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X-ray Nanoprobe Investigation of Residual Stress/Strain Formation in Ultra-Precision Machined Single-Crystal Sapphire

by

Rui Liang[1, 2], Rui Liu[2], Tao Zhou[2], Sangkee Min[1]

Presenting author: Prof. Sangkee Min, University of Wisconsin-Madison
Email: sangkee.min@wisc.edu

[1] Manufacturing Innovation Network Lab. University of Wisconsin-Madison
[2] Center for Nanoscale Materials, Argonne National Laboratory

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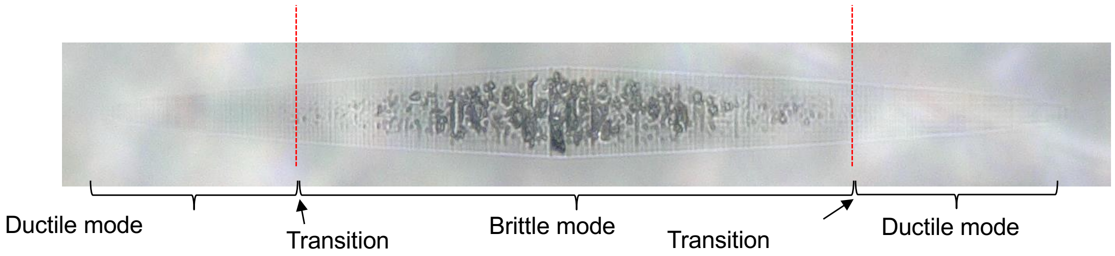
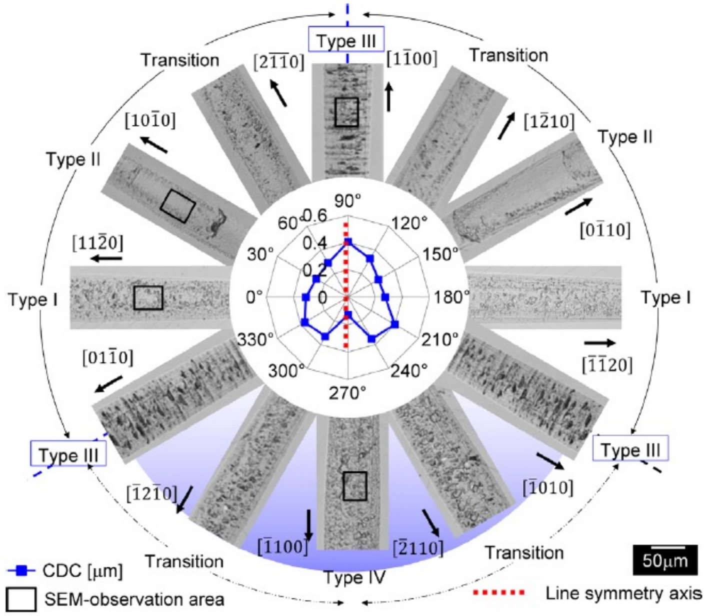
A journey to understanding ceramic machining

Can you cut sapphire?

Ductile machining

Found that ductile cutting is possible under a certain circumstances





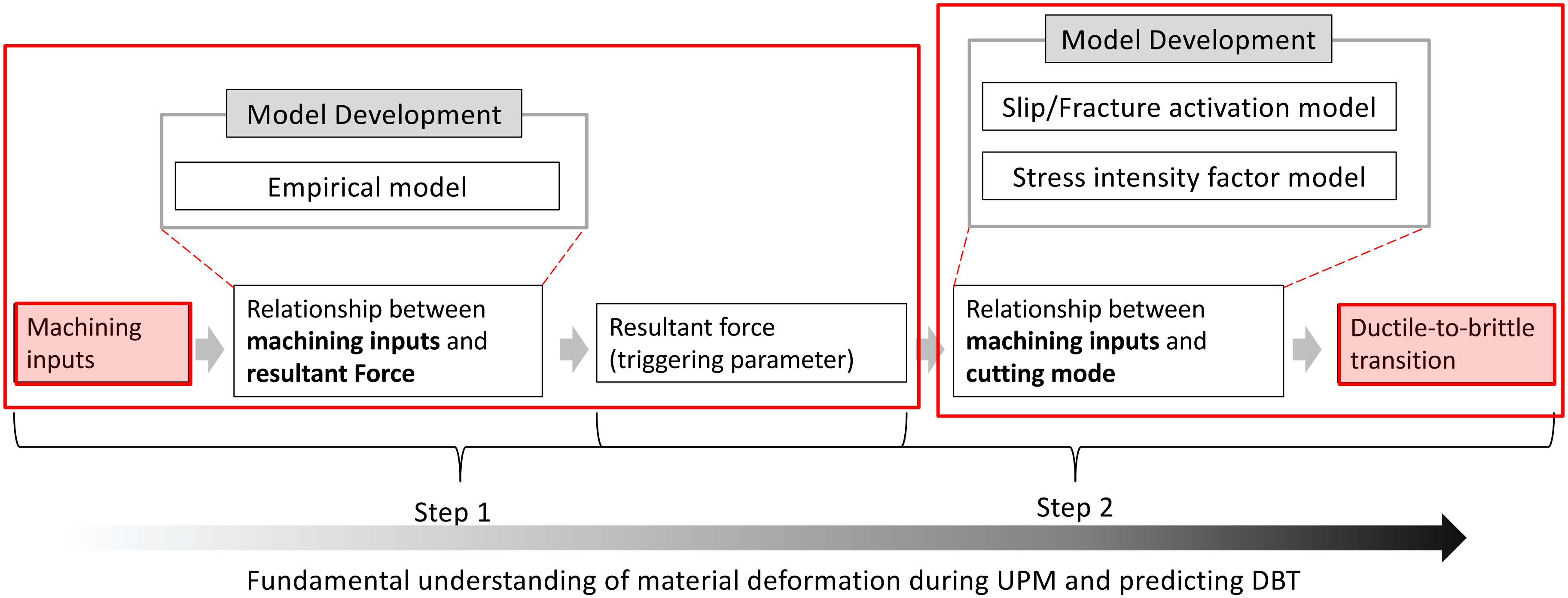
Questions are

- What mechanisms enable this brittle material to exhibit ductile behavior?
- Is this knowledge applicable to other crystalline materials?
- Does machining introduce subsurface cracks or damage even when the surface appears smooth?
- Is this process scalable?

Yet aggressive

Can you cut it at XX MRR?

