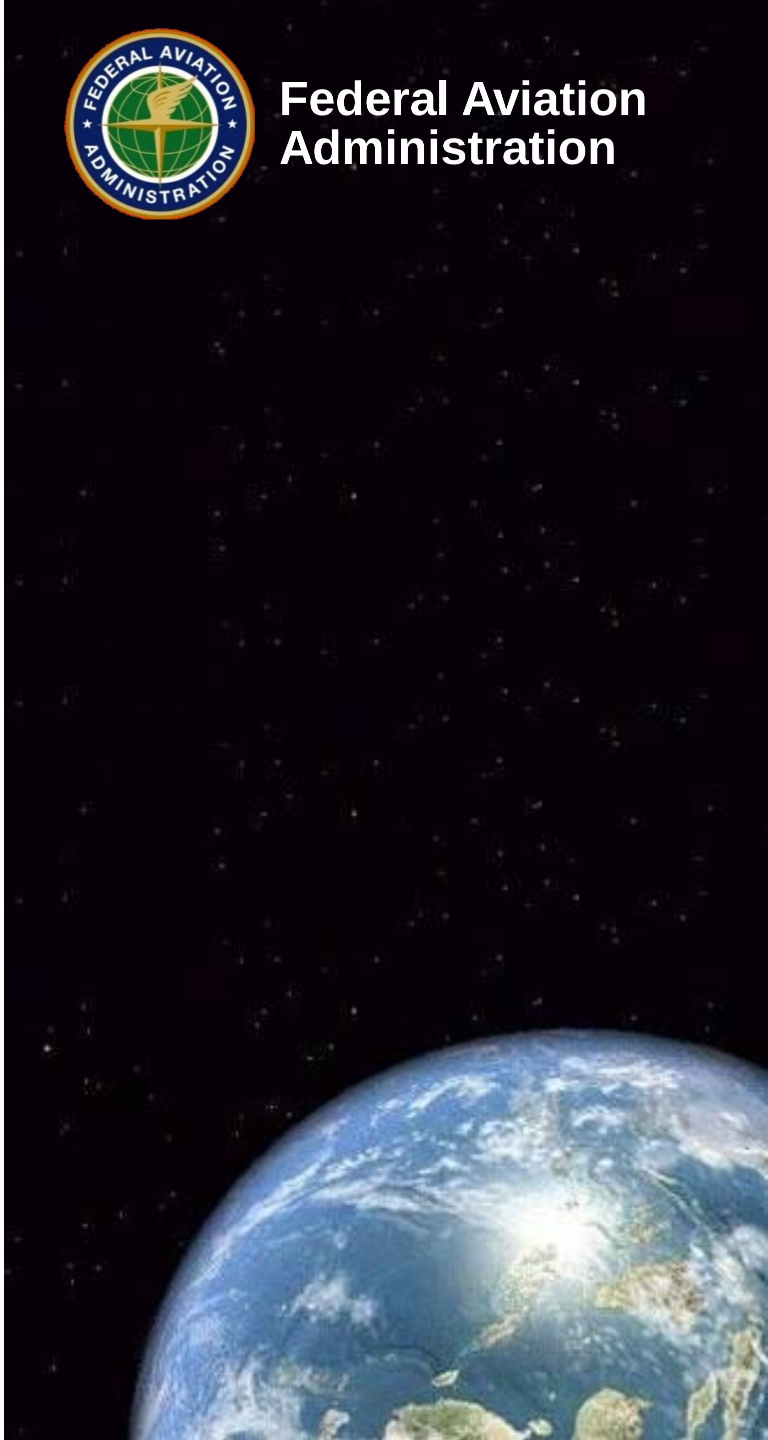
COE CST Second Annual Technical Meeting: Fracture Mechanics of Sapphire for High Temperature Pressure Transducers

Justin Collins

Advisor: William Oates

10/31/2012

Federal Aviation Administration



Team Members

- Mark Sheplak (UF)
- David Mills(UF)
- Daniel Blood(UF)

