COE CST Eleventh Annual Technical Meeting

241: High Temperature, Optical Sapphire Pressure Sensors

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Agenda

- Team Members
- Task Description
- Schedule
- Goals
- Results
- Conclusions and Future Work

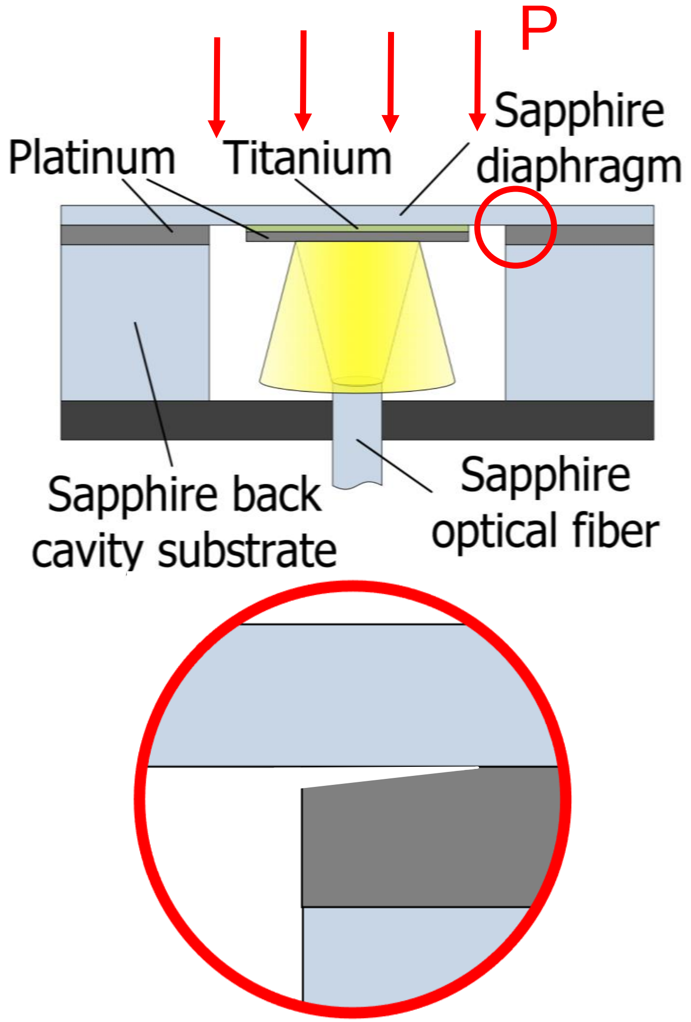
Team Members

- People
  - William S. Oates and Rajan Kumar
  - Jakob Consoliver-Zack

- Organizations
  - Florida Center for Advanced Aero-Propulsion
  - FAMU-FSU College of Engineering

Task Description

- Development of high temperature pressure sensors (~1300°C)
  - Applications: Structural health monitoring, morphing surface control, combustion control
- Challenge: Sensor material limits, manufacturing
  - Sapphire used in prior research
    - Difficult to machine, multiple components
    - Laser machining affects material properties
    - Debonding of diaphragm is common failure mechanism
- Opportunity: Characterize mechanical effects of laser ablation process and investigate fracture behavior
  - Conduct X-ray Diffraction experiments to infer strain state
  - Confirm inference using Finite Element Analysis and micro-indentation experiments.