Need a full understanding



Model Development

Empirical model

Machining inputs

Relationship between **machining inputs** and **resultant Force**

Resultant force (triggering parameter)

Model Development

Slip/Fracture activation model

Stress intensity factor model

Relationship between **machining inputs** and **cutting mode**

Ductile-to-brittle transition

Step 1

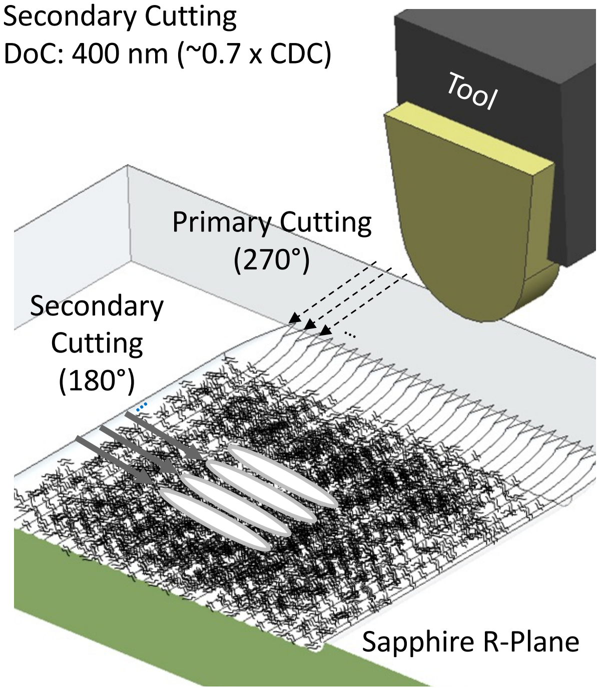
Step 2

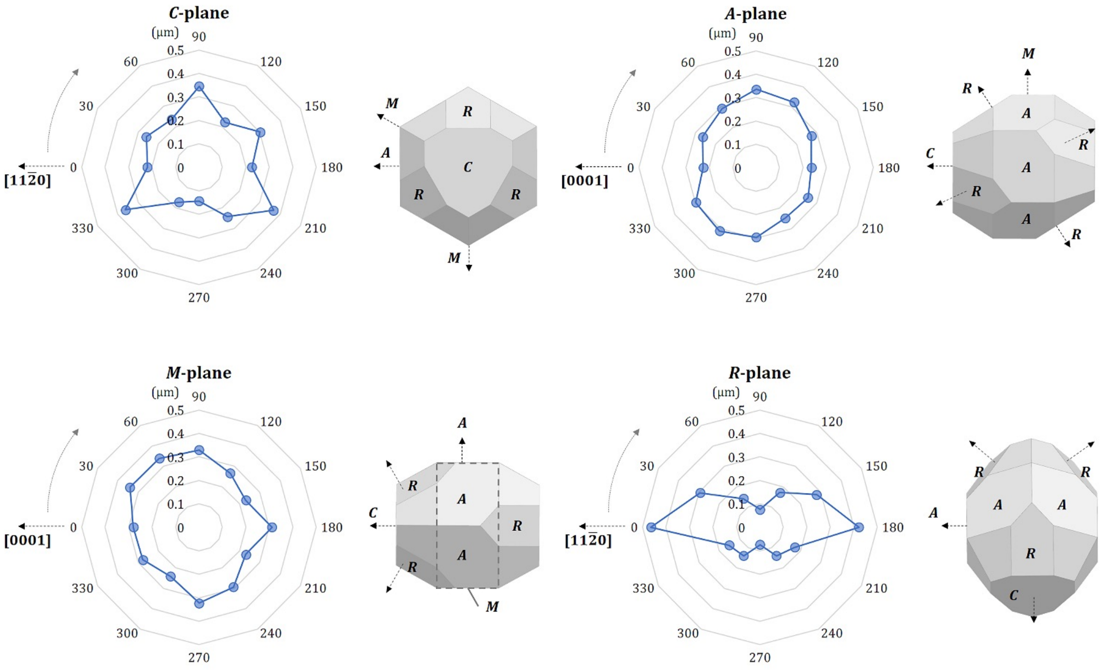
Fundamental understanding of material deformation during UPM and predicting DBT

Machining strategy

Primary Cutting
DoC: 300 nm (~3 x CDC)

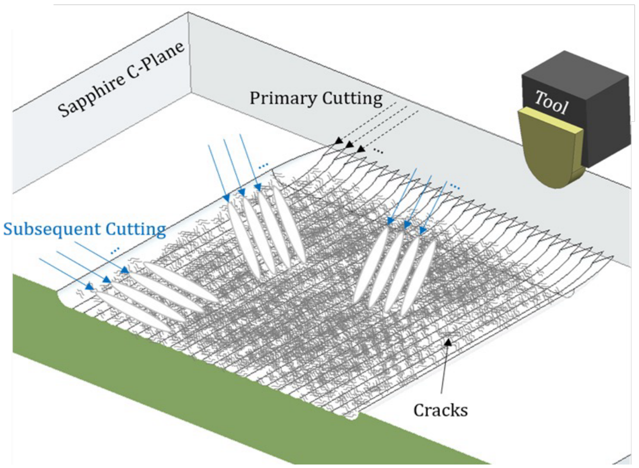
Secondary Cutting
DoC: 400 nm (~0.7 x CDC)



