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Advancement of Ceramic Machining
세라믹 재료 활용을 위한 절삭공정의 가능성

Hae-Sung Yoon, Suk Bum Kwon, Aditya Nagaraj

Sangkee Min

Manufacturing Innovation Network (MIN) LAB
University of Wisconsin-Madison

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Sangkee Min
Associate Professor, Mechanical Engineering
Fellow, Grainger Institute for Engineering
Manufacturing Innovation Network Laboratory (MIN LAB)

Expertise

- Machining: Conventional and Ultra-precision, Burr minimization/prevention
- Machine design: Hybrid machines, Ultra-precision machines
- Sustainable manufacturing: Energy consumption of machine tools and energy savings strategy using IIOT
- New manufacturing paradigm: MFD
- Manufacturing R&D policy

Previously

- Lawrence Berkeley National Laboratory, Berkeley, CA
- Mori Seiki, Davis, CA
- Otismed, San Francisco, CA

Contact info

Email: sangkee.min@wisc.edu
Website: https://min.me.wisc.edu/

Characteristics, potential, issues

INTRODUCTION

Engineering materials

- Requirements to be considered as an engineering material
  - Abundant
  - Cheap
  - Scalable

- Emerging materials
  - New materials: newly synthesized materials
  - Crisscrossing materials: unconventional set of materials for a specific industry
  - Transforming materials: transformation of non-engineering materials to engineering materials due to advancement of material technology, fabrication technology, and new applications requiring specific material properties

New requirements in manufacturing

- Emerging new materials and revaluation of existing materials
  - Crisscrossing materials
  - Transforming from non-engineering materials to engineering materials
  - Newly synthesized materials

- Materials strategy
  - Easy to manufacture materials: low energy life cycle
  - Critical materials including strategic materials
  - Light weight materials

- Manufacturing requirements
  - Fabrication method for new materials
  - Accommodation of emerging demand
  - Substituting existing manufacturing practice

What is ceramics?

- What's ceramics?
  - Types of atoms
  - Types of bonding between the atoms,
  - The way the atoms are packed together
- Bond: ionic and covalent
  - Ionic: one of the atoms (the metal) transfers electrons to the other atom (the nonmetal), thus becoming positively charged (cation), whereas the nonmetal becomes negatively charged (anion). The two ions having opposite charges attract each other with a strong electrostatic force. This is predominant.
  - Covalent: Covalent bonding instead occurs between two nonmetals, in other words two atoms that have similar electronegativity, and involves the sharing of electron pairs between the two atoms.

Properties of ceramics

General characteristics

- High hardness
- High elastic modulus
- High dimensional stability
- High wear resistance
- High resistance to corrosion and chemical attack
- High weather resistance
- High melting point
- High working temperature
- High compressive strength

- Low ductility
- Low thermal expansion
- Low to medium thermal conductivity
- Low to medium tensile strength
- Low thermal shock resistance
- Brittleness
- Poor impact strength
- Opacity
- Good electrical insulation
- Medium machinability

- Bio compatible
- Resistance to radioactive degradation

Fabrication method

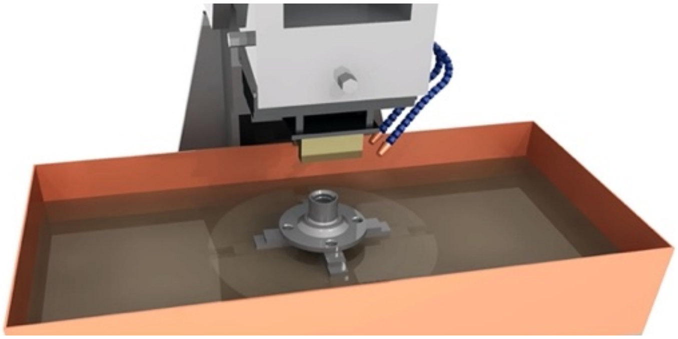
- Sintering
- Abrasive machining
- Energy based machining
- Mechanical machining

Fabrication method

Sintering

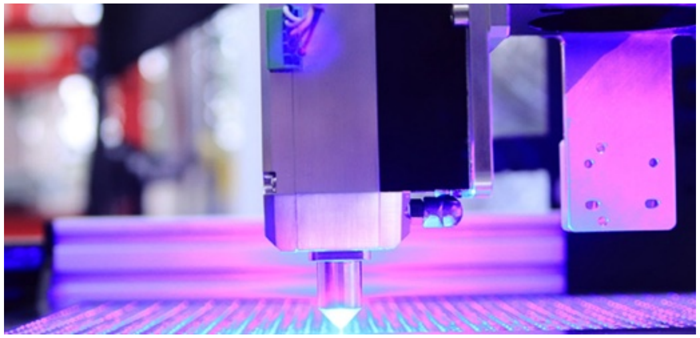
Source: https://www.axsysdental.com/noc/Content/Images/uploaded/FurnaceBackgroundWM.jpg

EDM



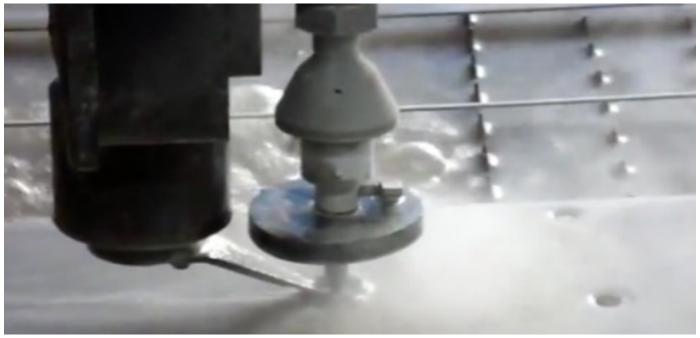
Source:https://www.iqsdirectory.com/

Laser machining



Source:https://precision-ceramics.com/

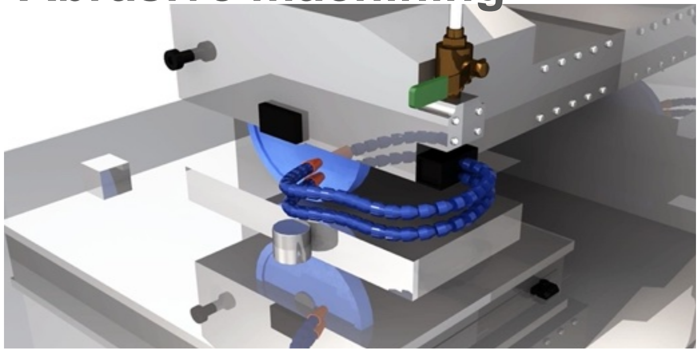
Abrasive jet machining



Source:https://www.manufacturingguide.com/

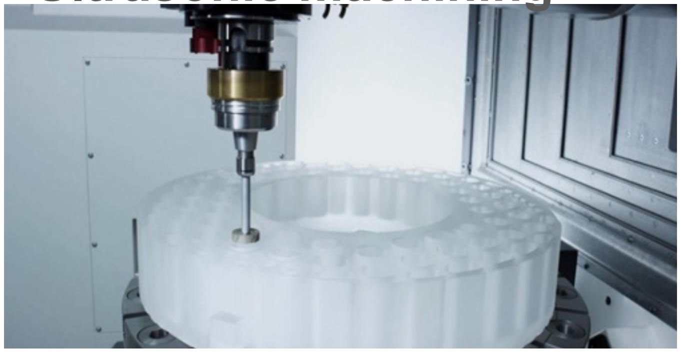
Fabrication method

Abrasive machining



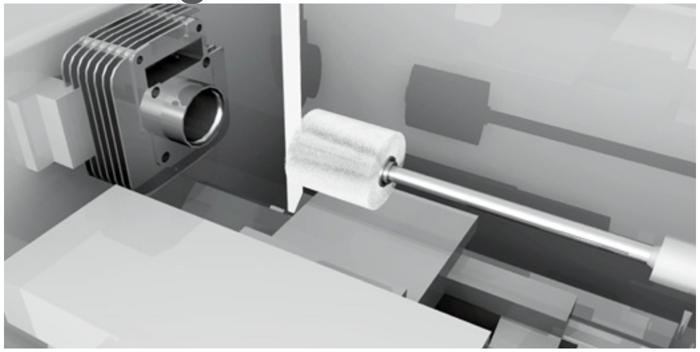
Source:https://www.iqsdirectory.com/

Ultrasonic machining



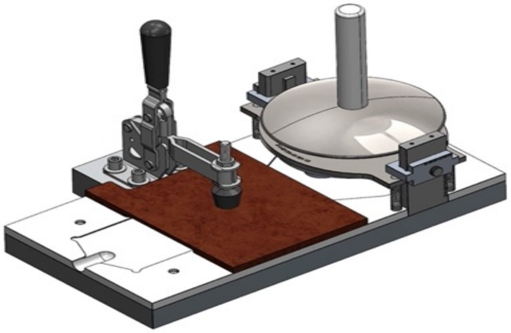
Source: https://immechanical.blogspot.com/

Honing



Source:https://www.iqsdirectory.com/

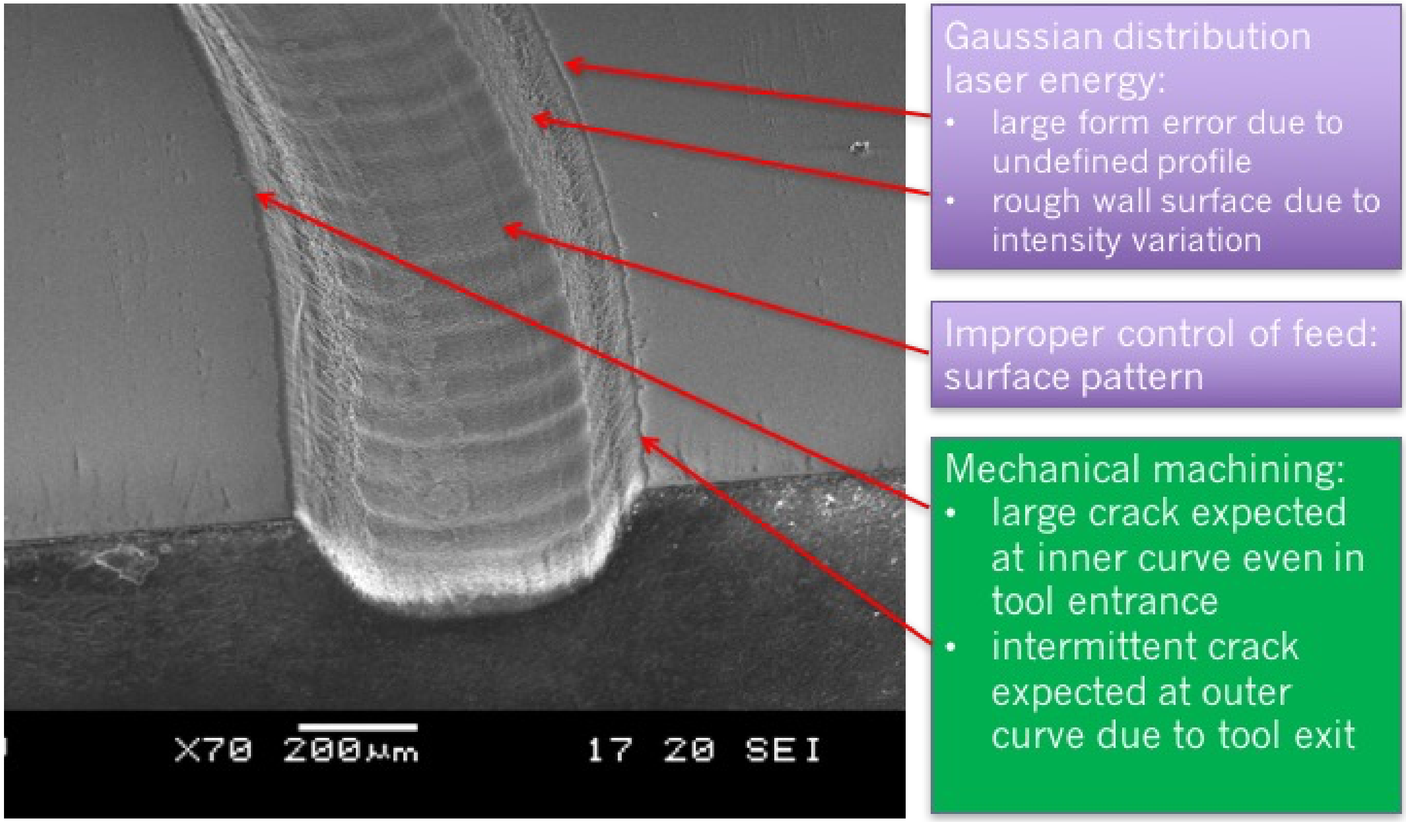
Lapping and polishing



Source:https://www.iqsdirectory.com/

Limitation

Curved channel by laser



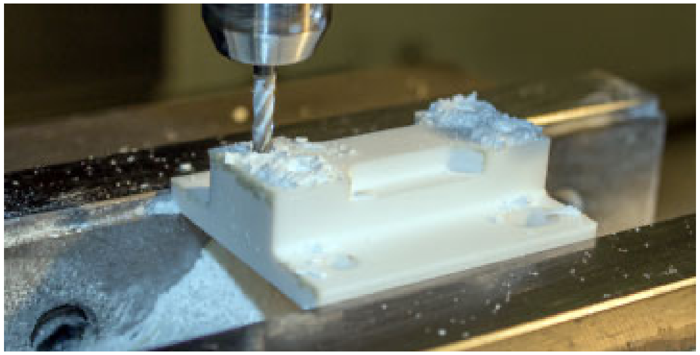
Gaussian distribution laser energy:
- large form error due to undefined profile
- rough wall surface due to intensity variation

Improper control of feed: surface pattern

Mechanical machining:
- large crack expected at inner curve even in tool entrance
- intermittent crack expected at outer curve due to tool exit

Mechanical Machining

Mechanical machining



Source: https://straton.com/wp-content/uploads/2017/06/ceramic-machining-2.jpg

- Advantage
  - Full 3D feature generation
  - Defined cutting edge
  - Precision
- Disadvantage: Machinability due to hard and brittle
  - Crack and fracture: uncontrollable?