Example Sensor and crack

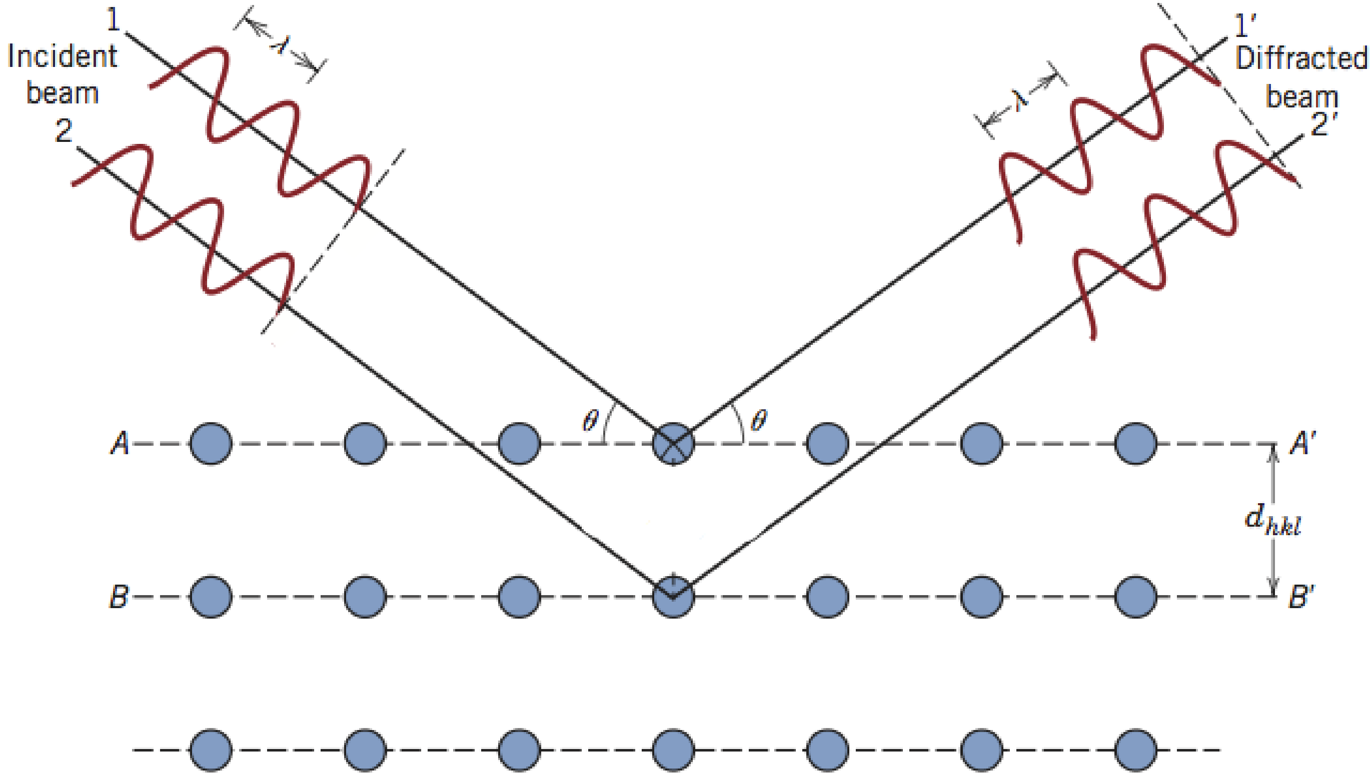
Final Schedule

- Complete multi-axial x-ray strain inference analysis
- Sapphire indentation electron microscopy and anisotropic crack tip toughness analysis
- Thermocompressive bonding sapphire-niobium-sapphire sandwiches
- Interfacial fracture toughness testing
  - Thermal cycling—time remaining