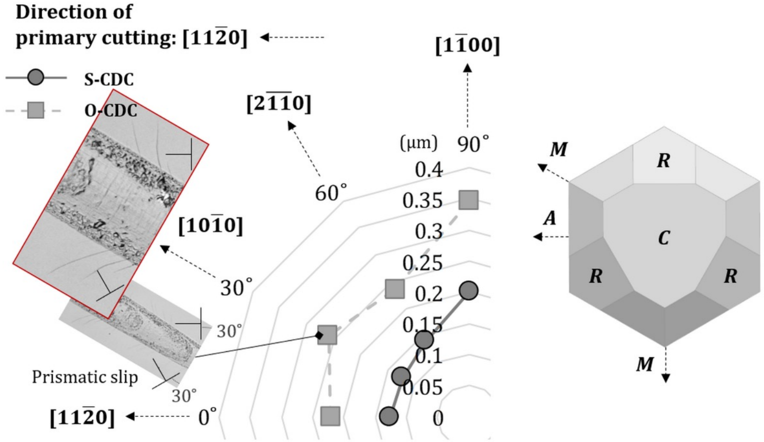


Residual stress and subsurface damage

Primary and subsequent cutting



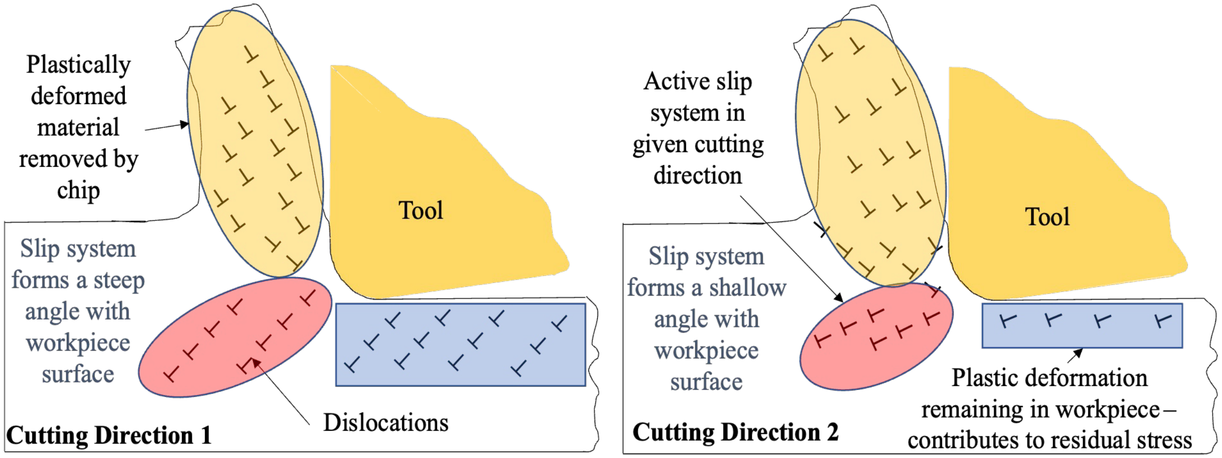
Change in CDC based on orientation of subsequent machining



- Tiny cracks influence the stresses of subsequent cutting in corresponding directions.
- The unique concave shapes due to the pile-up glide mechanism during plastic deformation (prismatic slip).

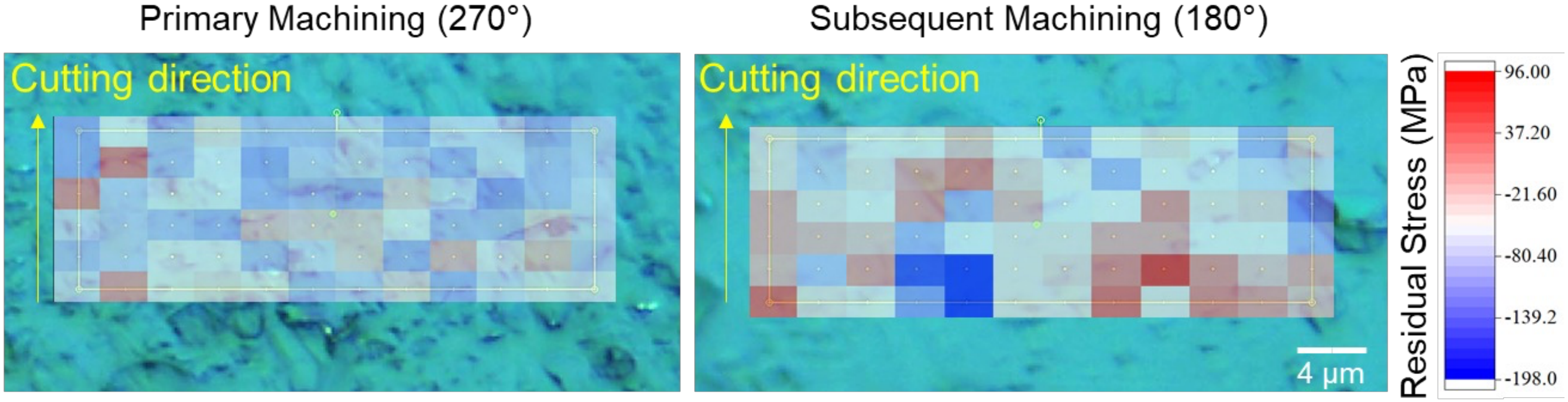
Hypothesis

How prior deformation and anisotropy can significantly affect machining outcomes: Residual stress



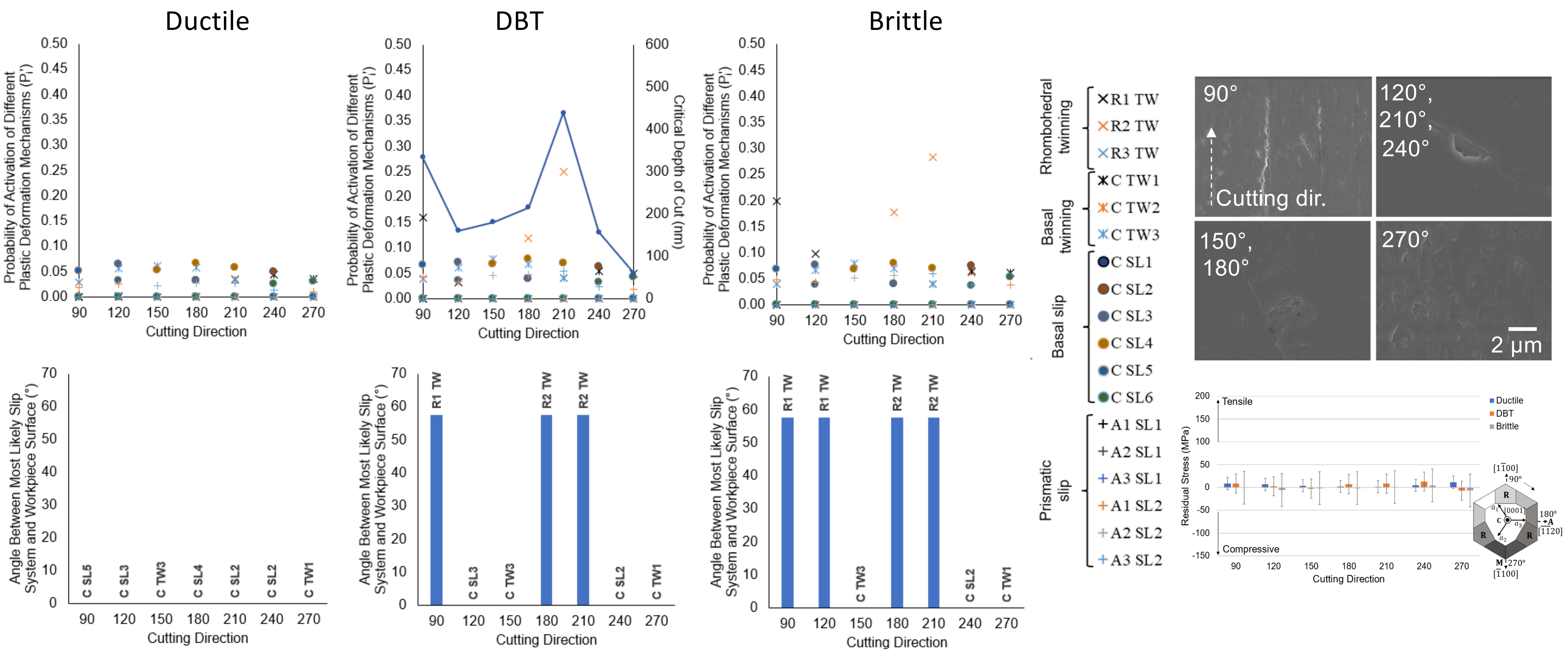
- Residual stresses left behind after machining of ceramics are anisotropic in terms of depth and direction of machining.