- Advantage
  - Full 3D feature generation
  - Defined cutting edge
  - Precision
- Disadvantage: Machinability due to hard and brittle
  - Crack and fracture: stochastic and unpredictable?

Machinability

Crack and fracture

- Stochastic event → Mechanics behind
- Unpredictable → Predictable
- Uncontrollable → Controllable

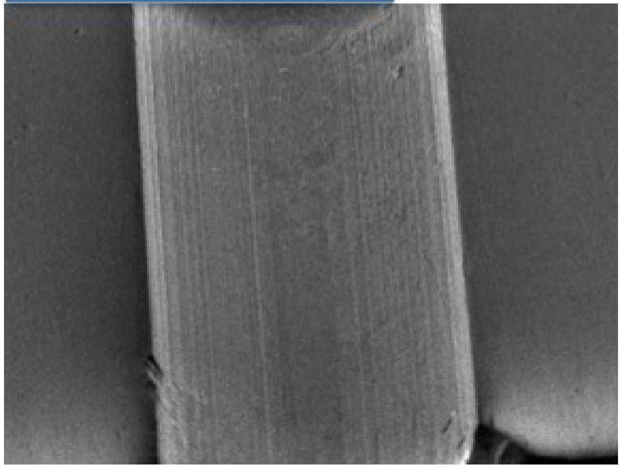
Material removal rate

- Critical depth of cut for ductile mode cutting
- Cutting speed
- Anisotropy

Comparison

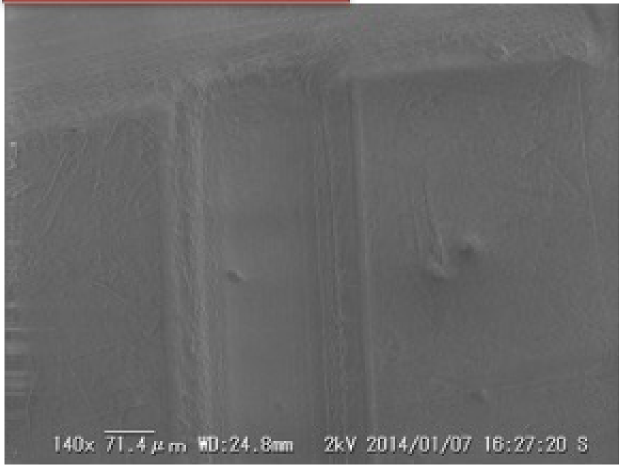
Surface comparison

Mechanical machining



RA: 0.452 *mm* PV: 1.980 *mm*

Laser processing



RA: 2.794 *mm* PV: 22.102 *mm*

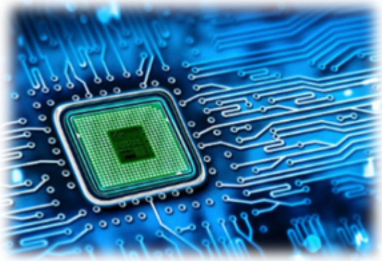
Potentials


Optics [1]


LED substrate [2]


Dental application [5]


Biomedical implants[3]


Electrical components [4]


Sapphire wafer [6]

Figure. Application of single-crystal ceramics

Source: [1] www.zamnesia.com; [2] www.newport.com; [3] ua.all.biz; [6] Yoon HS, Lee S, Min S. Investigation of ductile-brittle transition in machining of yttrium-stabilized zirconia (YSZ). Procedia Manufacturing. 2018 Jan 1;26:446-53. [4] https://www.edmundoptics.com [5] https://www.nsmedicaldevices.com/ [6] https://www.cryscore.com/ [7] gizmodo.com

Sapphire

The entire case -front bezel, caseband and back bezel- is cut and milled from solid blocks of sapphire.

Optical prism and lenses made from sapphire

Sapphire glass *(from web, gizmodo.com)*

Future iPhones might Have Sapphire Crystals Instead of Glass

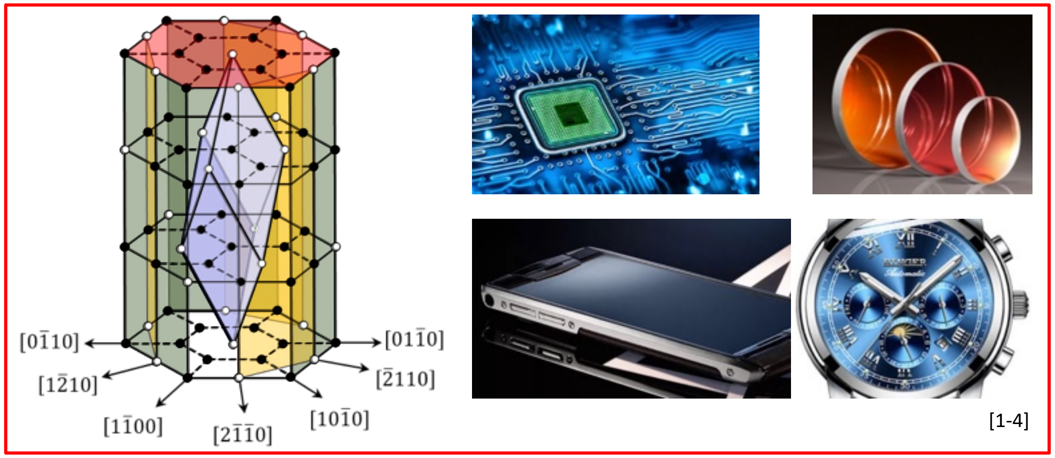
Optical domes are fabricated from sapphire, quartz, glass, silicon and germanium in sizes up to 100mm diameter with included angles to 160 degrees and dimensional tolerances to +/-10 microns. Manufactured on a highly repeatable 5-axis spherical machining center, they exhibit less than 25 microns wall thickness variation.

Sapphire

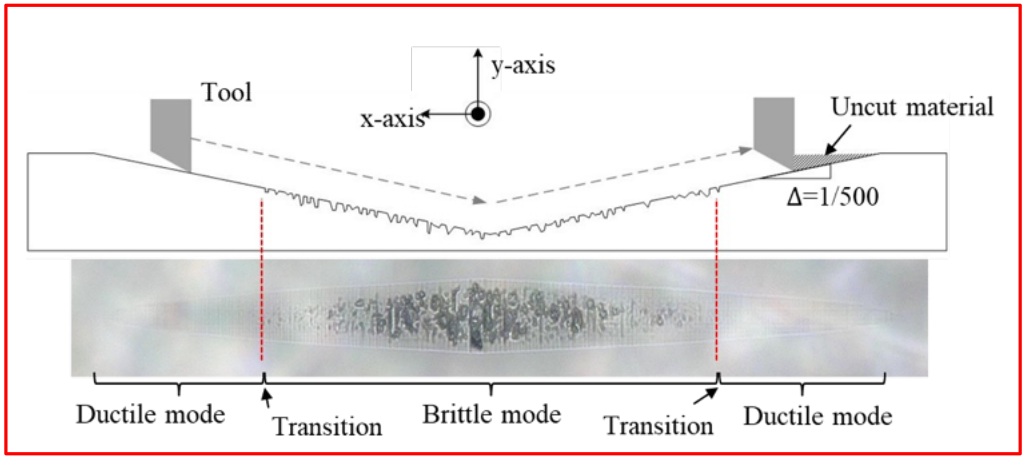
ANISOTROPY OF CRACK GENERATION

Motivation

- Single-crystal sapphire (α-Al_2O_3)
  - Hexagonal structure (space group R3c)
  - Superior material properties: mechanical, chemical, and optical properties
- Challenges in processing
  - High brittleness and hardness
  - Difficult to fabricate (low MRR, machining quality, full 3D structures or free-form surface)
- Ductile-to-brittle transition (DBT)
  - Under **very small depth of cut** (**DOC**), sapphire can be cut in ductile mode
  - Highly influenced by **crystallographic properties** and **depth of cut** (**DOC**)

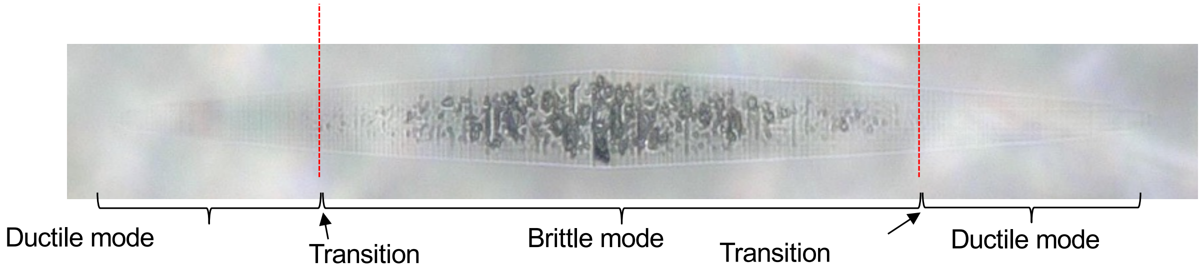


[1-4]



Potential in UPM

Found that ductile cutting is possible under a certain circumstances

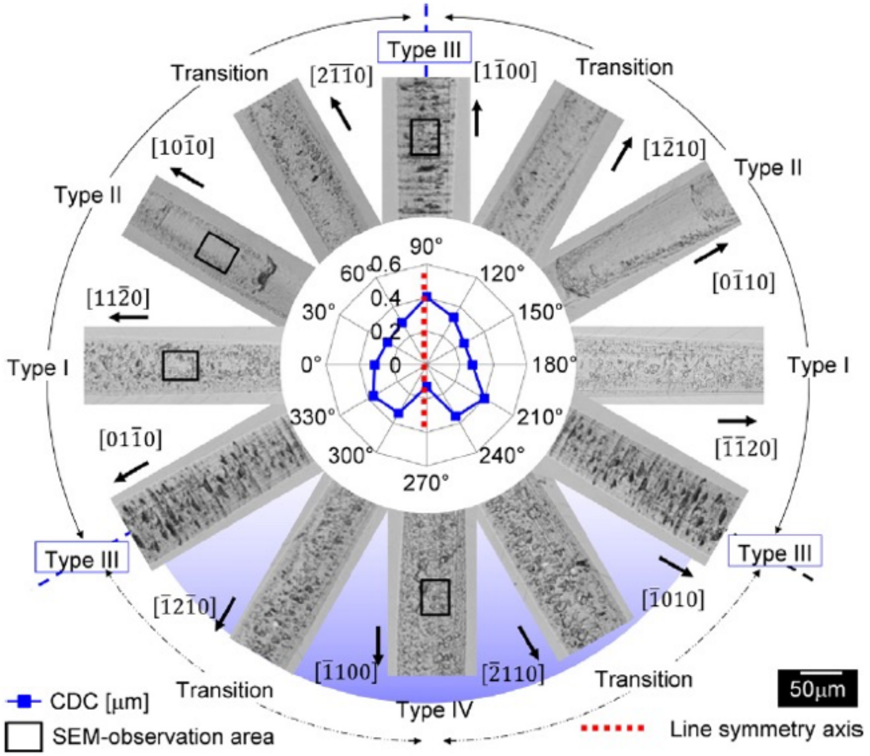


Question is

- What causes the brittle material behaves like a ductile material?
- Will this knowledge be applicable to other crystalline materials?
- Are there be any subsurface cracks or damages even the surface is smooth after machining?
- Is this process scalable?