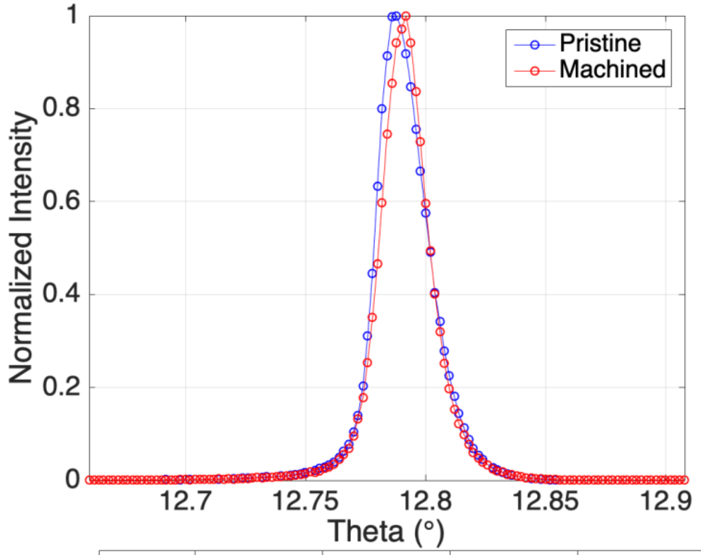
Goals & Motivation

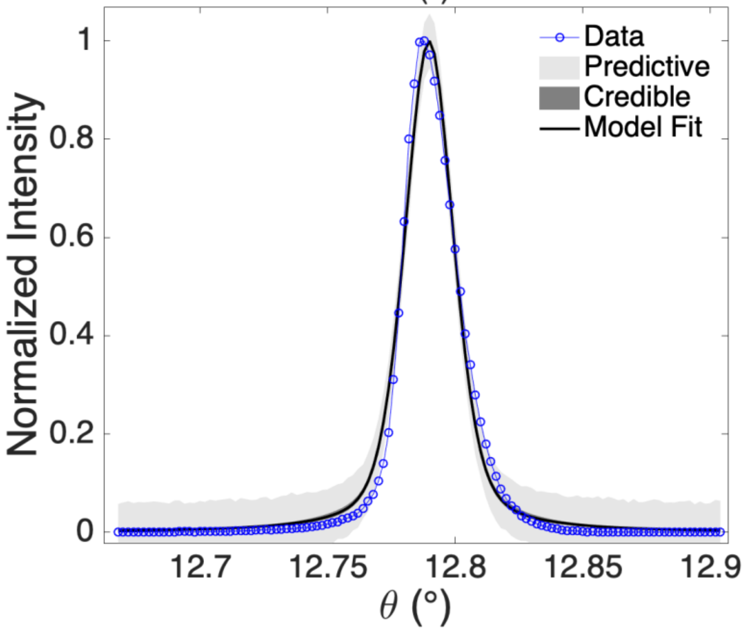
- *Rigorously understand how to manufacture sapphire into an advanced, high temperature pressure sensor*
- Relevance to Commercial Space Industry
  - Aerodynamic surfaces experience high pressures and high skin temperatures
  - Need: Real-time structural health monitoring
  - Need: Advanced aerodynamic control
- Materials and Manufacturing Tasks:
  - Understand material characteristics from picosecond laser ablation (complex balance between melting and electronic excitation)
  - Quantify interface strength at high temperatures
  - Continued collaborations with Prof. Mark Sheplak (UF) on sensor fabrication & testing