Raman spectroscopy



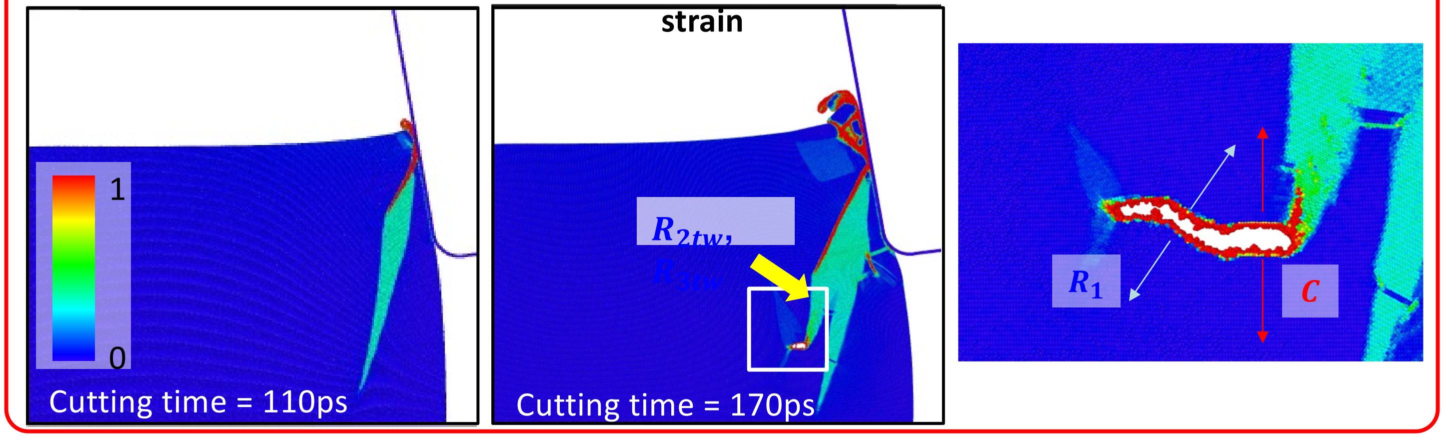
[19] Wei SL, Zhao H, Jing JT, Yun FH, Li XL. Investigation on surface residual stress distribution and evaluation of engineering ceramics in rotary ultrasonic grinding machining. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2017 Aug;231(15):2773-82.