Additional challenges

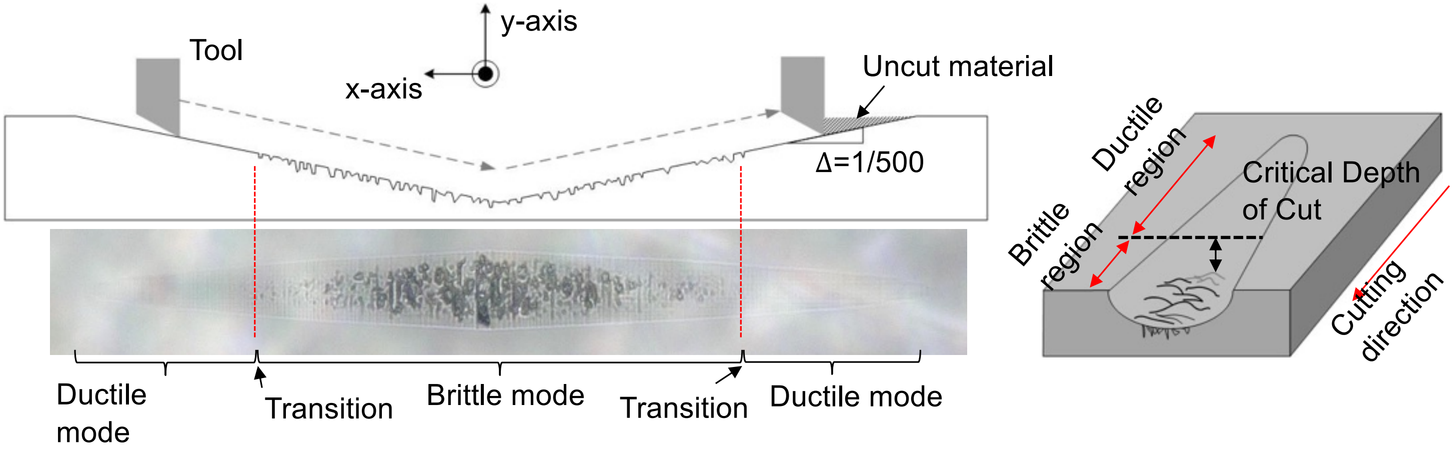
Anisotropy!



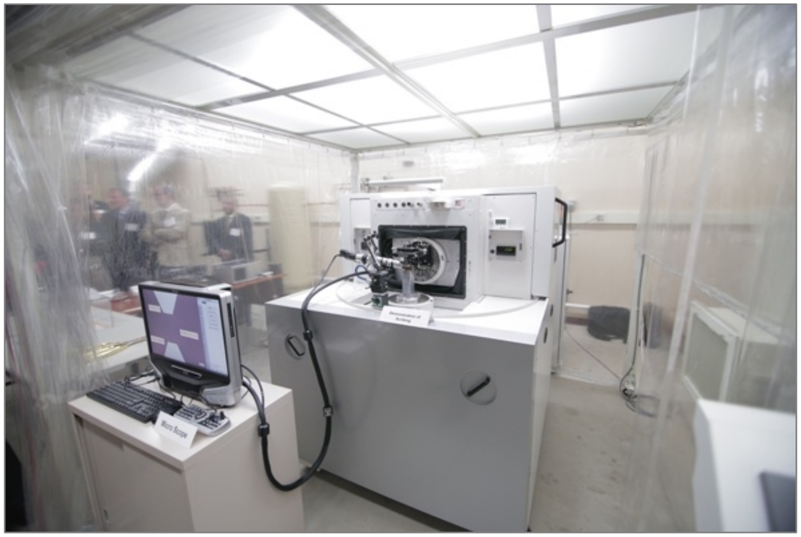
Cutting behavior of brittle materials

- Ductile, brittle, and transition mode cutting of sapphire
  - Ductile mode cutting (50 ~ 400 nm): providing better surface quality
  - Transition: Changing material removal behavior from ductile to brittle
  - Brittle mode cutting (>400 nm): crack initiations and propagations

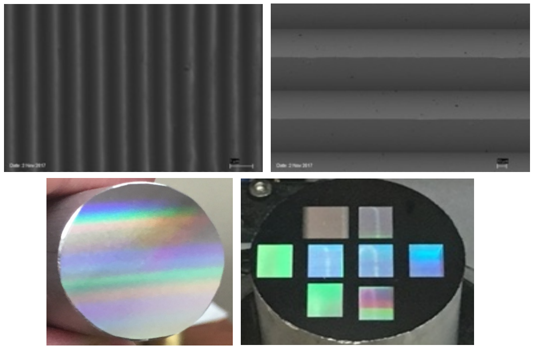
  - **Need to understand mechanism of ductile and brittle mode cutting**

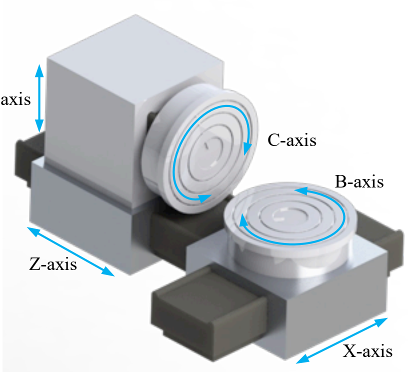


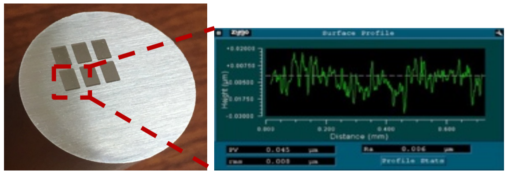
Machine



ROBONANO α-0iB
Linear axes: 1 nm
Rotary axes: 1 μ°





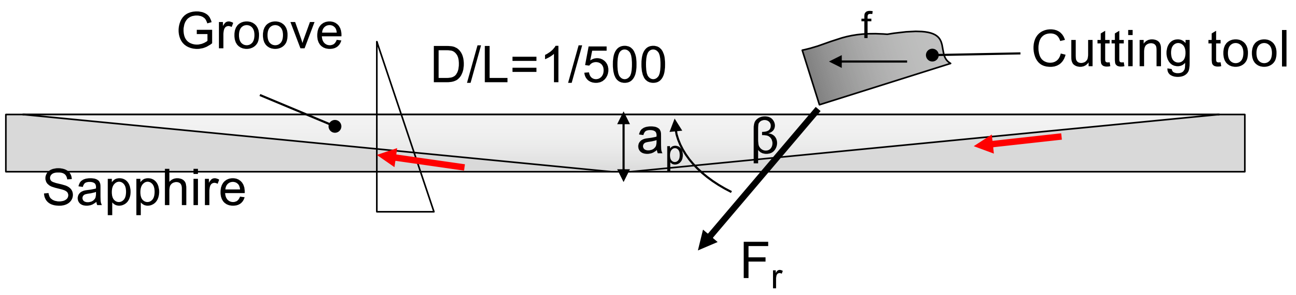


PV 0.045 μm
rms 0.008 μm
Ra 0.006 μm

Fine mirror surface: Ra 6 nm

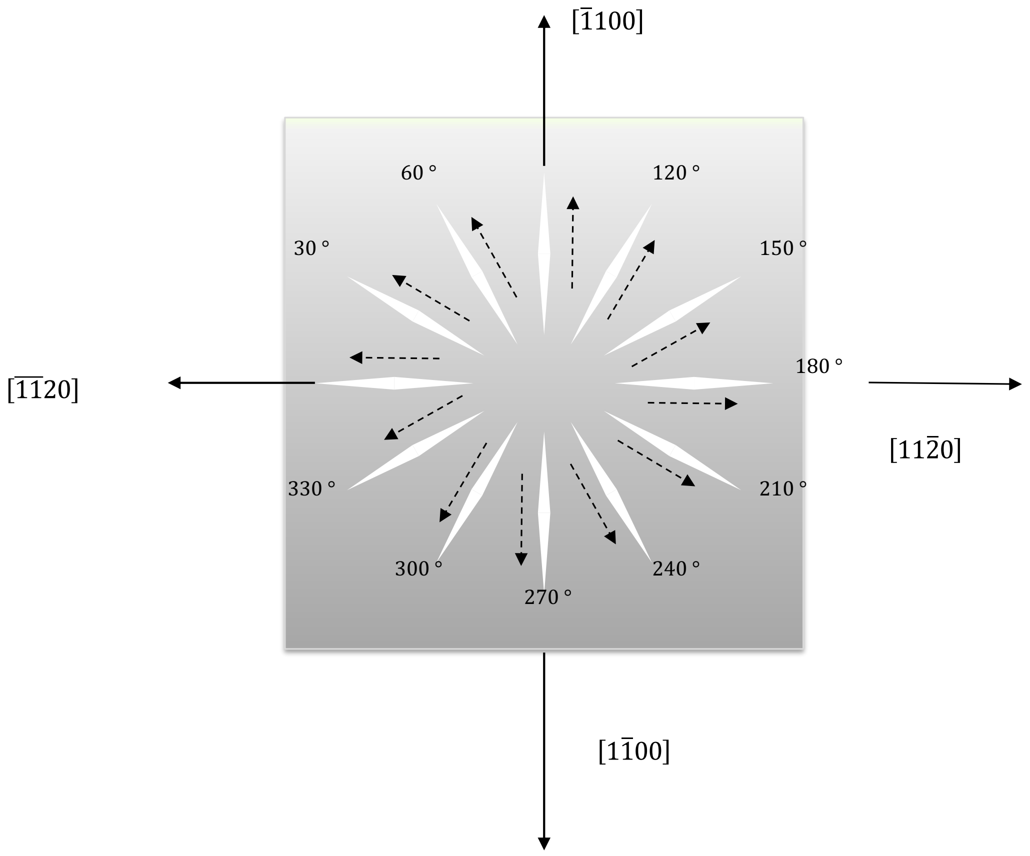
Examples of diffraction grating

Experimental procedure



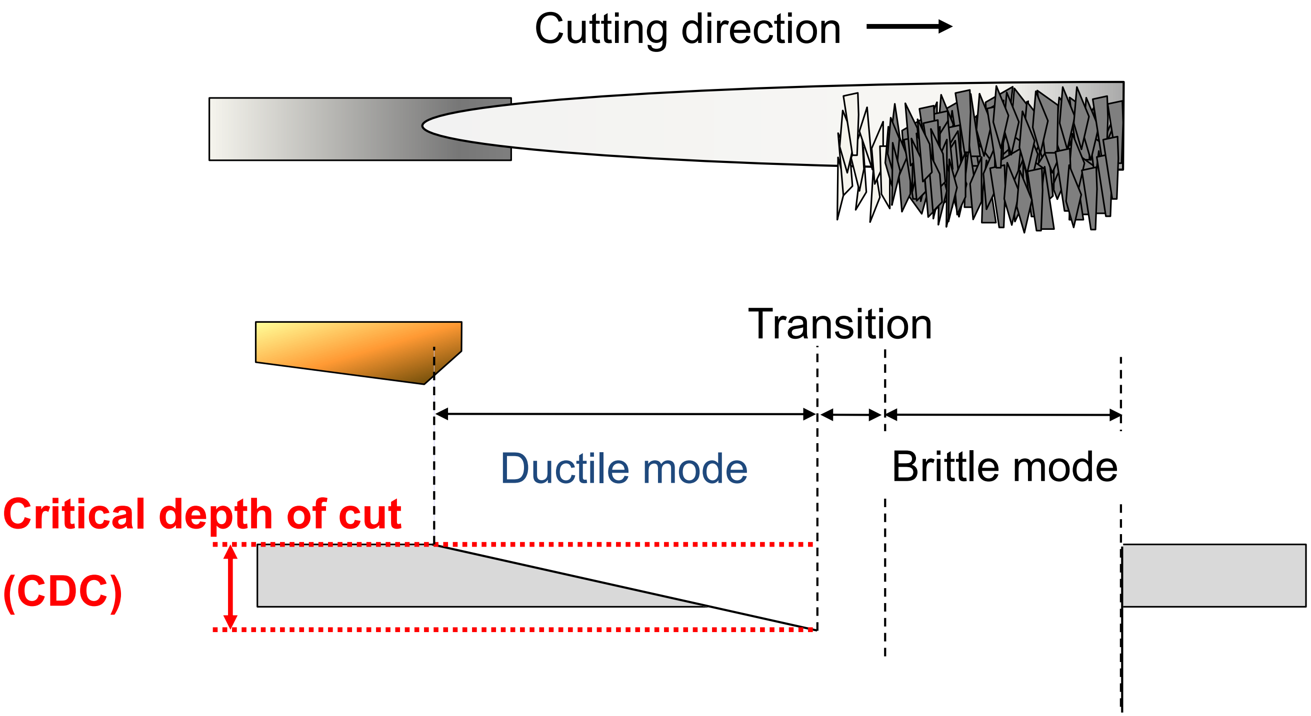
Cutting parameter	Parameter value
Feed rate f	20 mm/min
Cutting slope D/L	1/500 (0.1146°)
Depth of cut a_p	0 – 1500 nm
Cutting tool	NPD-tool (0.5 mm nose radius, 0° rake angle)