Results



$$d_{hkl} = \frac{\lambda}{2 \sin \theta}$$



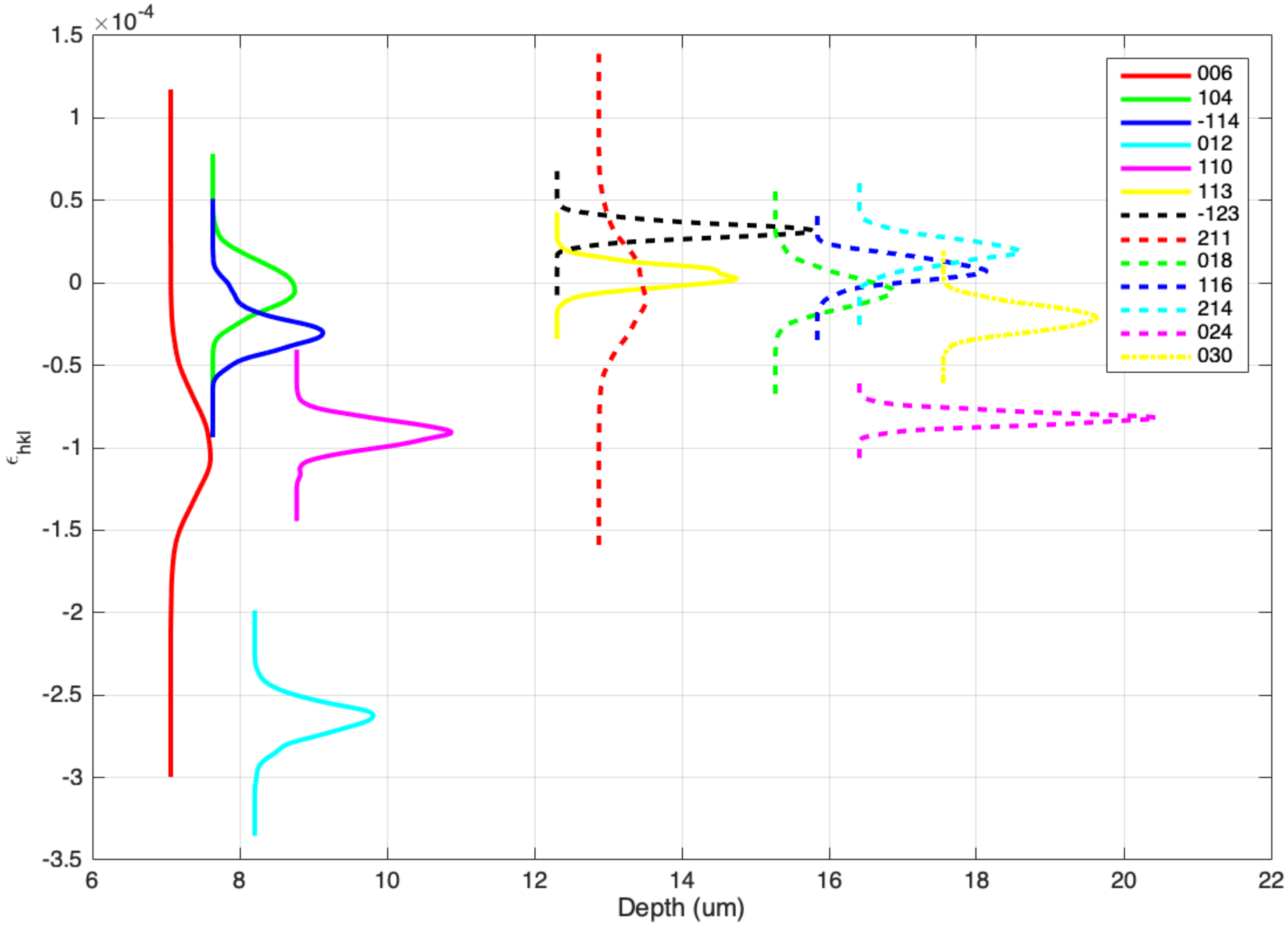


Results

- Compressive strain gradient exists and decays with increasing depth.