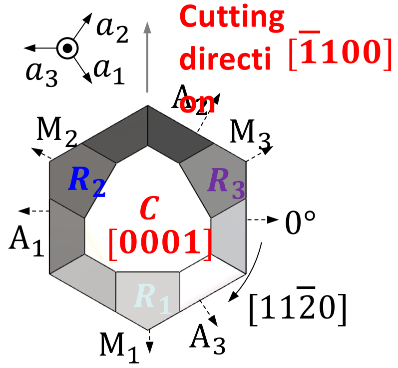
Prediction and measurement



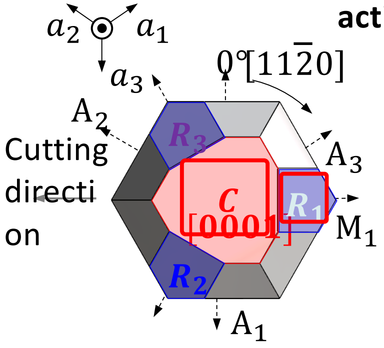
Interactions

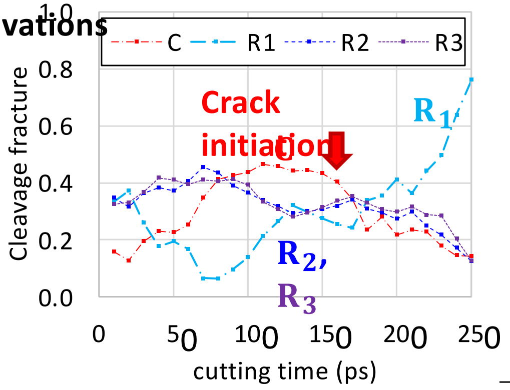
Shear strain



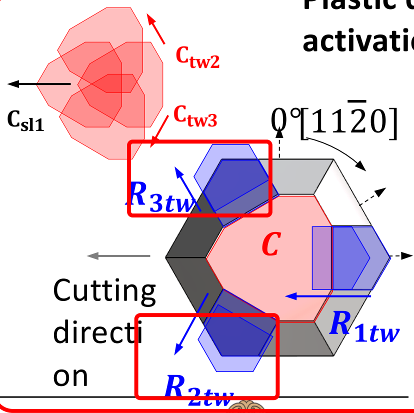


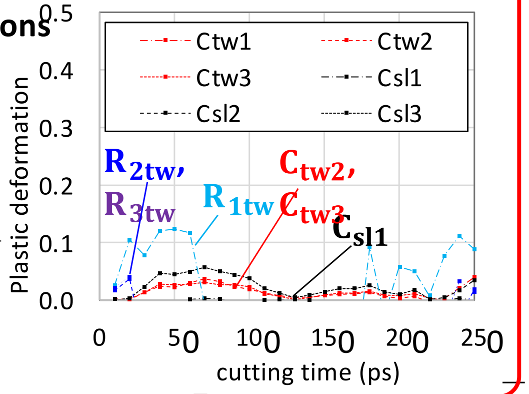
Fracture activations





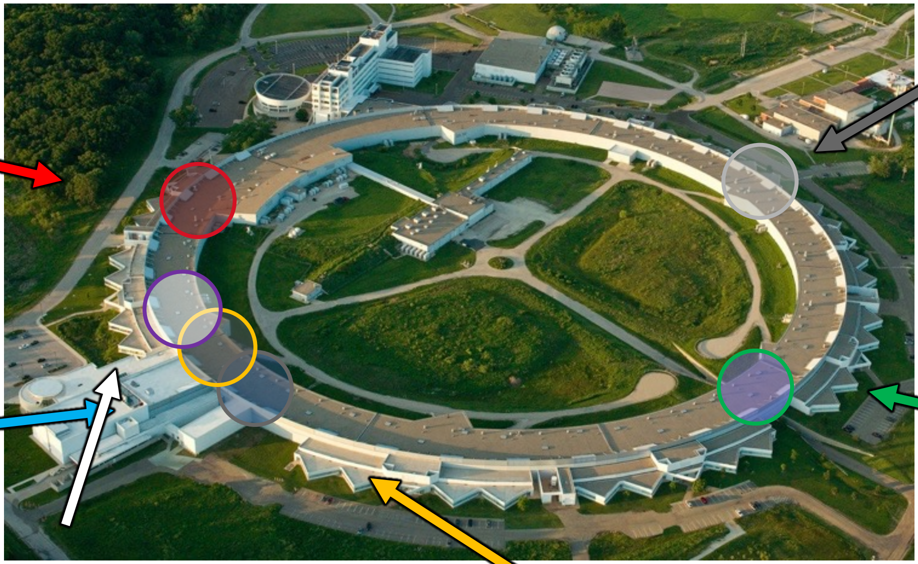
Plastic deformation activations



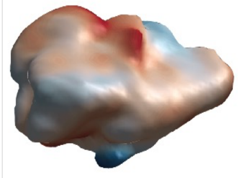


Synchrotron Imaging of material structure and dynamics

Advanced Photon Source @ Argonne

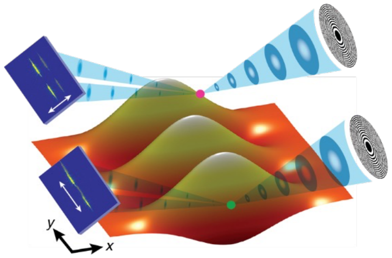


Bragg Coherent Diffraction Imaging (Sec. 34)

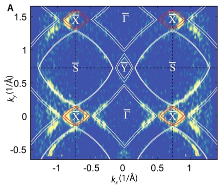


S. O. Hruszkewycz et al. APL Mater. 2017, 5 (2), 026105.

Nanofocused X-ray diffraction and ptychography (Sec. 26)

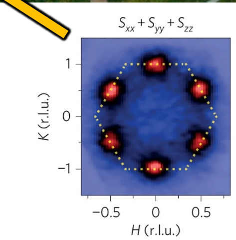


S. J. Whiteley, *et al. Nature Physics*, 15, 490–495 (2019)



IEX ARPES

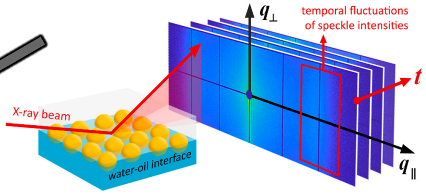
S. Lei et al. *Sci Adv* 6 6407 (2020)



Inelastic X-ray Scattering (Sec. 27)

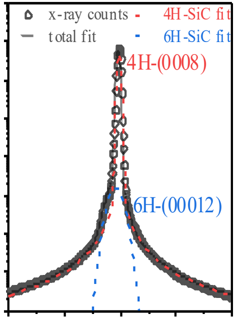
S.H. Chun. et al. *Nature Physics* 11 462-466 (2015)

X-ray Photon Correlation Spectroscopy (Sec. 8)



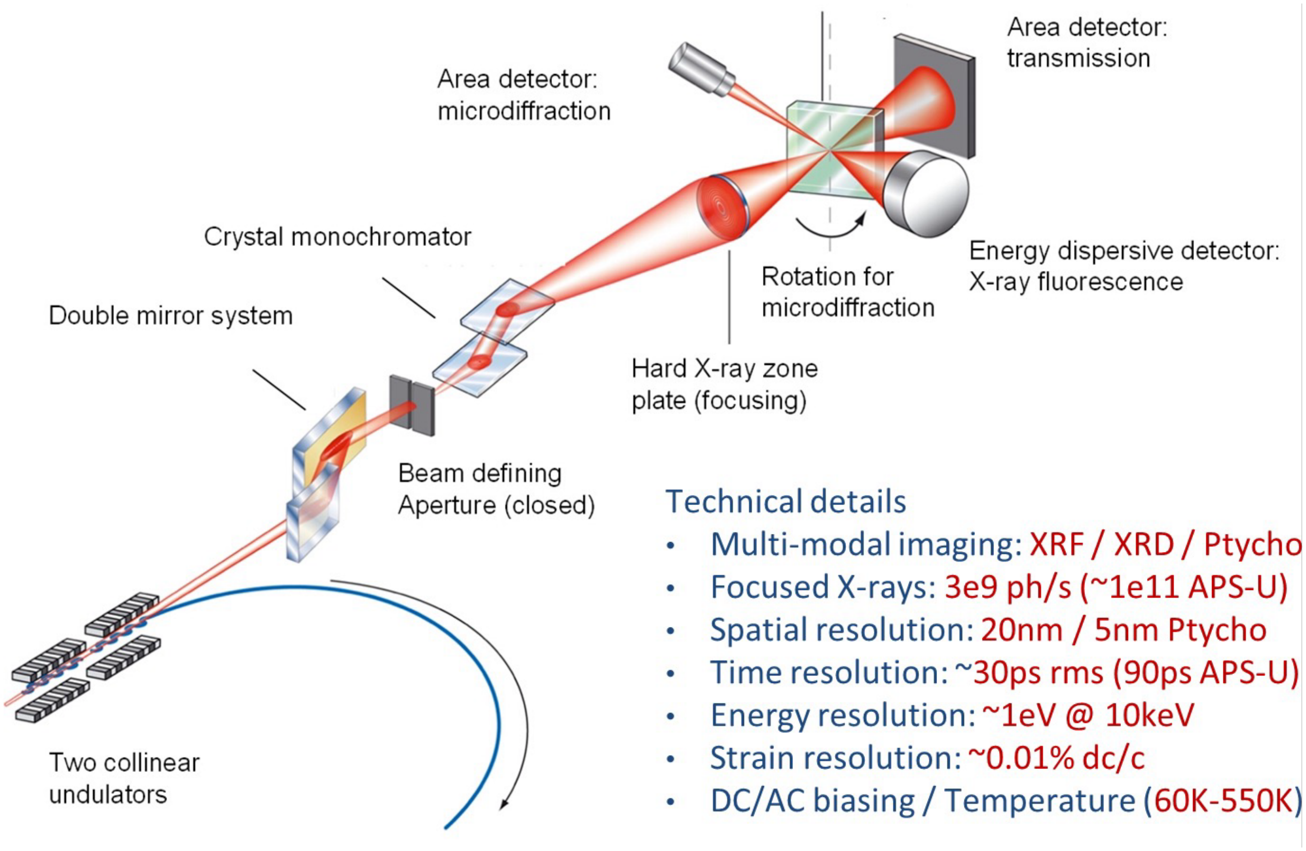
P Y Kim, et al. *ACS Nano.* 16 8967 (2022)

