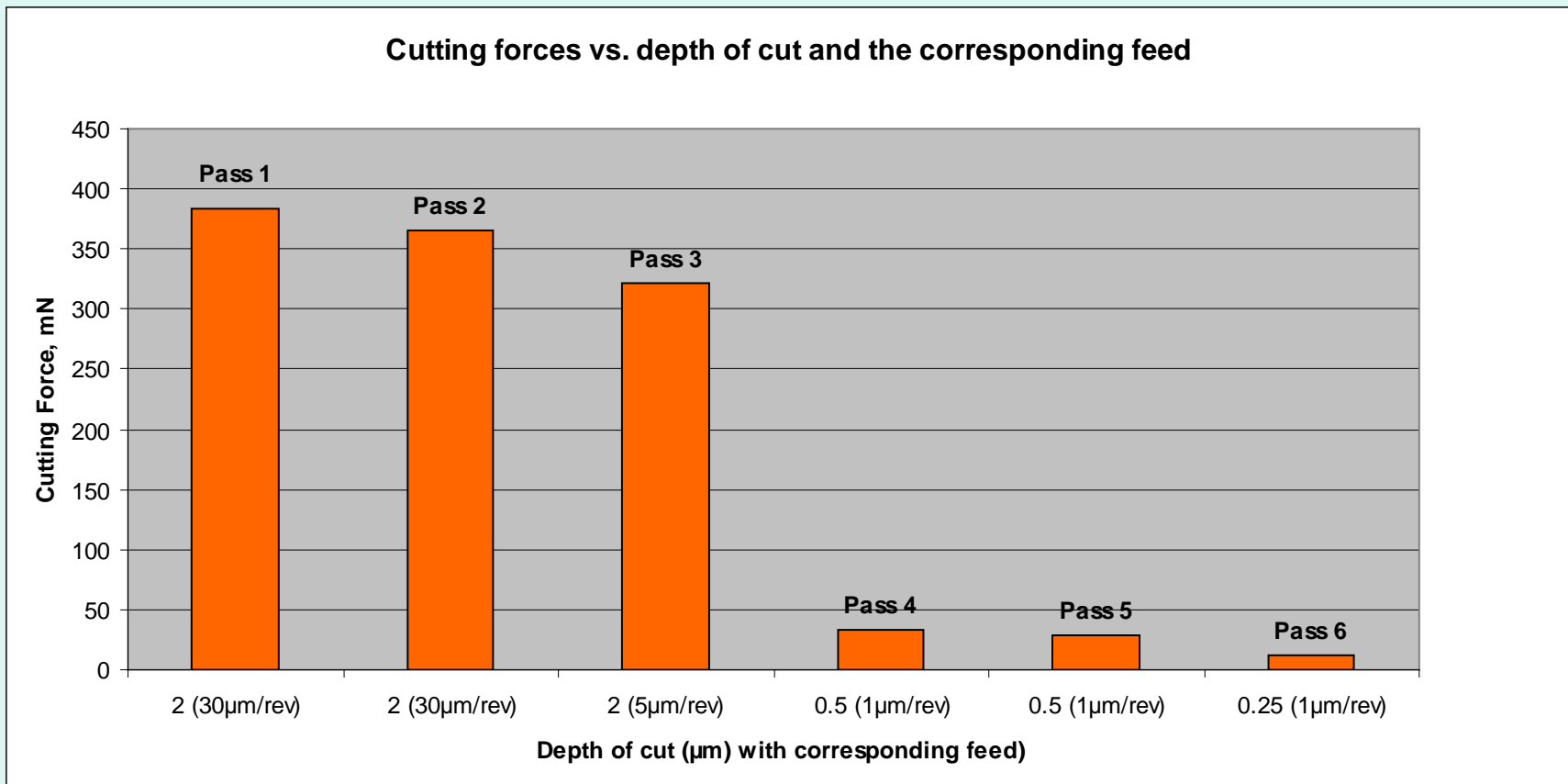
- Image was taken at 50x magnification
- Surface continuously improved after each pass
- Band between pass 4 & 5 was due to tool chatter