Cutting direction



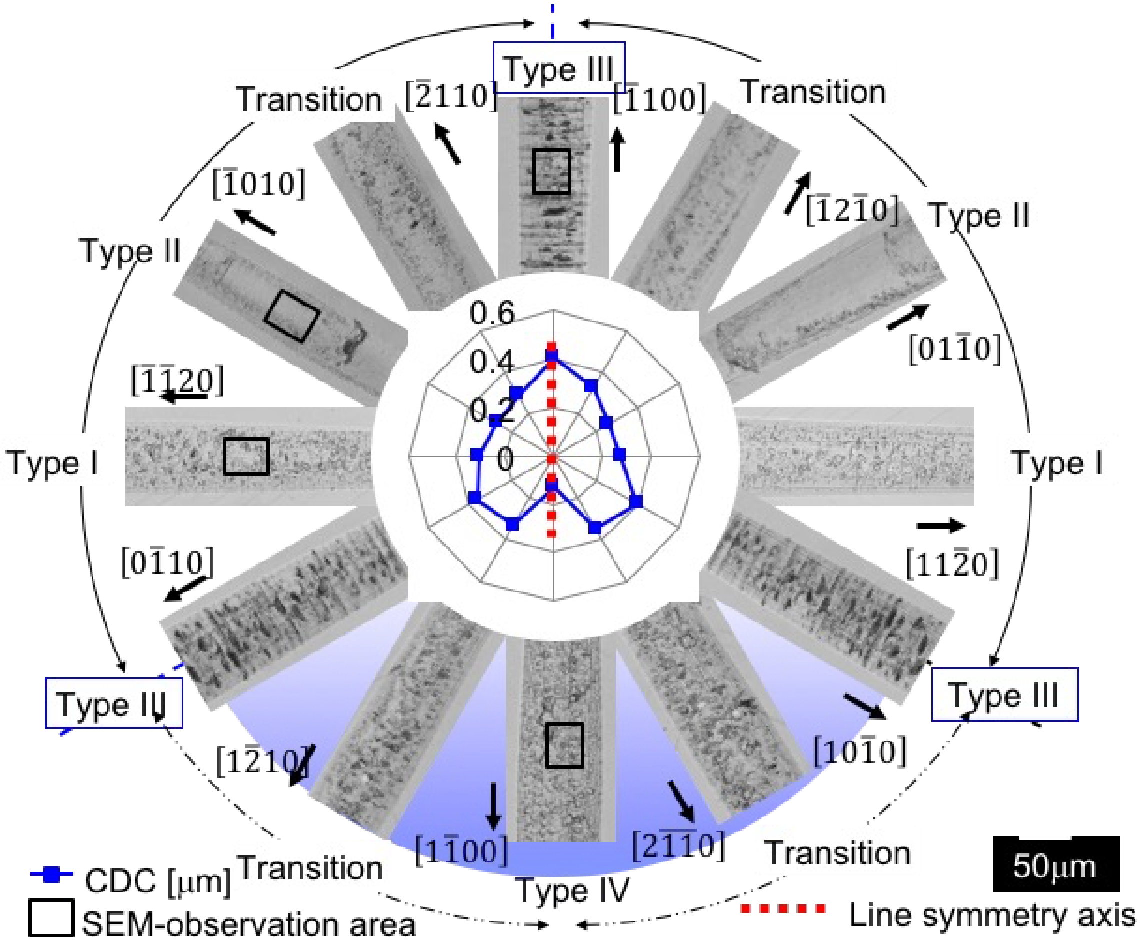
Schematic image of cutting direction

Cutting behavior of brittle materials

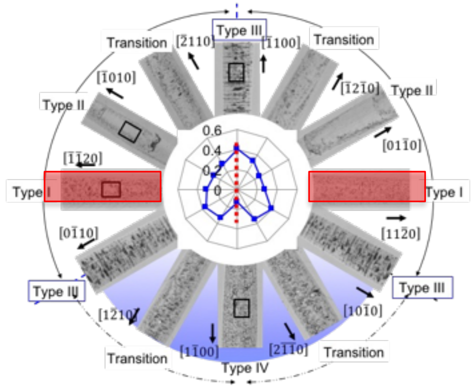


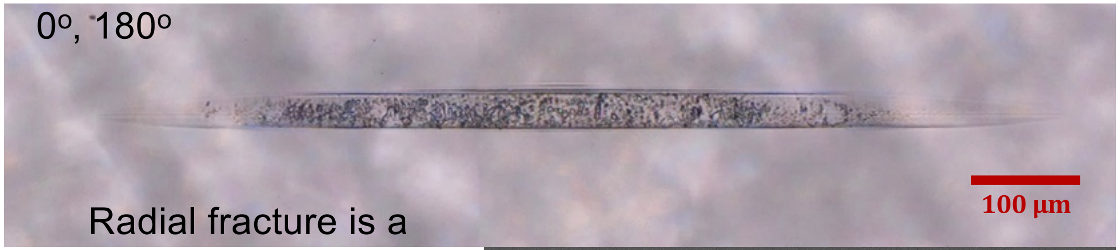
References: Mizumoto, Y., et al. (2011). "Basic study on Ultraprecision machining of Single-crystal Calcium Fluoride." Procedia Engineering ***19****: 264-269.;* Yan, J., et al. (2009). "Fundamental investigation of subsurface damage in single crystalline silicon caused by diamond machining." Precision Engineering **33**(4): 378-386.

CDC: Anisotropic behavior

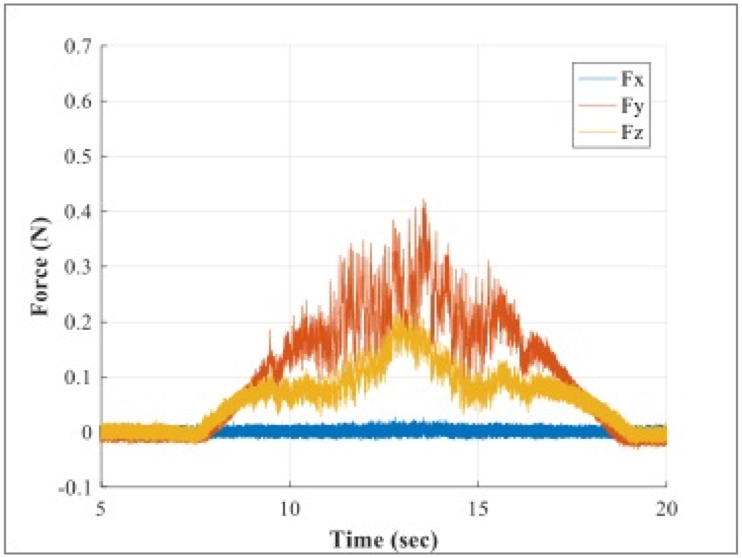


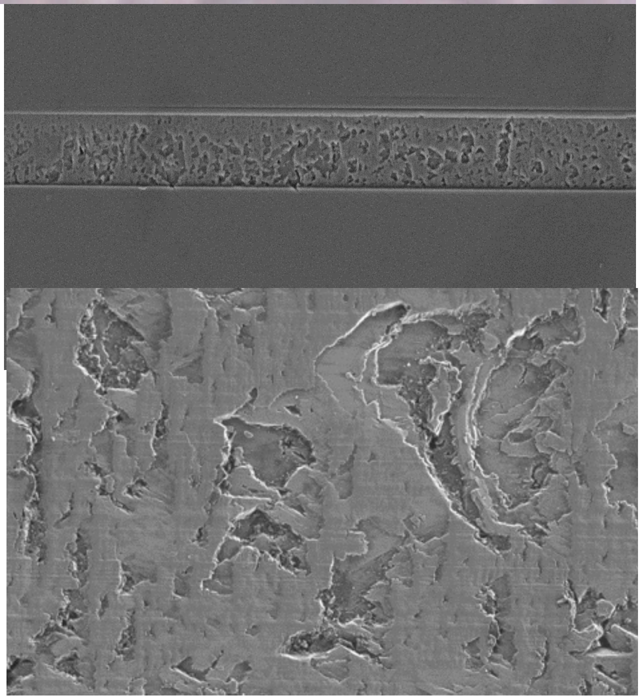
Type I: Radial fracture



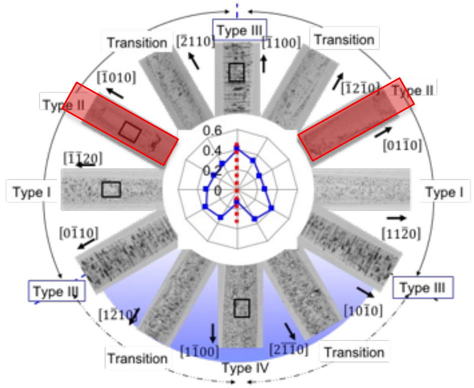


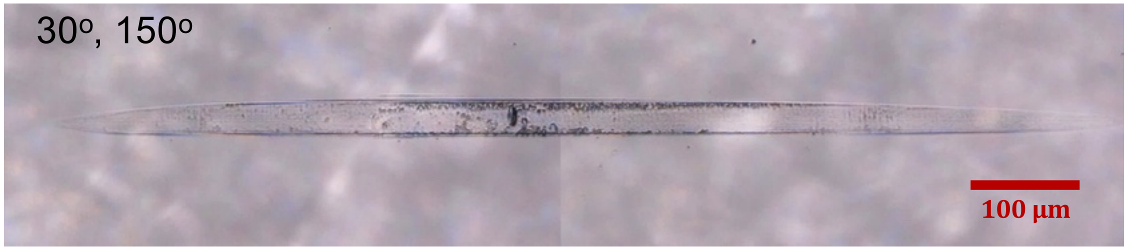
Radial fracture is a result of rhombohedral and prismatic cleavage.



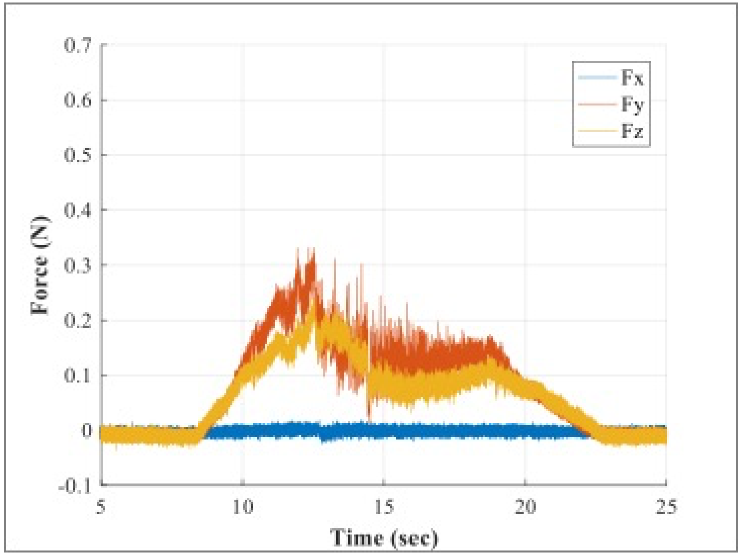


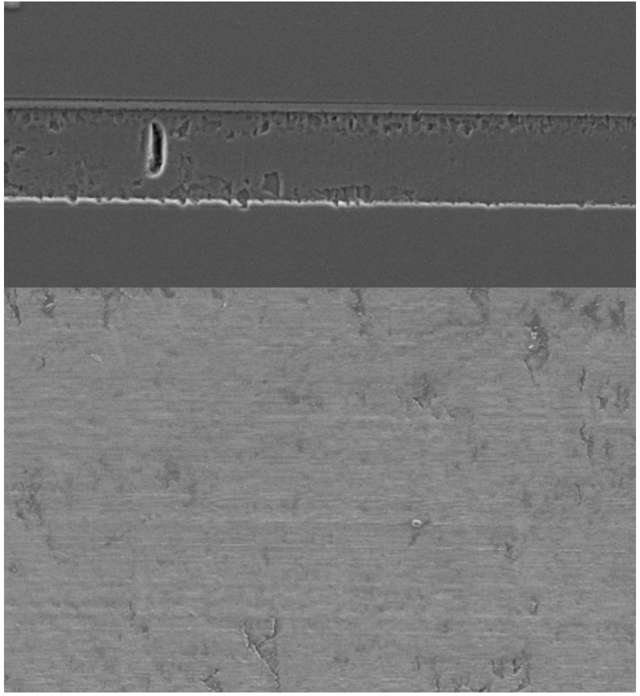
Type II: Micro-fracture



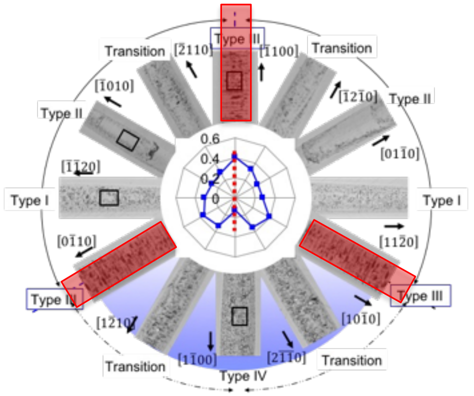

30°, 150°

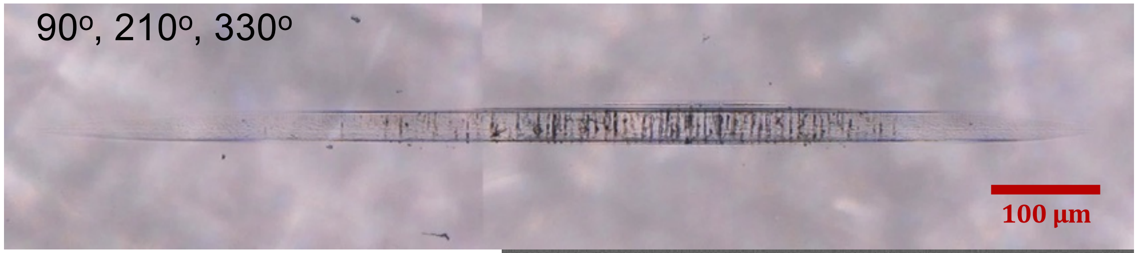
Interchanging patterns of the ductile and brittle regions