In-situ surface scattering (Sec. 12)



V. Ivády, et al. *Nat. Comm.* 10 5607 (2019)

The CNM / APS hard X-ray nanoprobe beamline



Technical details

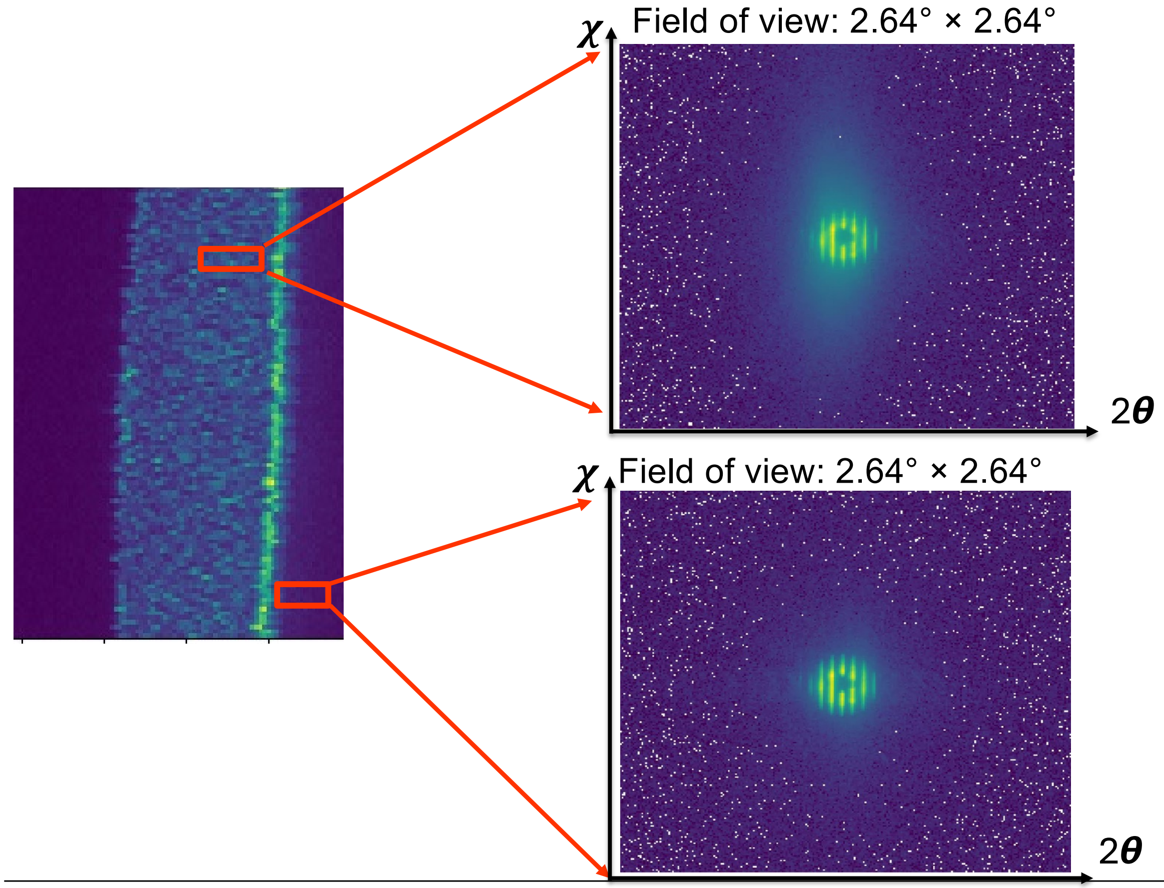
- Multi-modal imaging: XRF / XRD / Ptycho
- Focused X-rays: 3e9 ph/s (~1e11 APS-U)
- Spatial resolution: 20nm / 5nm Ptycho
- Time resolution: ~30ps rms (90ps APS-U)
- Energy resolution: ~1eV @ 10keV
- Strain resolution: ~0.01% dc/c
- DC/AC biasing / Temperature (60K-550K)

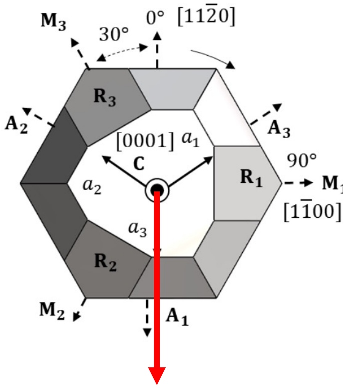
Why we use X-ray nanoprobe to investigate residual stress

Comparison of X-ray Nanoprobe and Raman Spectroscopy

Feature	X-ray Nanoprobe	Raman Spectroscopy
Spatial Resolution	$20\ nm$	$2 \mu m$
Strain Resolution	$\sim 10^{-6}$	$\sim 10^{-4}$
X-ray Transmission	Yes (nondestructive; bulk-sensitive; tens–hundreds of µm penetration)	No (typically backscattering, surface/near surface sampling)