Results *(Surface image comparison)*



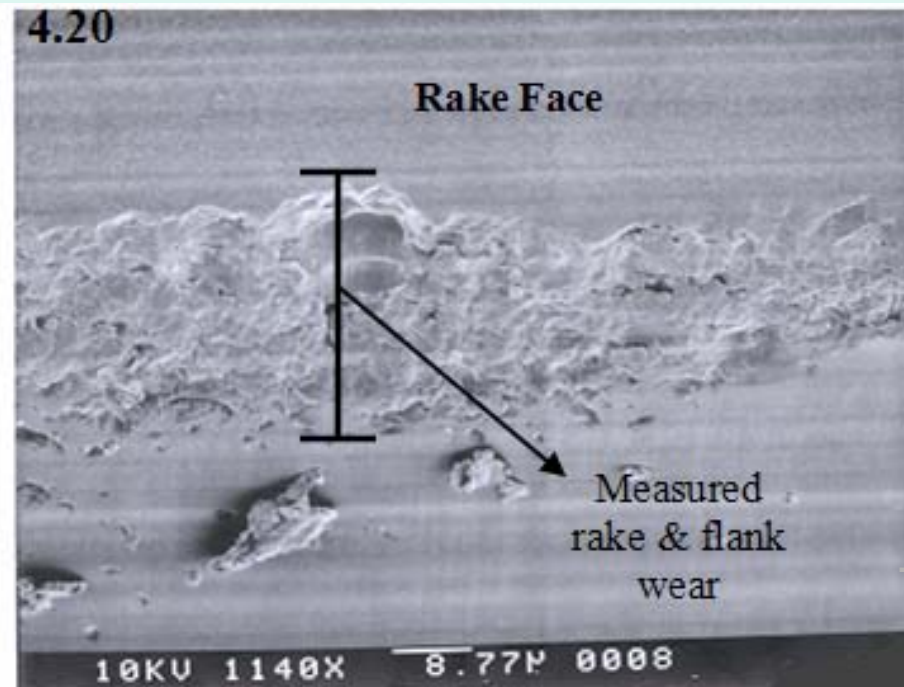
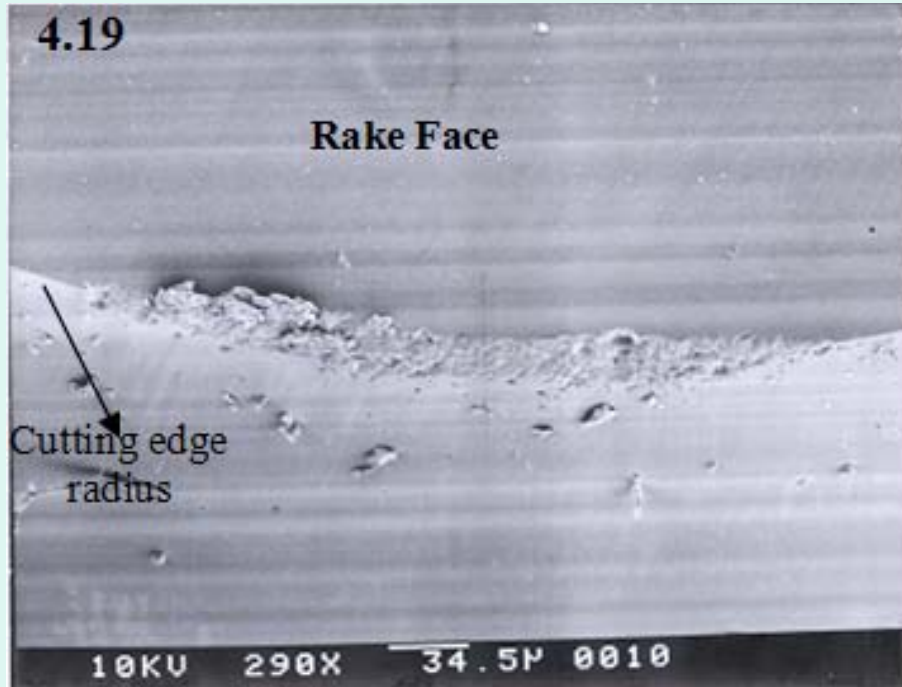
- Images comparing the surface before (left) and after (right) SPDT
- Images were taken at a 1000x magnification
- The sharp/uneven peaks on the surface disappeared after the SPDT operation