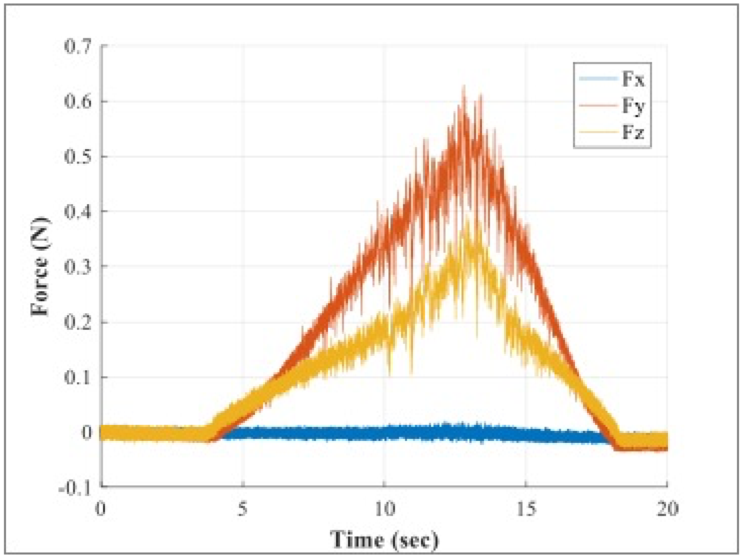


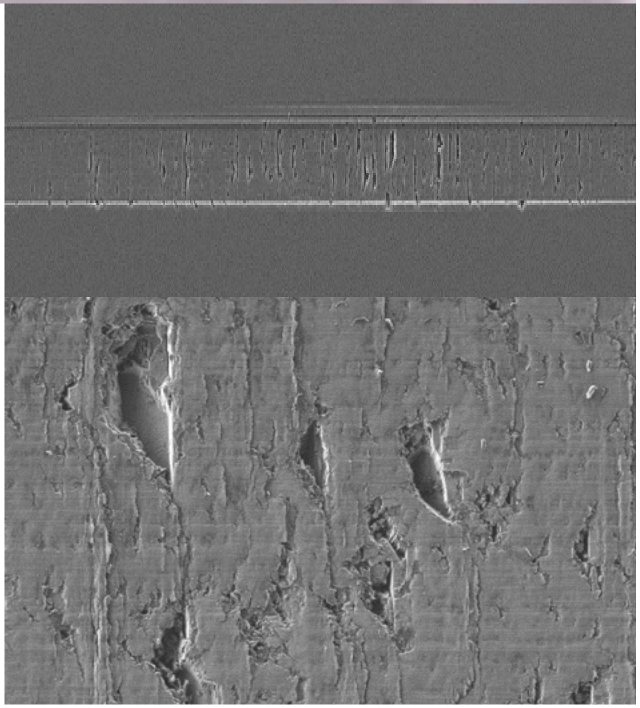
Type III: Lamella fracture



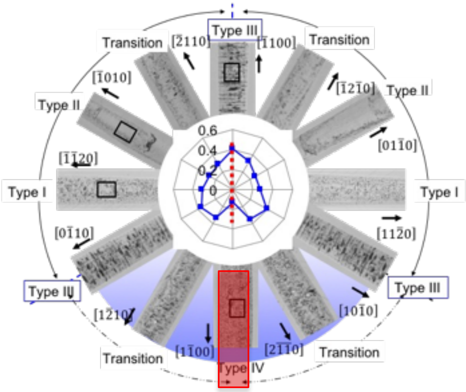

90°, 210°, 330°

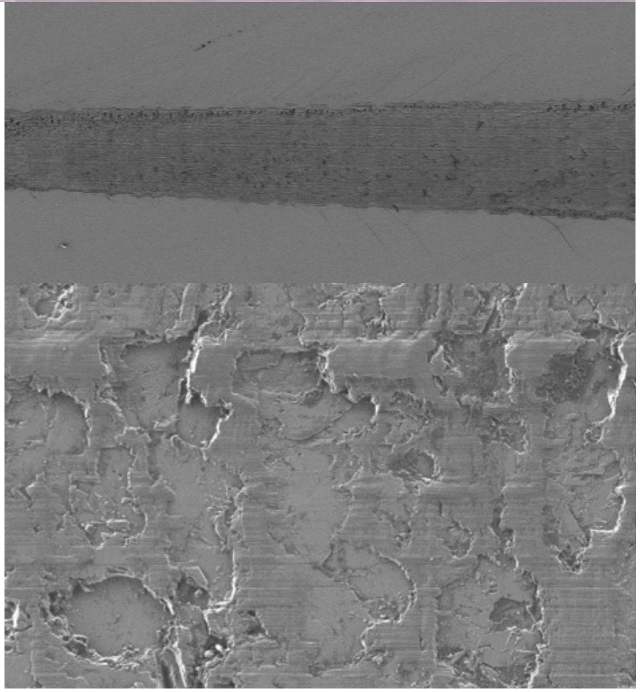
Planar breakage along the rhombohedral cleavage plane

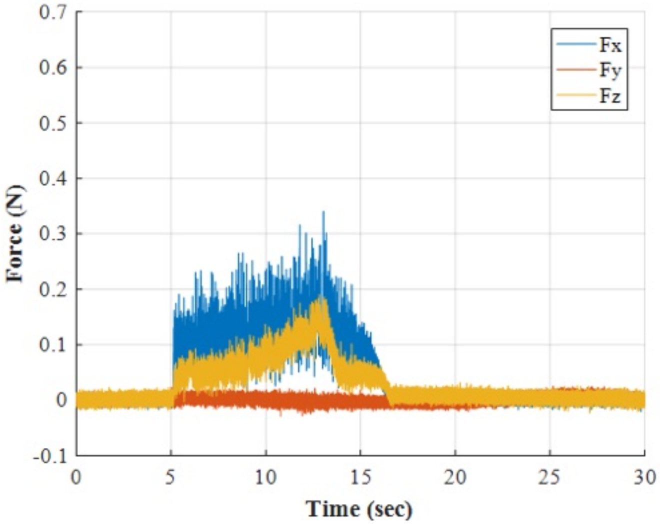




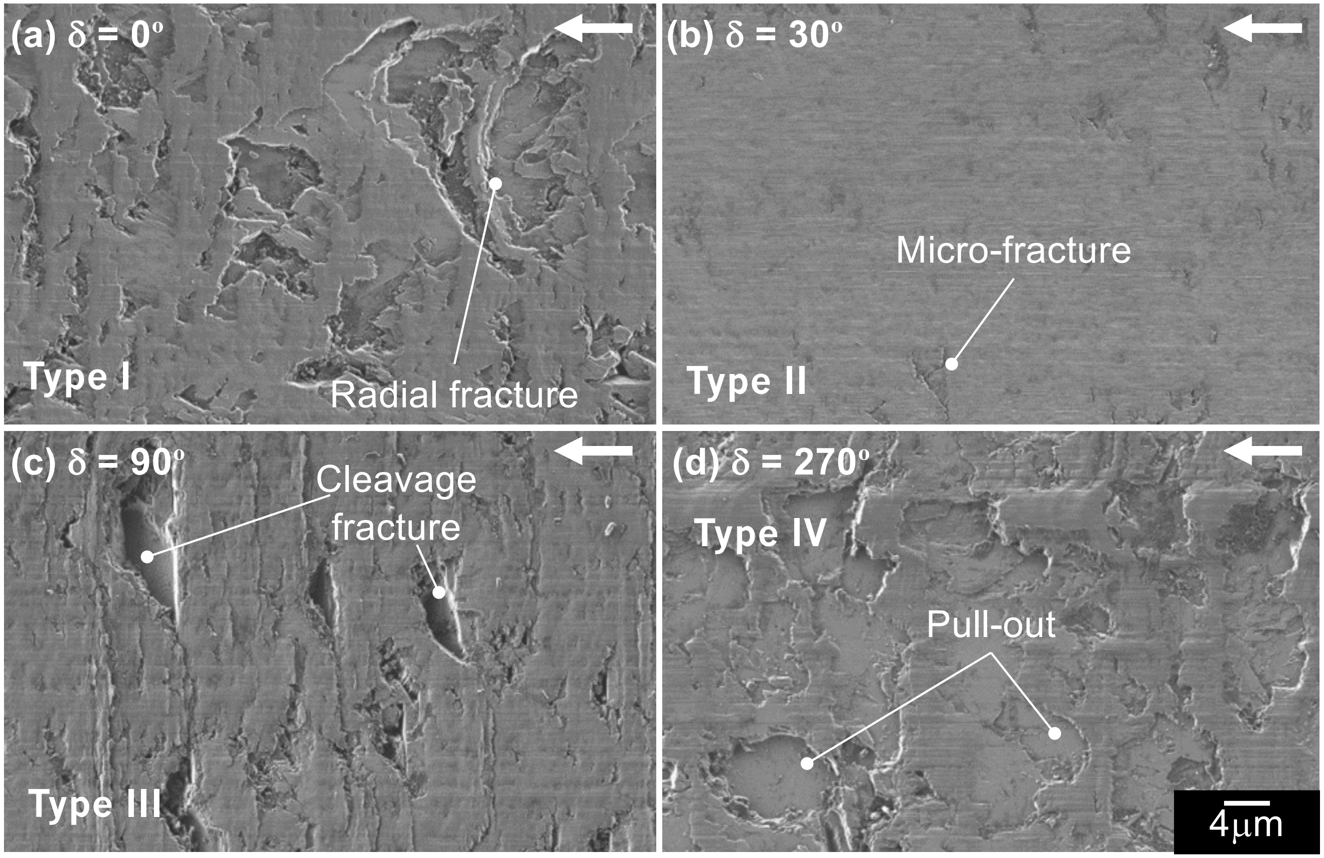
Type IV: Pull-out







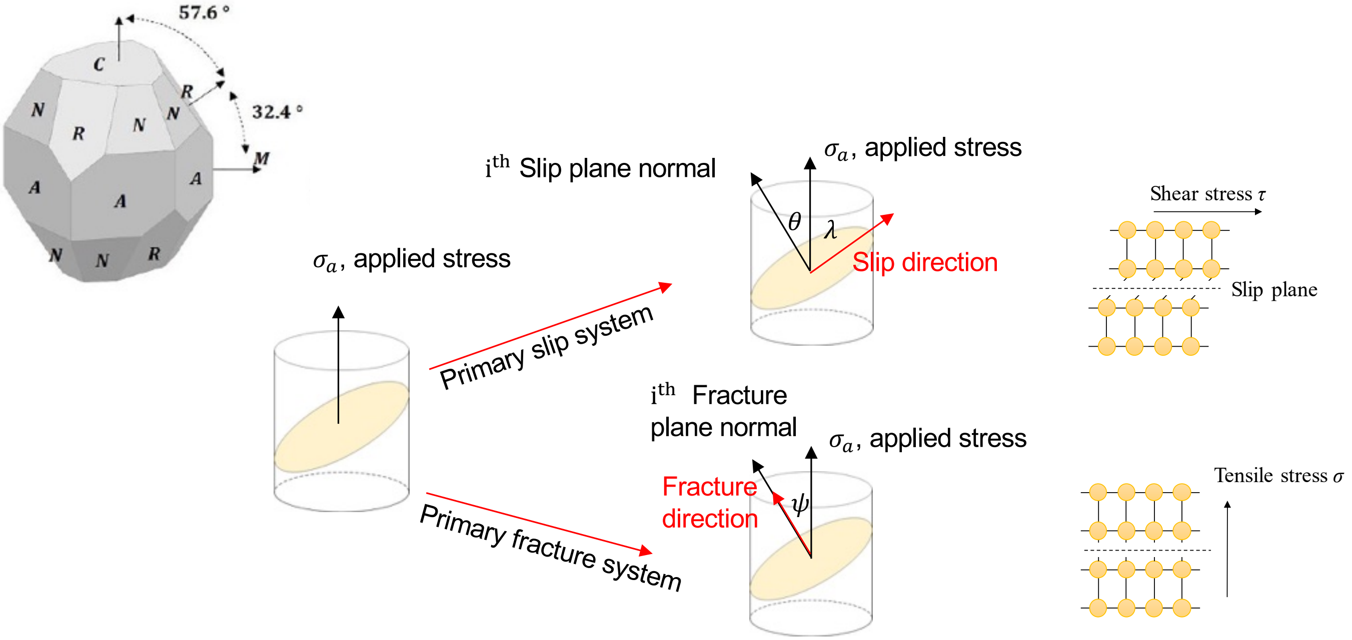
Detailed crack morphologies



THEORY

Slip – fracture model

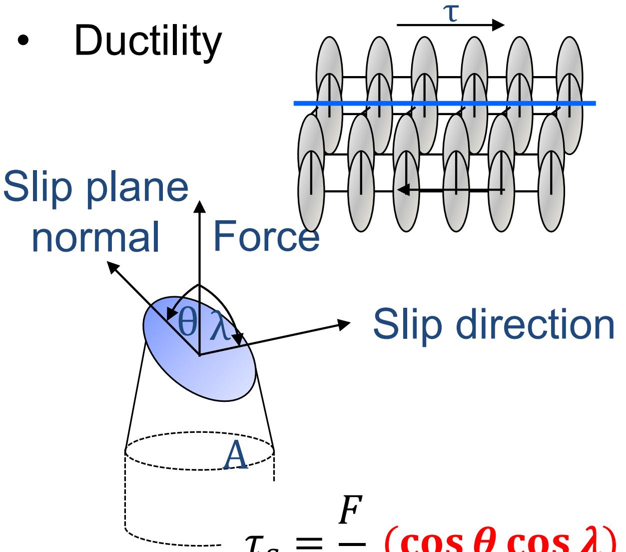
- Slip-Fracture Model
  - Ductile-Brittle transition depending on crystallographic characteristics
  - Slip system: shear stress → activation→ deformation → ductile cutting
  - Fracture system: tensile stress → activation → crack → brittle cutting
  - Ranked each system’s activation tendency in terms of cutting direction