High-resolution strain and stress mapping in 180° cutting orientation

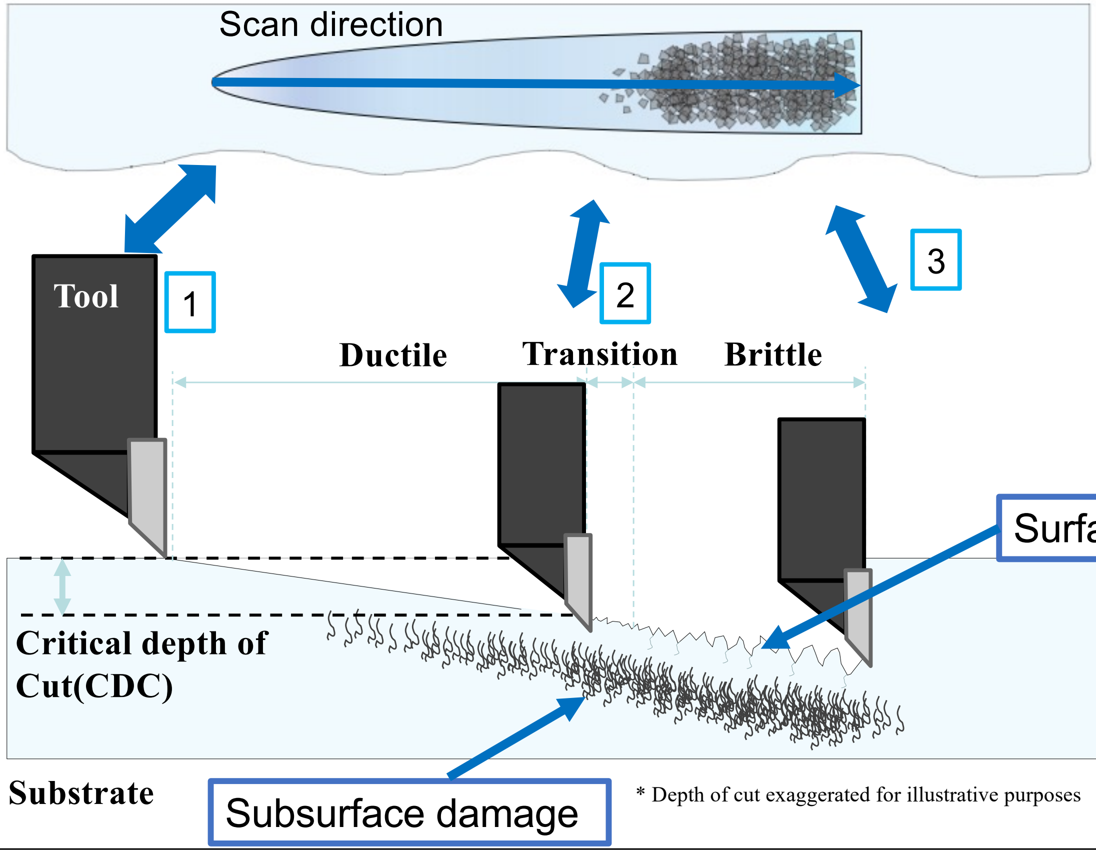




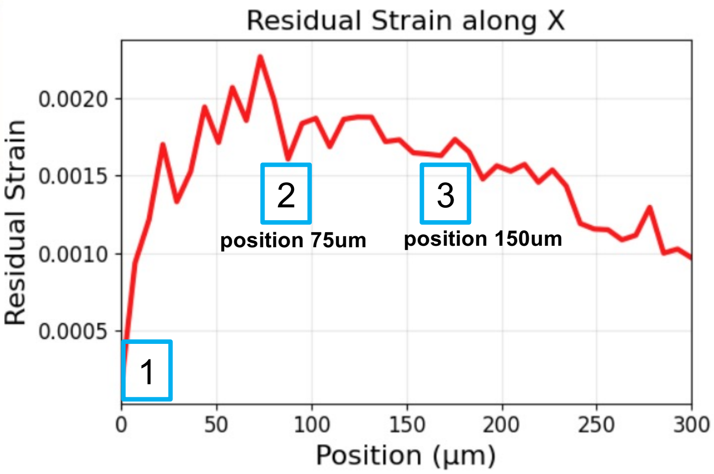
Sapphire C-plane schematic with red arrow showing the 180° cutting direction.

- These results include clear comparisons between unmachined areas and machined regions.

Residual strain on the 180° of sapphire C-plane

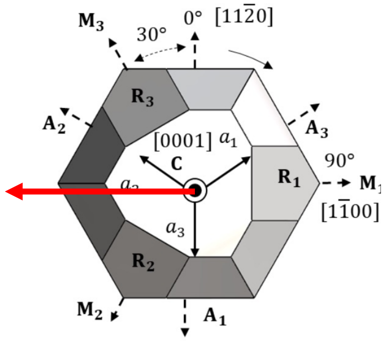


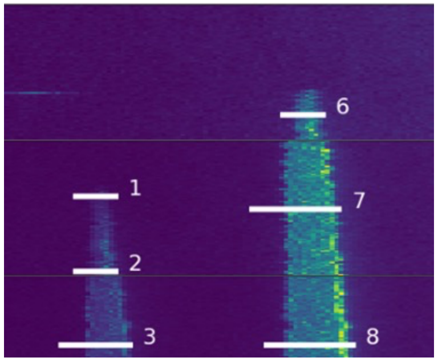
* Depth of cut exaggerated for illustrative purposes



1	⇒ 2	**Dutile Region**
2		**Dutile To Brittle Region**
3		**Brittle Region**

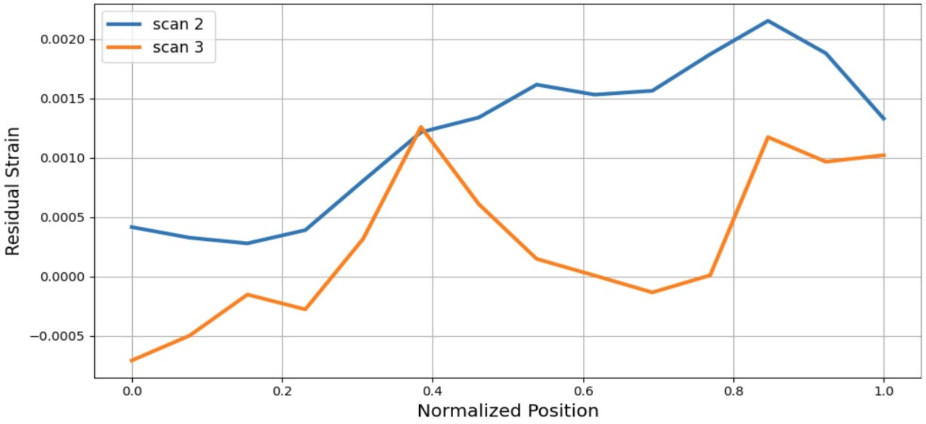
Compare residual strains at different DoC for scratching direction 270°