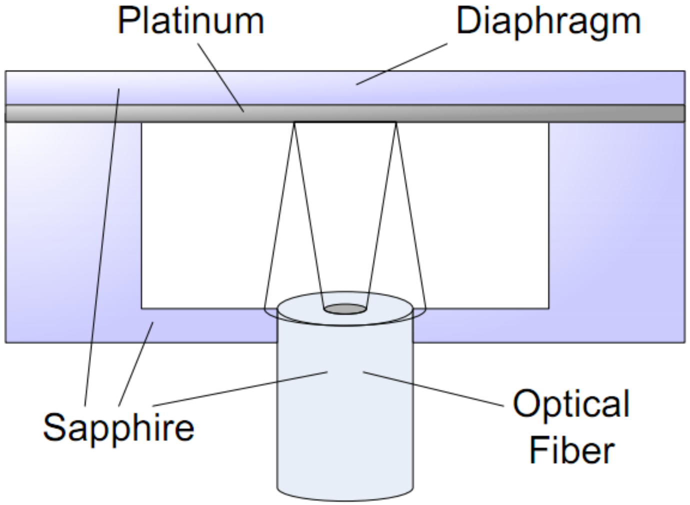
Overview

- Motivation
- Background
  - Structure property relations
- Experimental work
  - TEM Characterization
- Theoretical calculations
  - Anisotropic fracture mechanics
- Summary and future work

Motivation

- Commercial sensors capable of up to approximately 600℃
    - Uses SOI technology
- Alternative material sapphire: potentially capable of up to 1500℃
- Laser machining to cut specimens
    - Hard
    - Chemically Inert

Kulite Pressure Transducer

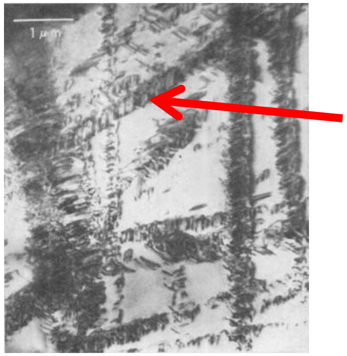


Structure-Property Relations

- Sapphire crystallographic structure
  - Complicated by hexagonal cage & internal rhombohedral structure
- *Anisotropic elastic behavior
  - Rhombohedral—not hexagonal

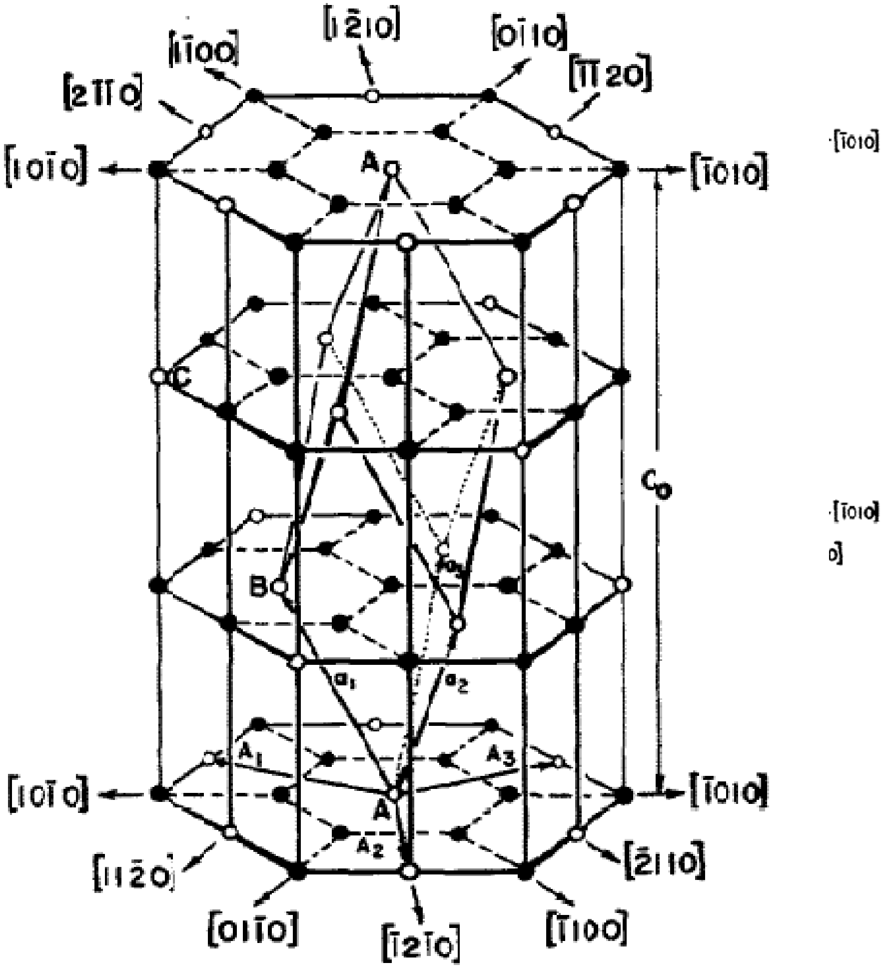
$$\sigma_{ij} = c_{ijkl}\varepsilon_{kl}$$