$$\epsilon_{hkl} = \frac{d_{hkl} - d_{hkl,0}}{d_{hkl,0}}$$

- *What does this say about the residual state of the material?*

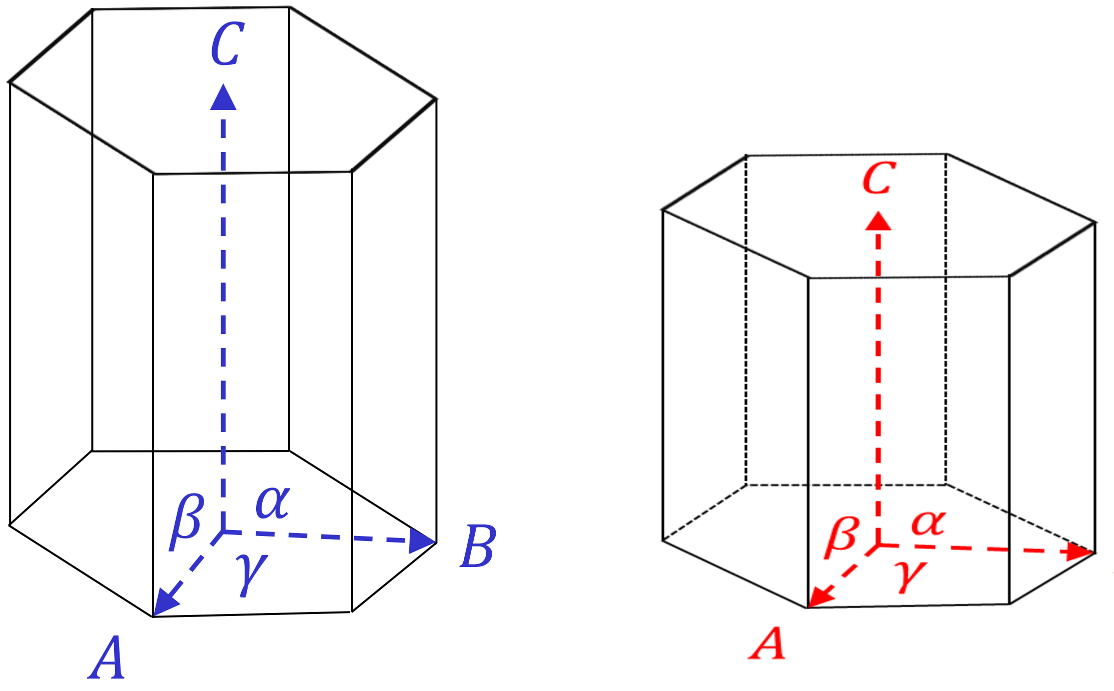


Results

- Evaluate data by inferring the crystal's lattice parameters in machined and pristine zones
- Bragg angle—crystal structure equations:

$$\frac{\lambda}{2\sin\theta_{b,PR}^{DATA}} - d_{hkl}(A, B, C, \alpha, \beta, \gamma) = 0$$

$$\frac{\lambda}{2\sin\theta_{b,LM}^{DATA}} - d_{hkl}(A, B, C, \alpha, \beta, \gamma) = 0$$