Deformation in brittle materials

Slip deformation

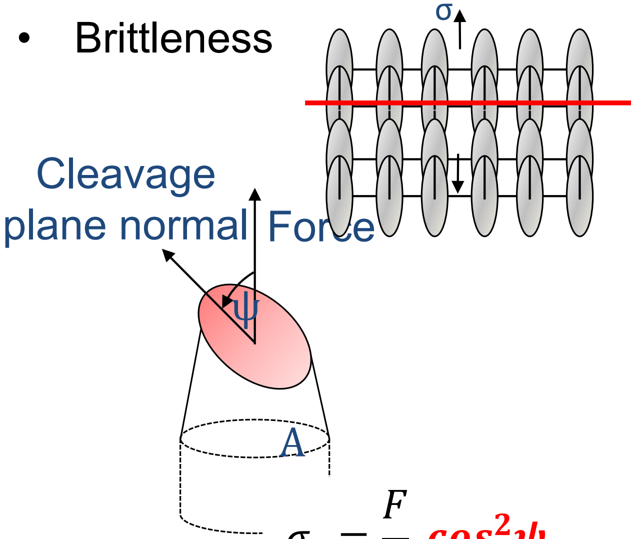
- Plastic deformation
- Ductility



$$\tau_s = \frac{F}{A}\underbrace{(\cos\theta\cos\lambda)}_{\text{Schmid factor m}}$$

Cleavage fracture

- Cracking & fracture
- Brittleness



$$\sigma_c = \frac{F}{A}\underbrace{\cos^2\psi}_{\text{Cleavage factor C}}$$

References: Clayton, J. (2009). A continuum description of nonlinear elasticity, slip and twinning, with application to sapphire. Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, The Royal Society.; Wiederhorn, S. (1969). "Fracture of sapphire." Journal of the American Ceramic Society **52**(9): 485-491.

Deformation systems in sapphire

Slip deformation

Slip (twinning) system	CRSS [GPa]
Rhombohedral twinning (RT)*	0.4066
Basal twinning (BT)	2.2255
Basal slip (BS)	2.2255
Prismatic slip (PRS)	1.6487
Pyramidal slip (PYS)**	4.4817

Plastic deformation factor, P

$$P_i \propto \frac{m_i}{\tau_{CRi}/\min_i \tau_{CRi}}$$

Weight factor

*Unidirectional loading with compression of c-axis
** Unidirectional loading with tension of c-axis

Cleavage fracture

Fracture plane	Fracture energy [J/m^2]
Basal cleavage (BC)	>40
Prismatic cleavage (PC)	7.3
Rhombohedral cleavage	6

Fracture factor, F

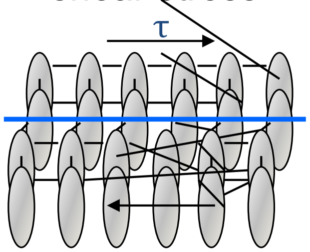
$$F_i \propto \frac{C_i}{E_{Fi}/\min_i E_{Fi}}$$

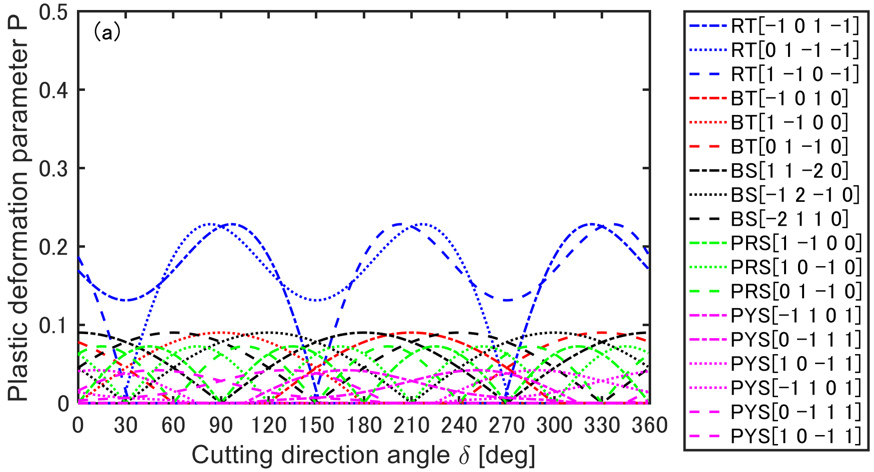
Weight factor

References: Clayton, J. (2009). A continuum description of nonlinear elasticity, slip and twinning, with application to sapphire. Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, The Royal Society.; Wiederhorn, S. (1969). "Fracture of sapphire." Journal of the American Ceramic Society **52**(9): 485-491.