- Melting temperature 2030 ℃



Basal half loop dislocation

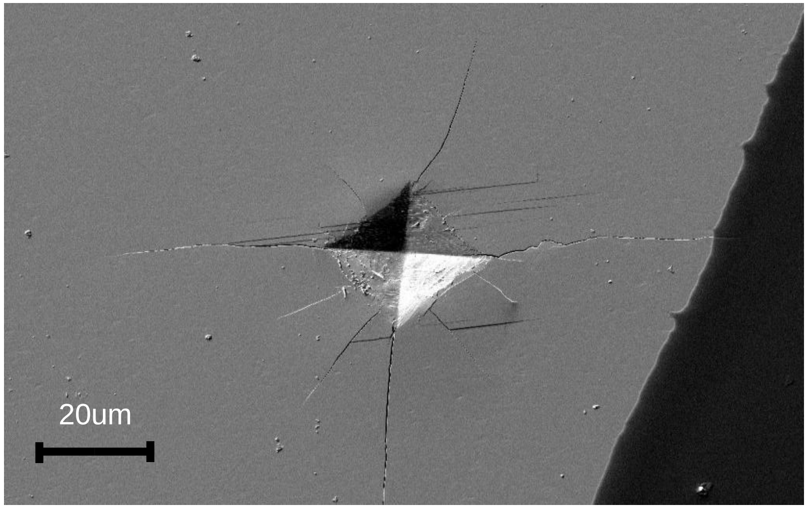
Hockey, Journal of the American Ceramic Society, May 1971, Vol. 54, No. 5