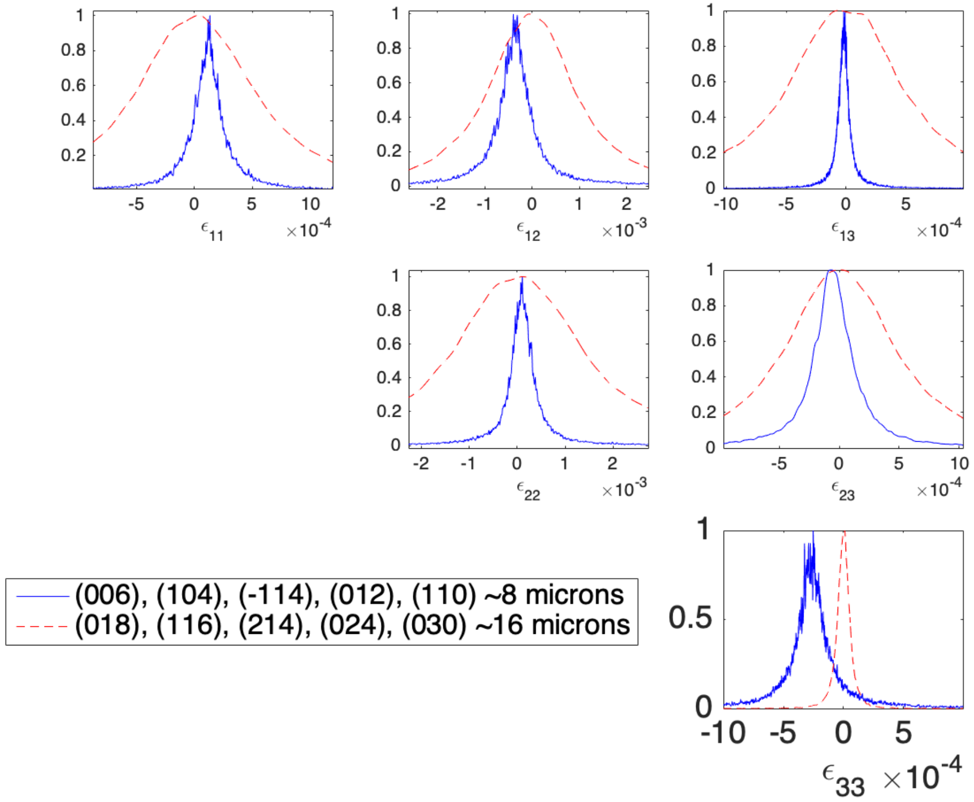


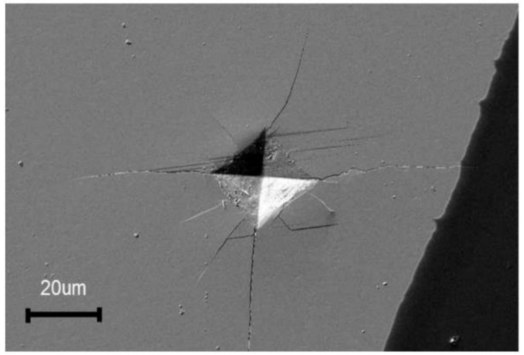
Initial State

Deformed State

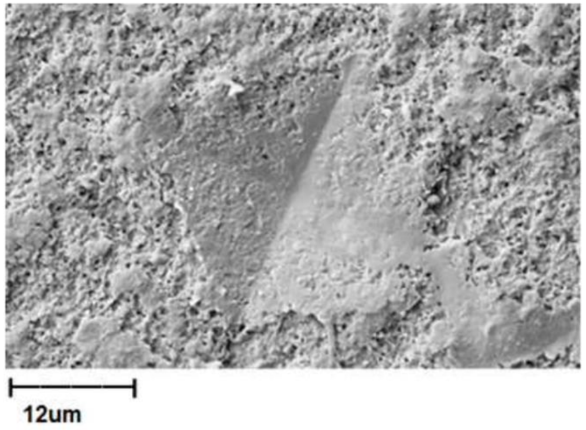
Results

- Laser machining induces in-plane compressive stresses/strains
- Observed increase in fracture toughness





A 1 kg Vickers indent in R-plane sapphire before laser machining [3].



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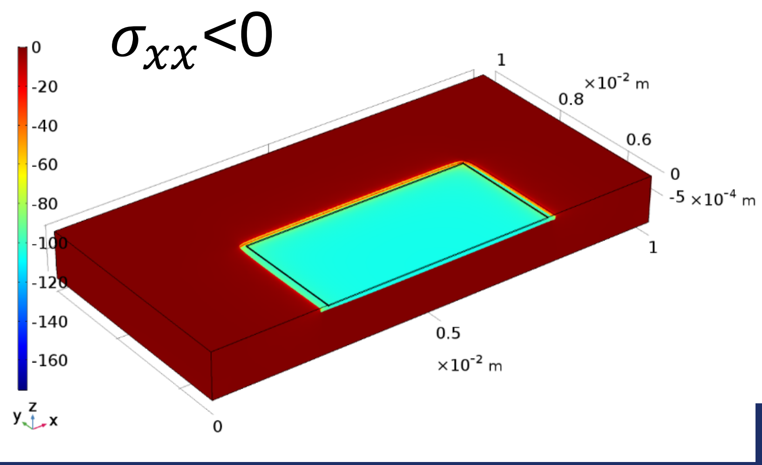
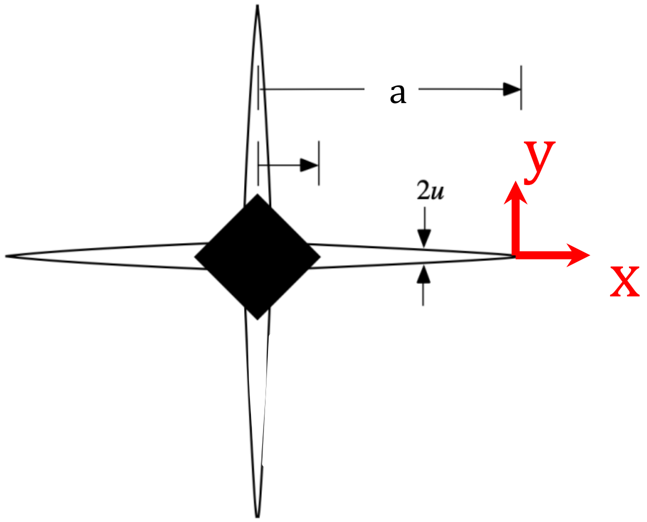
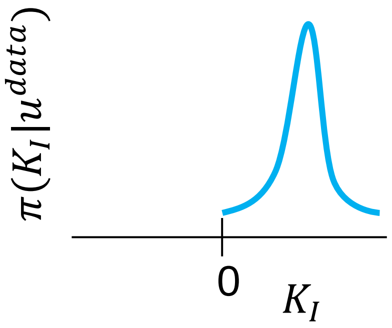