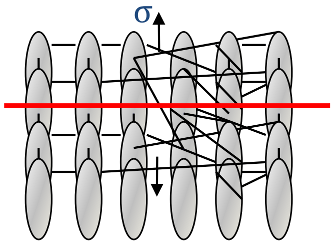
Calculated deformation parameter

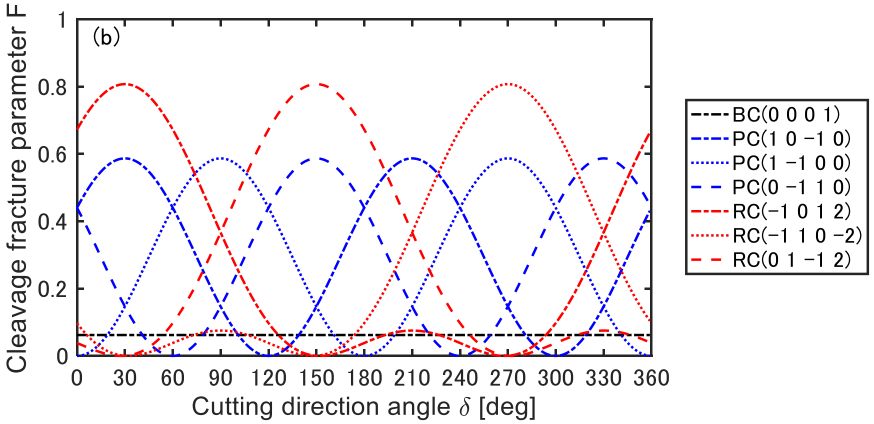
Resolved shear stress



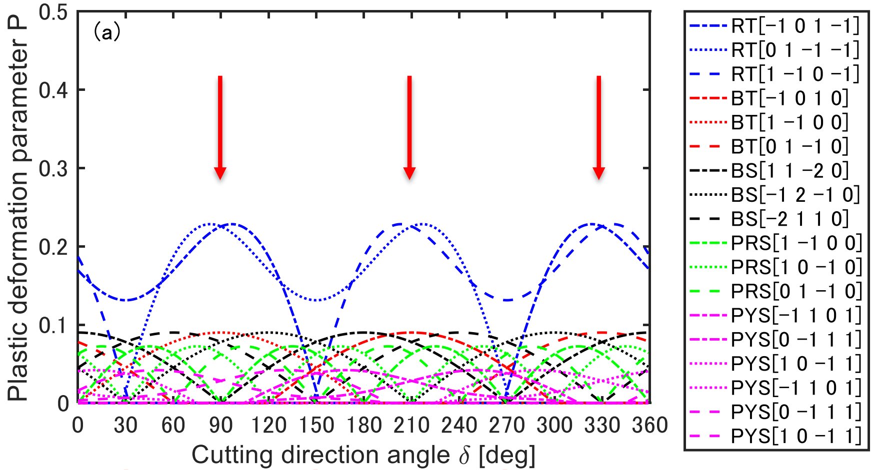


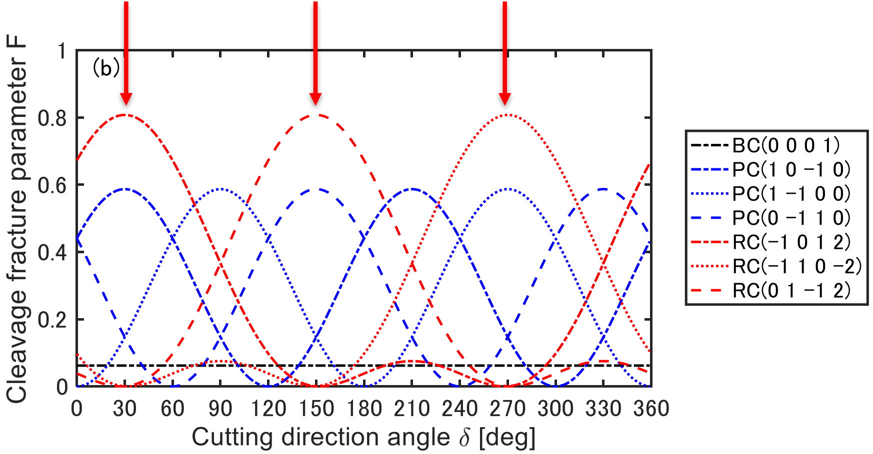
Resolved tensile stress

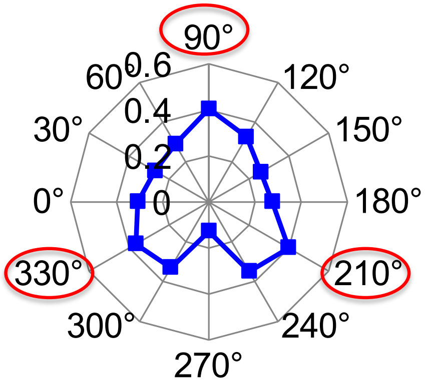


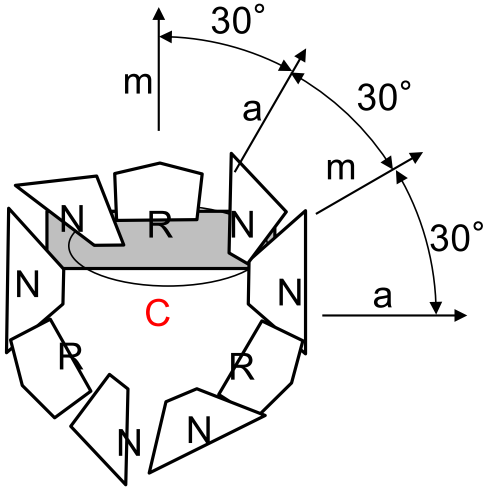


Calculated deformation parameter

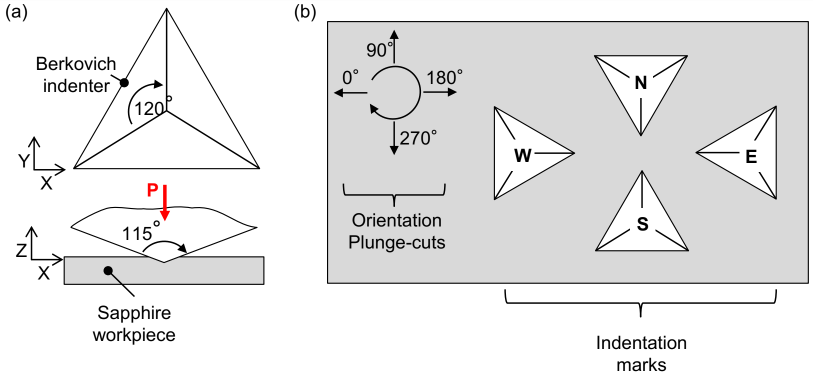




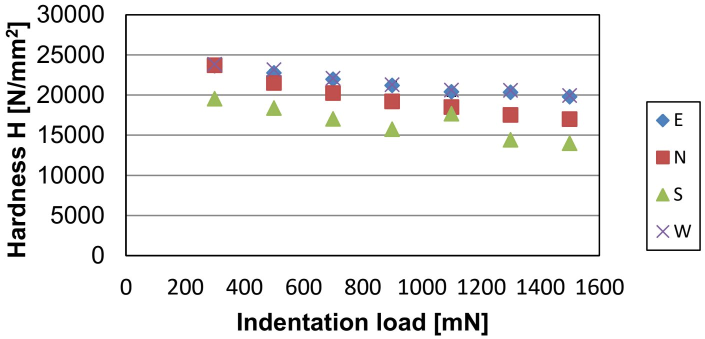




Symmetry



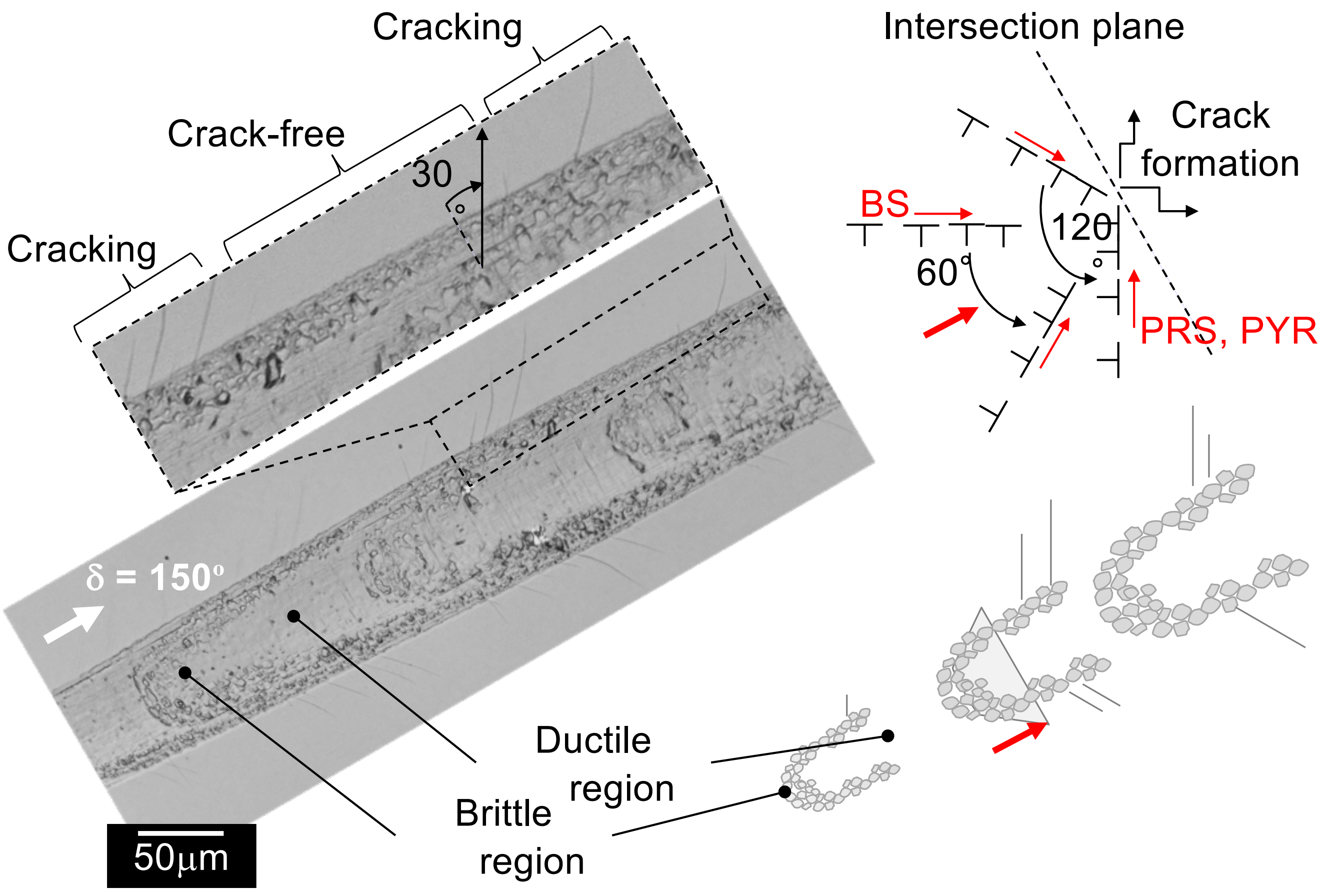
(a) Schematic Berkovich-indentation process and (b) Indenter orientation in regards to the plunge-cut orientation



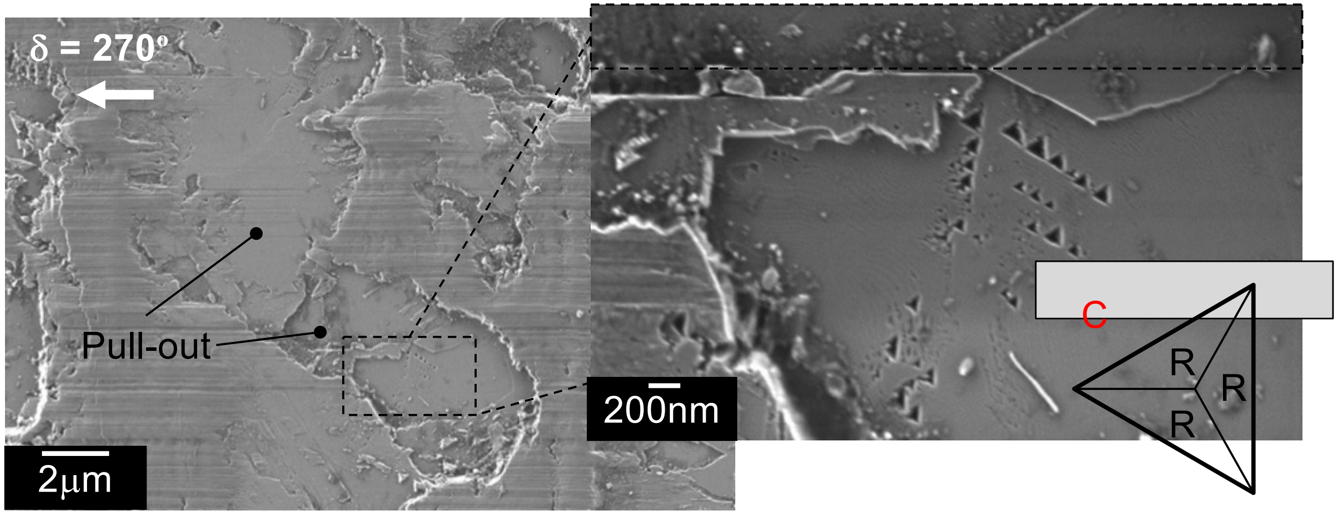
Hardness of the c-plane sapphire depending on the indenter orientation

References: Nowak R. Sakai M. (1994). The Anisotropy of Surface Deformation of Sapphire: Continuous Indentation of Triangular Indenter. Acta *Metallurgica et Materialia,* 42(8): 2879-2891.

Pile-up and glide mechanism



Pull-out mechanism

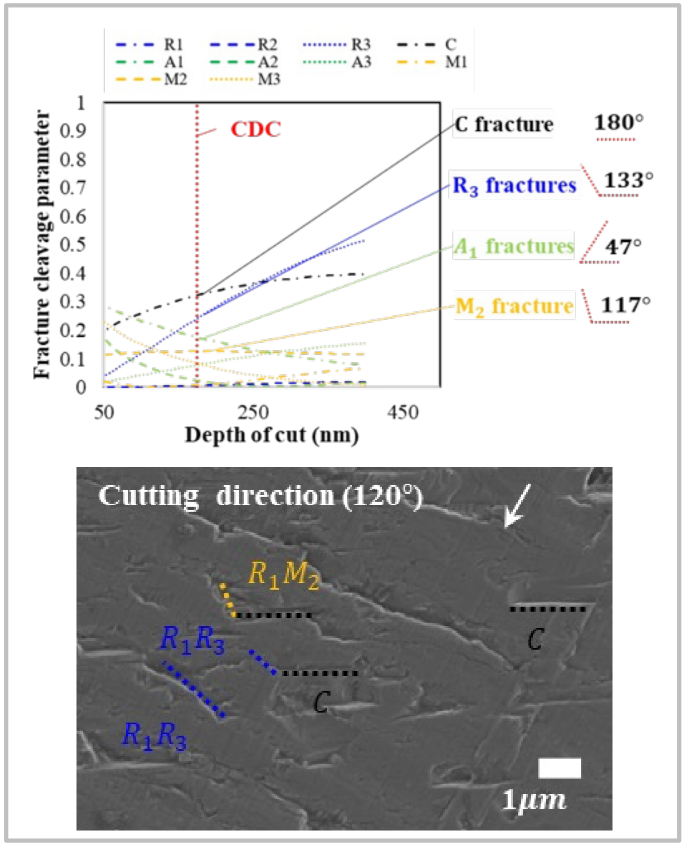


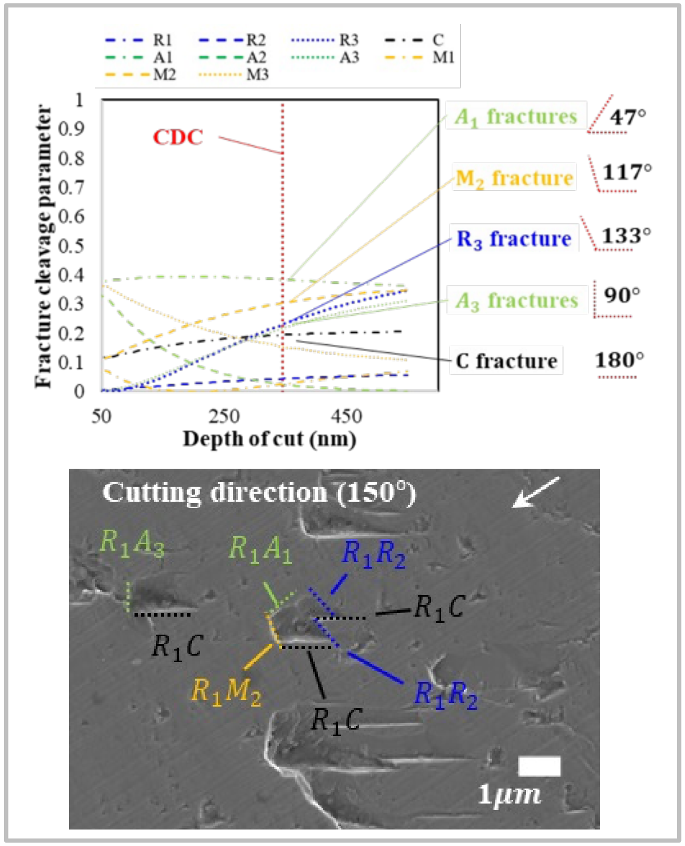
Pyramidal pits

- In material pull-out sections well-defined cleavage
- Lowest fracture energy required for R-plane
- Origin: pre-defects, weakened atomic bonds

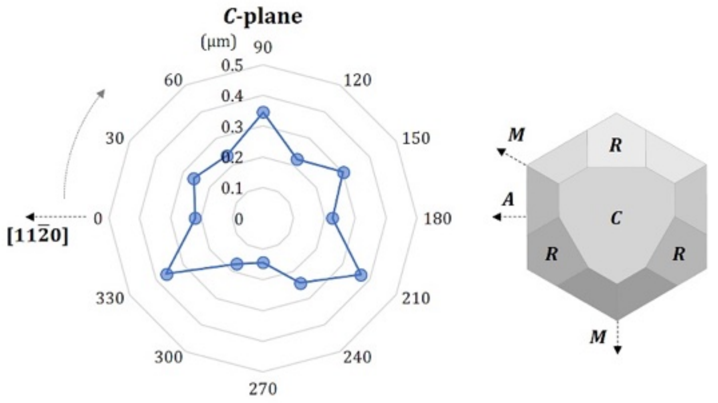
Slip/fracture activation model

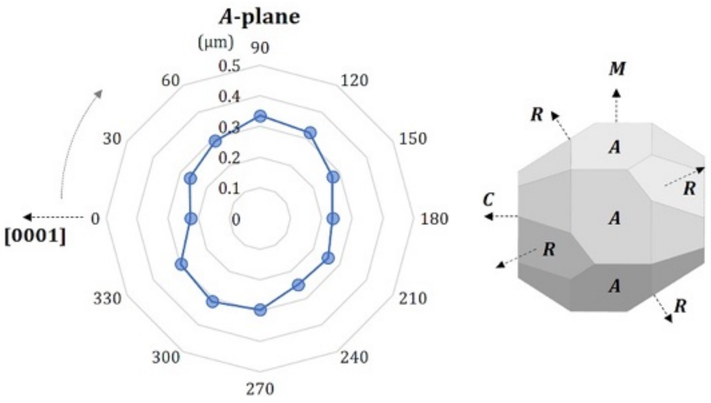
- Prediction of crack morphologies
  - 120 ° and 150 ° cutting directions