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

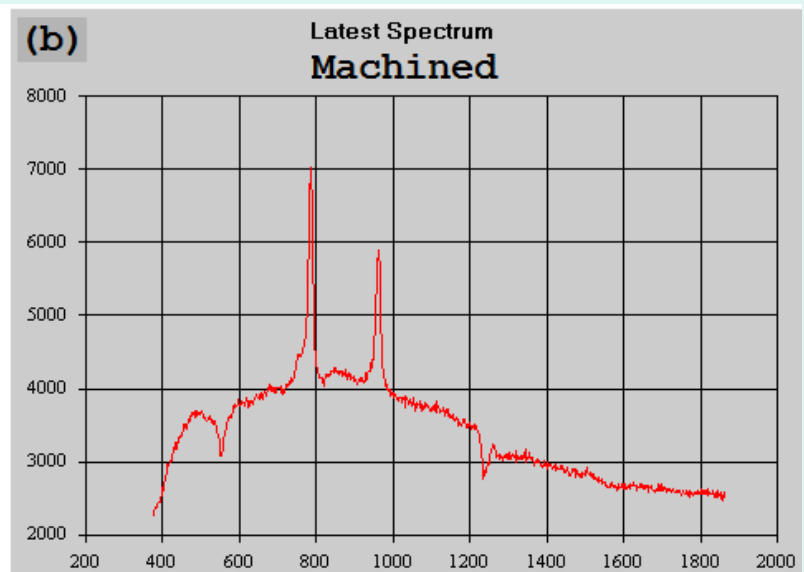
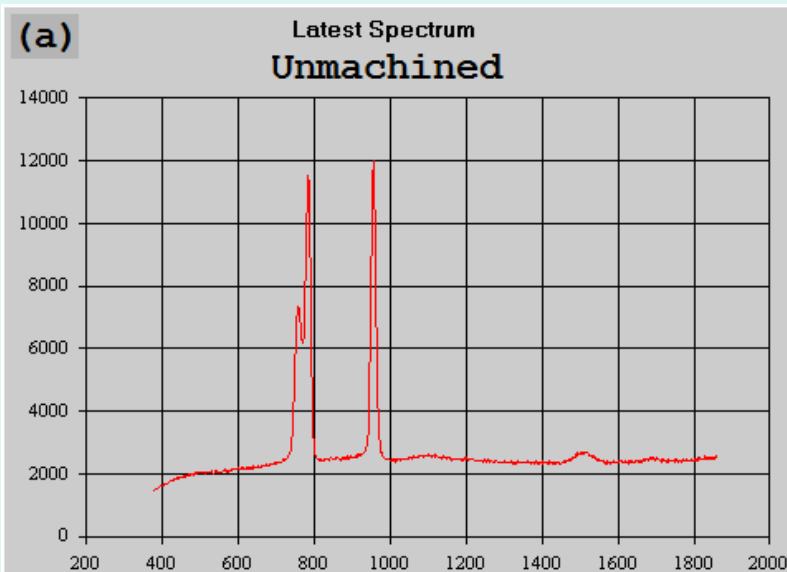
Results (*SEM images of tool wear*)



- Tool was used for pass 1 (2 μ m depth & 30 μ m/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)