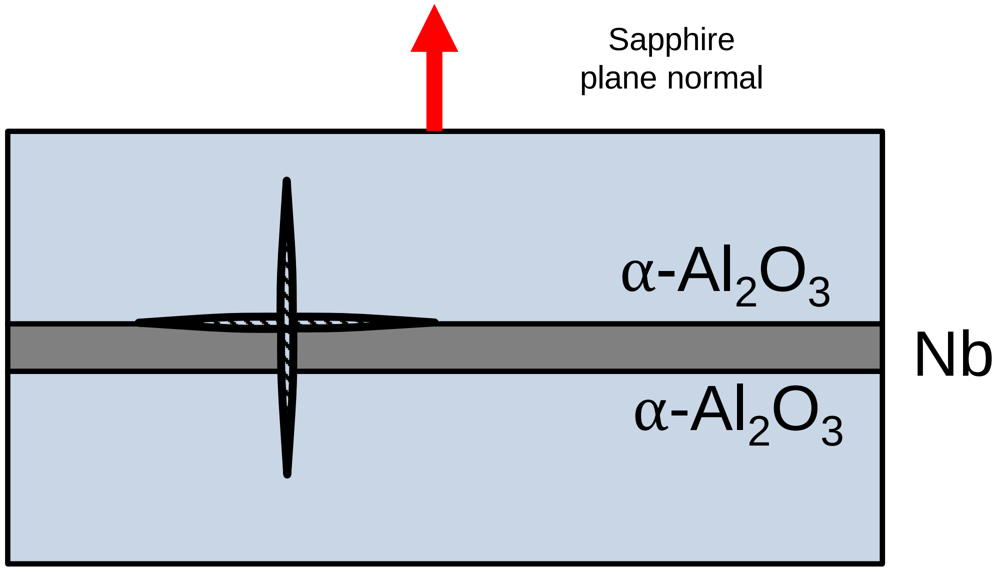
On-Going Work

- Thermo-compressive bond sapphire—niobium sandwich
- Indent ceramic-metal interface
- Quantify interfacial fracture properties.



$$K_I = \min_{K_I} \left\{ \sum_{data} \left(u_i^{data} - u_i^{theory}(K_I)\right)^2 \right\}$$





Sandwich specimen, not to scale.

Publications, Presentations, & Recognitions

PUBLICATIONS:

1. Jakob Consoliver-Zack, Theo Siegrit, William S. Oates, A New Bayesian Uncertainty Methodology for Inferring Strain Gradient Residual States via Multi-Axial X-Ray Data in Single Crystal Sapphire, in preparation, 2022.
2. Harman Singh Bal, Jakob Consoliver-Zack, and William S. Oates. New Space. Mar 2019. 43-55. http://doi.org/10.1089/space.2018.0036
3. Woerner, P., Blood, D., Mills, D., Sheplak, M., Oates, W. S. "Quantifying the uncertainty of picosecond pulsed laser ablation in sapphire," Journal of Manufacturing Processes, vol. 35, pp. 687-699. 2018.
4. Peter Woerner, William S. Oates, Mark Sheplak, Daniel Blood and David A. Mills. "Laser Ablation of Dielectrics for Development of High Temperature Sapphire Based Pressure Transducers," AIAA 2016-0244. 54th AIAA Aerospace Sciences Meeting. January 2016.
5. Justin Collins, William S. Oates, Mark Sheplak and Daniel Blood. "Experimental Investigation and Modelling of Laser Machining of Sapphire for High Temperature Pressure Transducers," AIAA 2015-1120. 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. January 2015.

RECOGNITIONS

Justin Collins, MS 2016
Harman Singh Bal, MS 2015
Peter Woerner, PhD 2018
Jakob Consoliver-Zack, PhD, est. summer 2022

Conclusions and Future Work

- Conclusions
  - Confirmed the presence of a residual strain gradient due to laser machining.
  - Inferred the full strain state with limited data for the first time
    - Combined multi-axial x-ray data with Bayesian inference and nonlinear solid mechanics
- Future work
  - Interface material optimization—e.g., high entropy alloy interface (low thermal stress & corrosion, high strength & toughness)
  - Process dependence on sensor fabrication
    - Thermocompression bonding vs. spark plasma sintering
  - Acoustic characterization at high temperatures (M. Sheplak, UF)
  - Cyclic thermomechanical testing sensor subsystems
  - Material/process optimization for sensor performance across extreme operating regimes

Thank you.

We greatly appreciate the generous support from the FAA CST funding over the years of this Center.