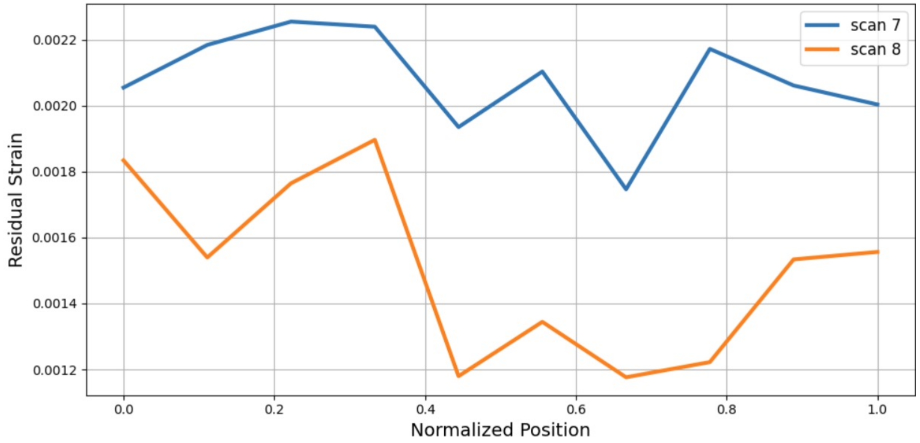




Comparison of Ductile region(scan2) to Brittle region(scan 3)

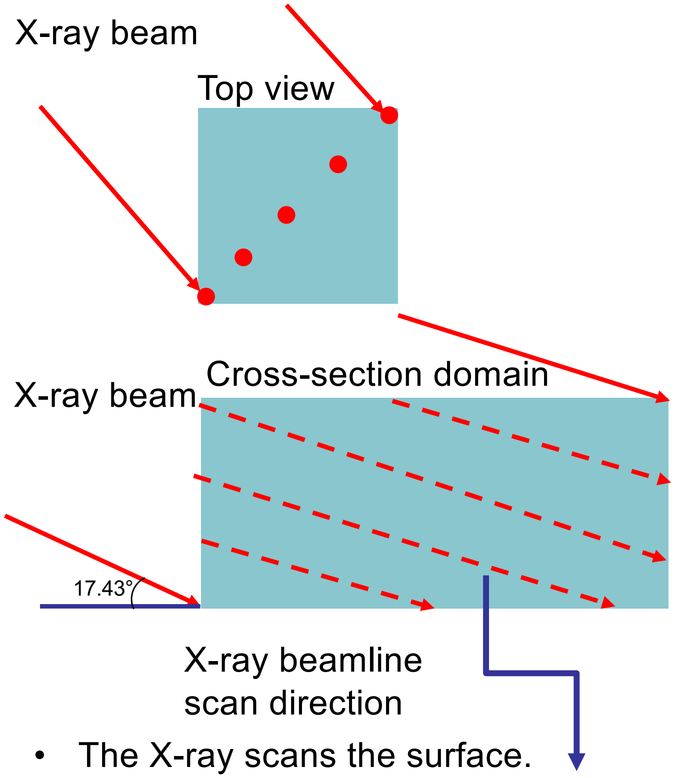
Comparison of Ductile region(scan7) to Brittle region(scan 8)



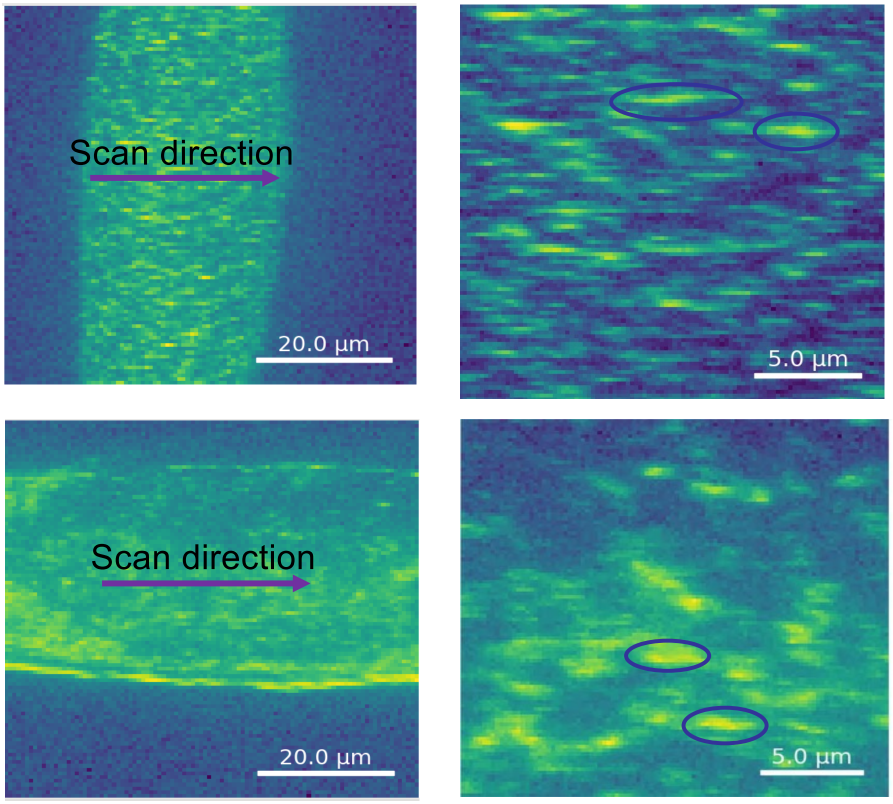


Conclusion: The ductile region shows a significantly higher strain level relative to the brittle region.

Depth profile (ongoing project)



- The X-ray scans the surface.
- Depth-information included in the elongated domains.



On-going and future

- On-going
  - Precise measurement and analysis
  - MD simulation

- Future
  - Interaction among slip and fracture systems
  - Interaction among residual stress/subsurface damage and the above systems
  - Machining strategy

Acknowledgement

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U.S. DEPARTMENT of ENERGY

FANUC

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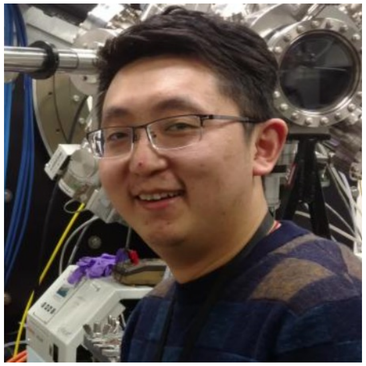
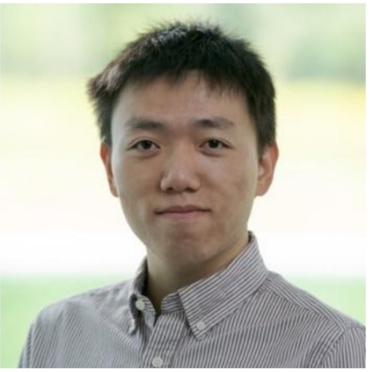
Rui Liang, University of Wisconsin-Madison


Rui Liu, Argonne National Laboratory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