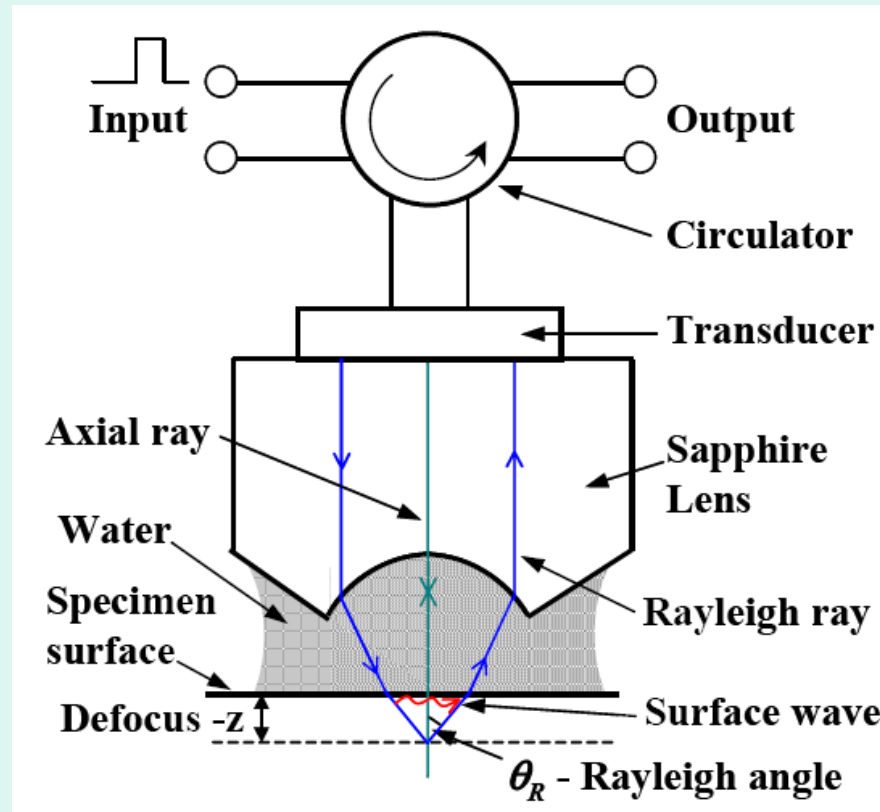
Laser μ -Raman

- 633nm wavelength He-Ne laser



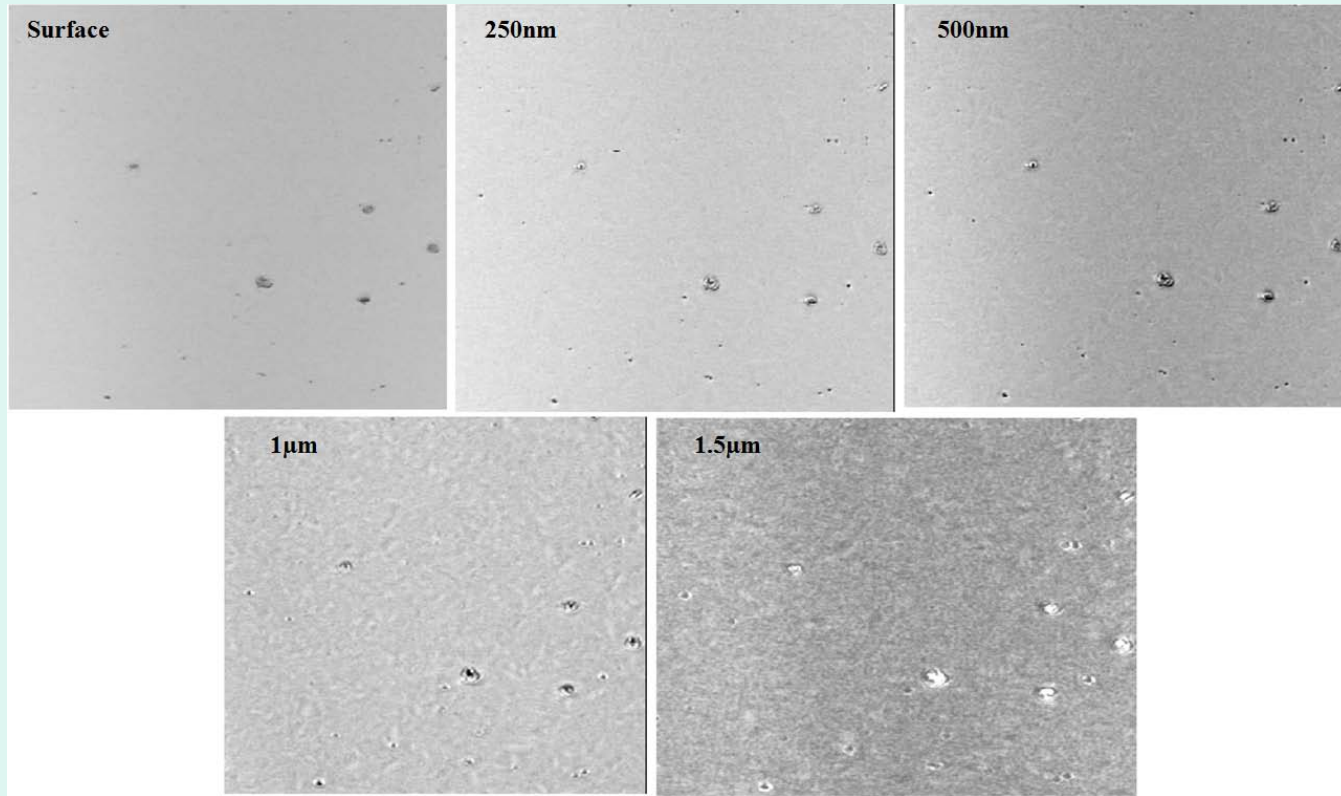
- Amorphous peak is observed in the machined region