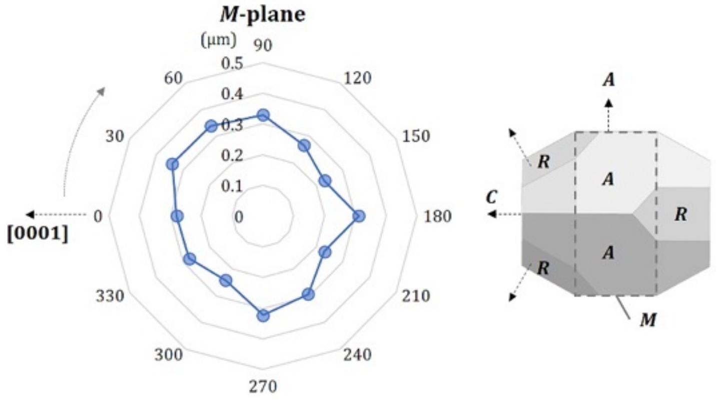


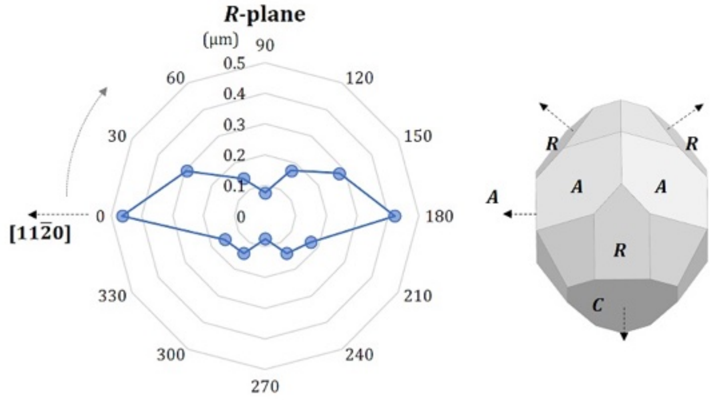


CDC of other planes



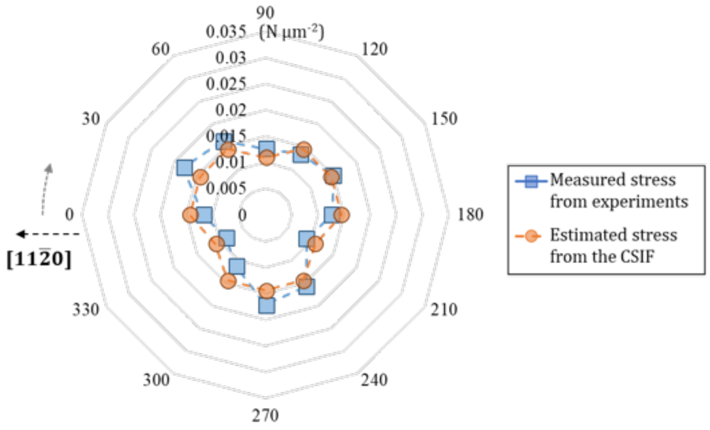


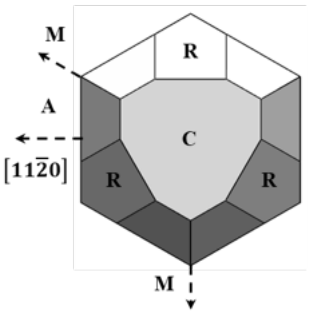


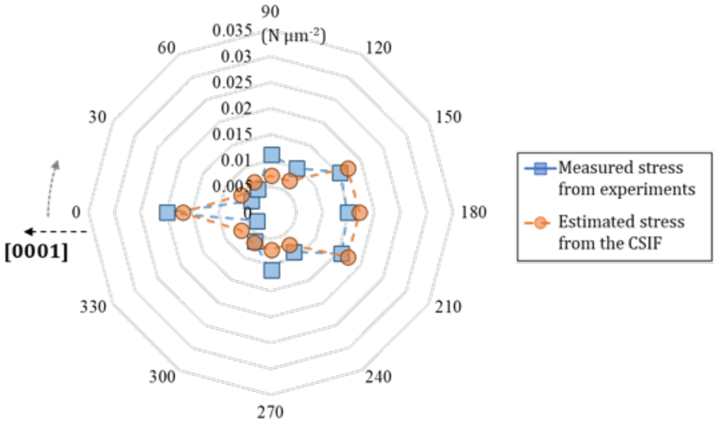


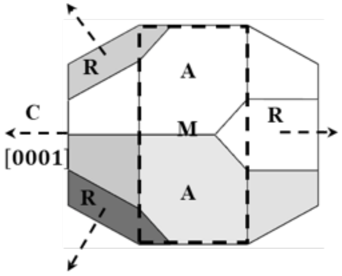
Stress intensity factor model

C- and M-cutting plane: stress prediction





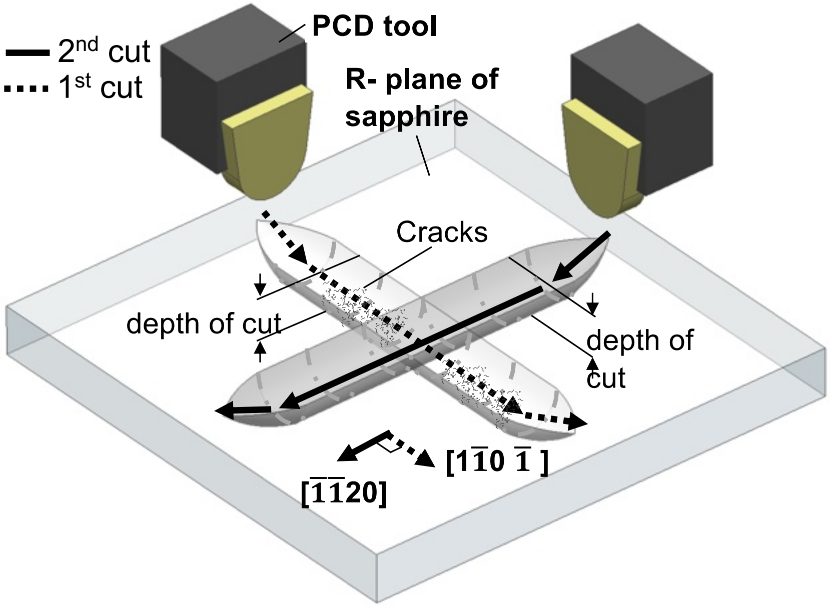




scalable machining

MACHINING STRATEGY

Crack removal



Schematic image of experiment

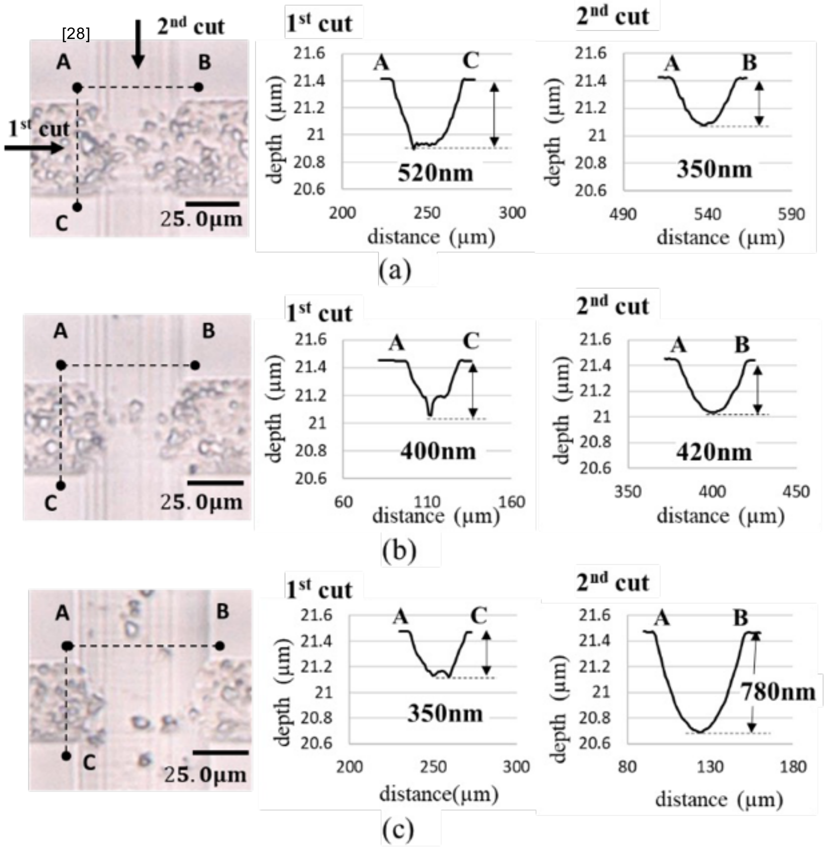
Parameter	**Values**
Cutting slope (D/L)	1/500 (At entry and exit)
Max. depth of cut	1st cut – 350nm – 520nm 2nd cut – 350nm – 780nm

R- plane of sapphire

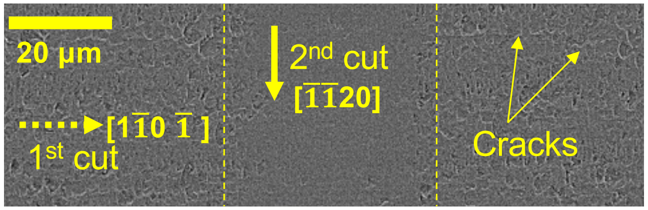
- CDC in $[1\bar{1}0\bar{1}]$: 90 nm
- CDC in $[\bar{1}\bar{1}20]$: 420 nm
- R-plane was chosen due to the large difference in CDC

Crack removal

[28]



[28]



SEM Image of Intersection Region

- Cracks from the first cut at removed under a small window of depth of the second cut
  - The second cut must be deeper than the depth of cracks formed by the first cut.
  - The second cut should not exceed CDC in that direction and not exceed crack initiation factors to form new cracks.

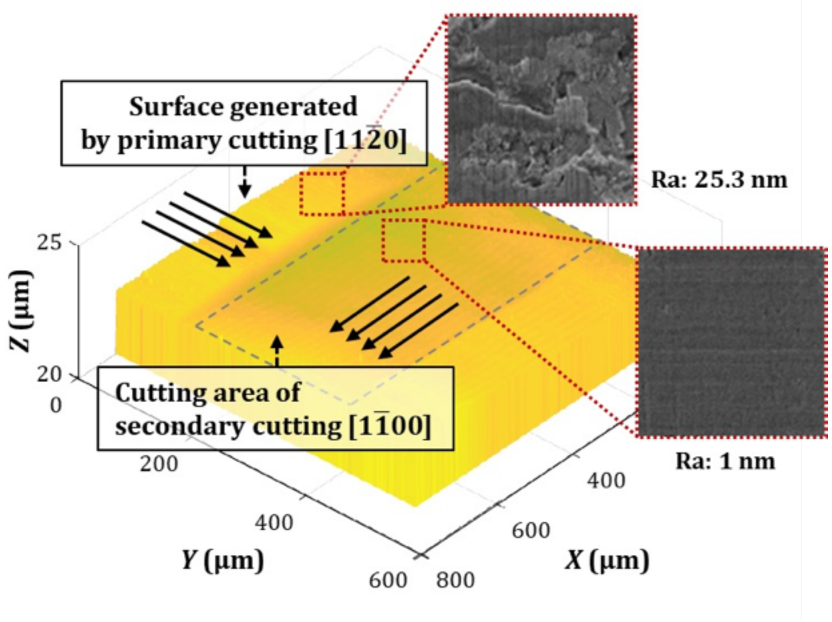
Validation through a machining strategy

Experiment details

- Machining on C-plane of sapphire
- Feature to be created – pocket 1000 μm long, 300 μm wide and 550 nm deep with smooth, crack free surfaces

Machining Strategy

- First cut in $[11\bar{2}0]$ - 0° direction at depth of 400 nm (CDC: 220 nm)
- Second cut in $[1\bar{1}00]$ 90° direction at depth of 150 nm (S-CDC: 200 nm)
- Pitch – 15 μm



Due to limitation of S-CDC, conventional strategies of machining in same direction would take 3 passes whereas, knowing the material behavior during repeated machining, number of machining passes was reduced improving throughput by 1.5 times.

Conclusion

- Crack can be predicted with given machining process parameters
  - Covered
    - Depth of cut
    - Cutting speed, feed
  - Uncovered
    - Tool geometry
    - Etc.
- Machining strategy
  - Multi-step cutting
  - High speed milling
- Future work
  - Residual stress
  - Subsurface damage

Future potentials

- Many companies are putting efforts to develop manufacturing technology for ceramics.
  - Consumer electronics: product and process
  - Semiconductor
  - Medical
  - Nuclear
  - Space and aerospace
  - Science exploration
  - Defense