Scanning Acoustic Microscopy



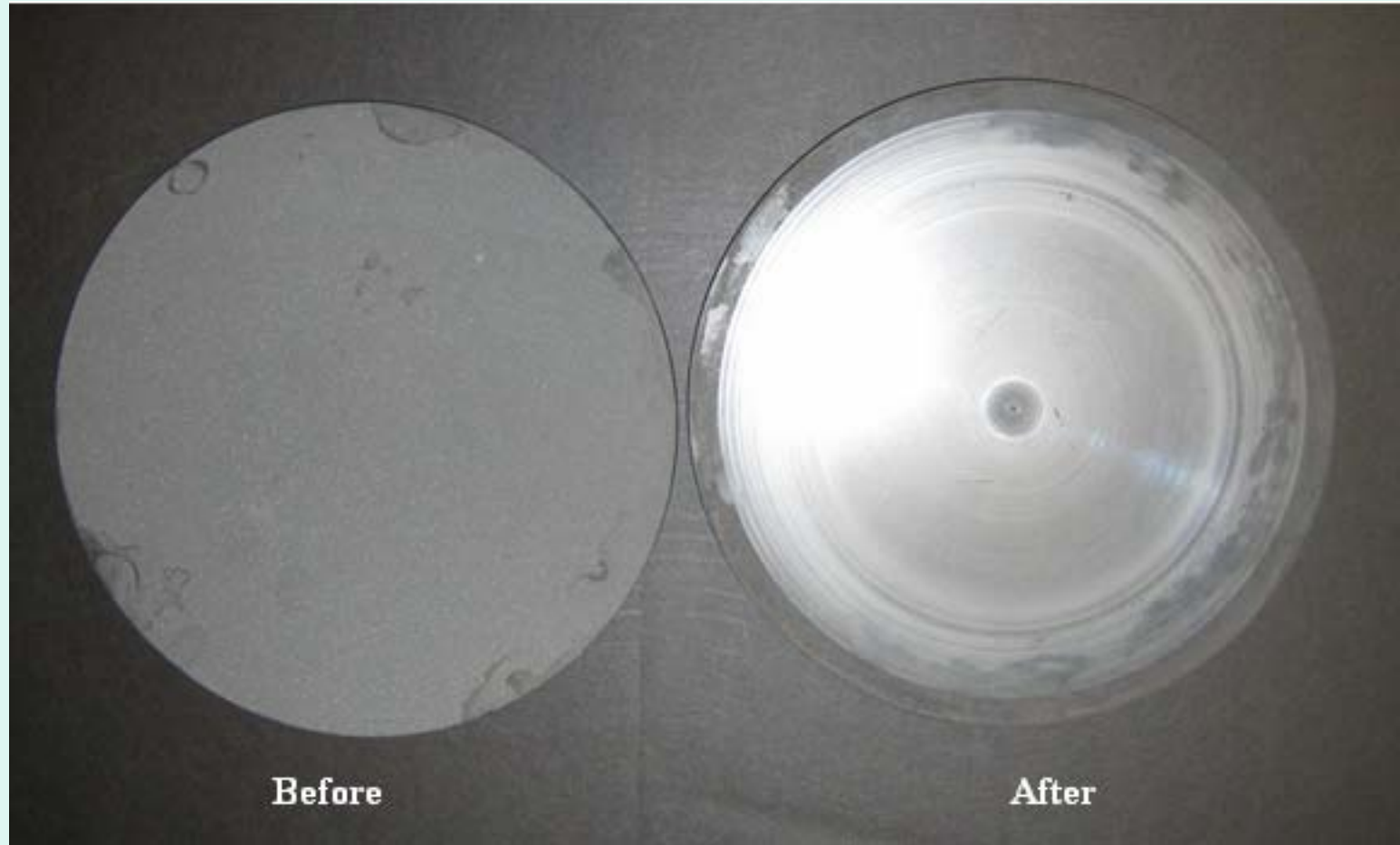
- Scientific Instruments (KSI) SAM2000 (ORNL)
- High-frequency acoustic waves (60MHz to 2.0GHz)

Scanning Acoustic Microscopy



- Images show no signs of subsurface cracks or damage
- Features seen are pits and voids that existed in the as received material

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



Use of final SiC & Quartz disk



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

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 of AlTiC
 - Scratch tests using variable loads
 - Cuts were imaged using AFM, while light Interferometer & profilometer

Other projects accomplished...continued

- 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
- Ductile to Brittle Transition of Sapphire
 - Scratch tests using variable loads
 - Cuts were imaged using AFM, while light Interferometer & profilometer
- Ductile to Brittle Transition of AlON
 - Scratch tests using variable loads
 - Cuts were imaged using AFM, while light Interferometer & profilometer

Ongoing Work

- 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
- Identifying preferred machining direction (if any) for single crystal CVD-SiC
 - Scratch tests in different cutting directions on single crystal SiC wafers to observe ductile to brittle transition (DBT)
 - Cuts in different cutting directions should yield various DBT's (possibly identify the most preferred cutting direction)
- Development of In-situ Nanomachining instrument (in a SEM)
 - Able to monitor real time material removal
 - Possibly observe real time phase transformation

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).

Thank you