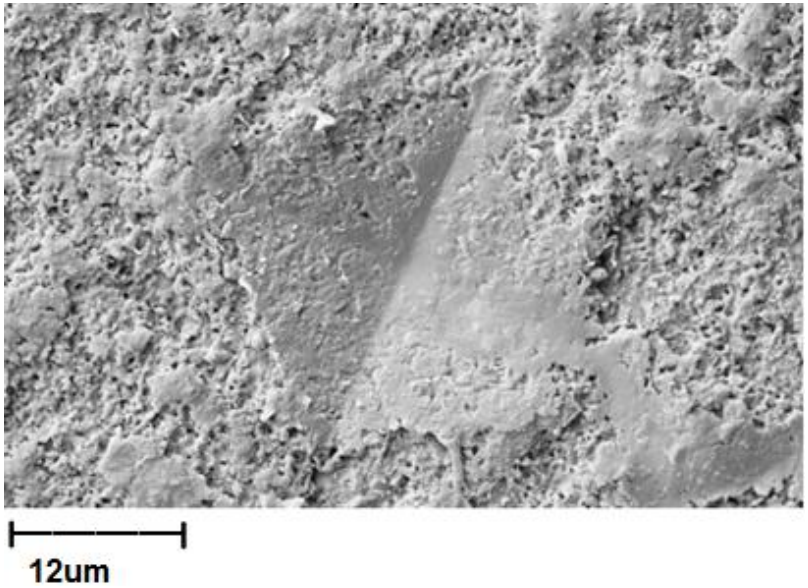


*Ohno, *Phys. Chem. Solids Vol. 47, No. 12. pp.* I ION 108. *1986*

Toughness Induced Laser Machining

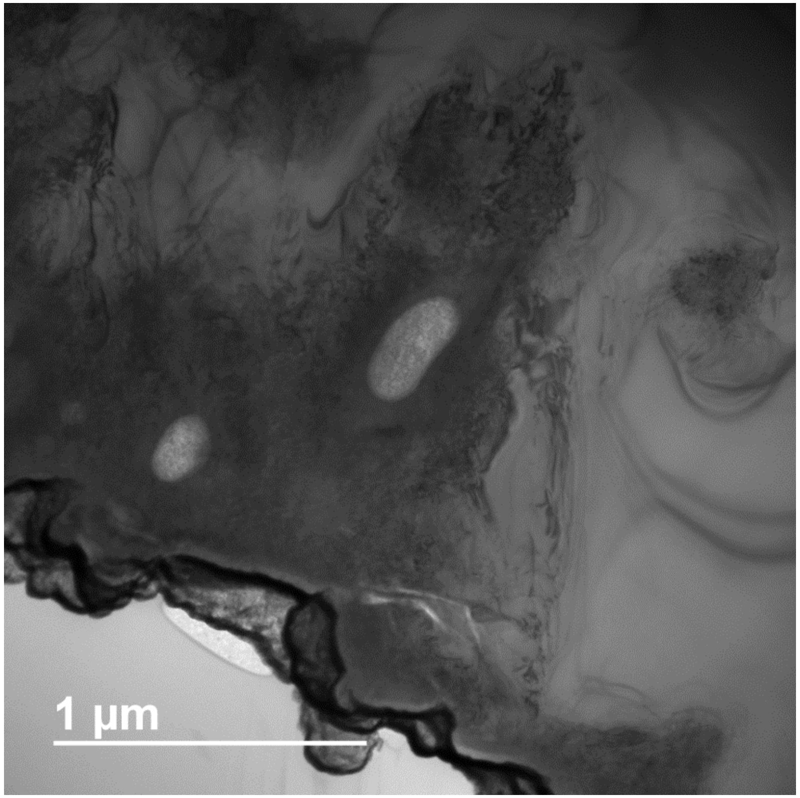
- Vicker's indentation characterization
- No visible cracks in laser machined specimens
- Laser machining parameters
  - 10 kHz rep rate, 10 mm/s scanning speed, 3.8 J/cm^2 fluence, 3um stepover

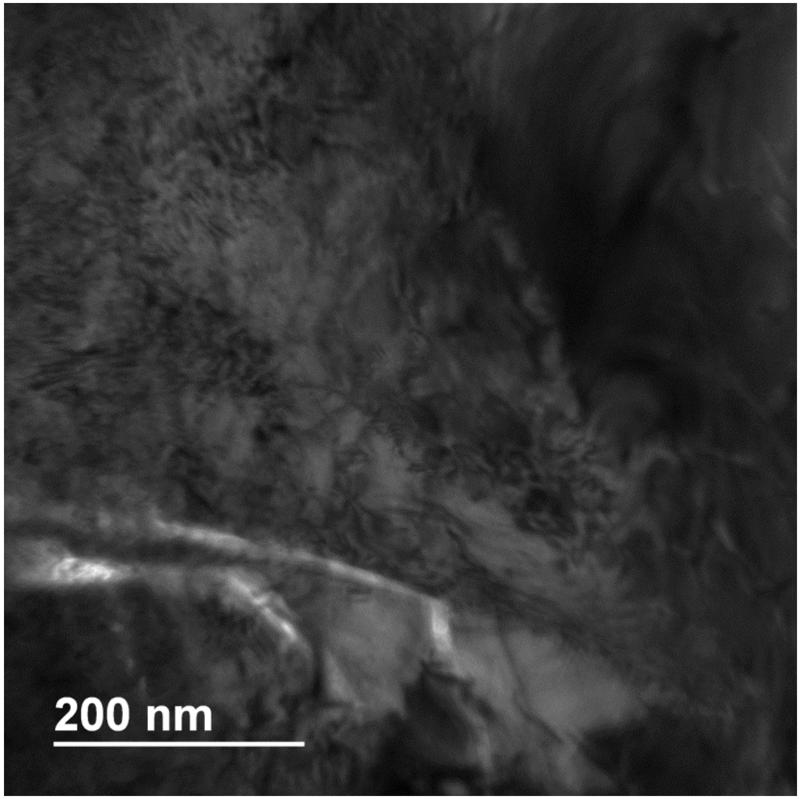




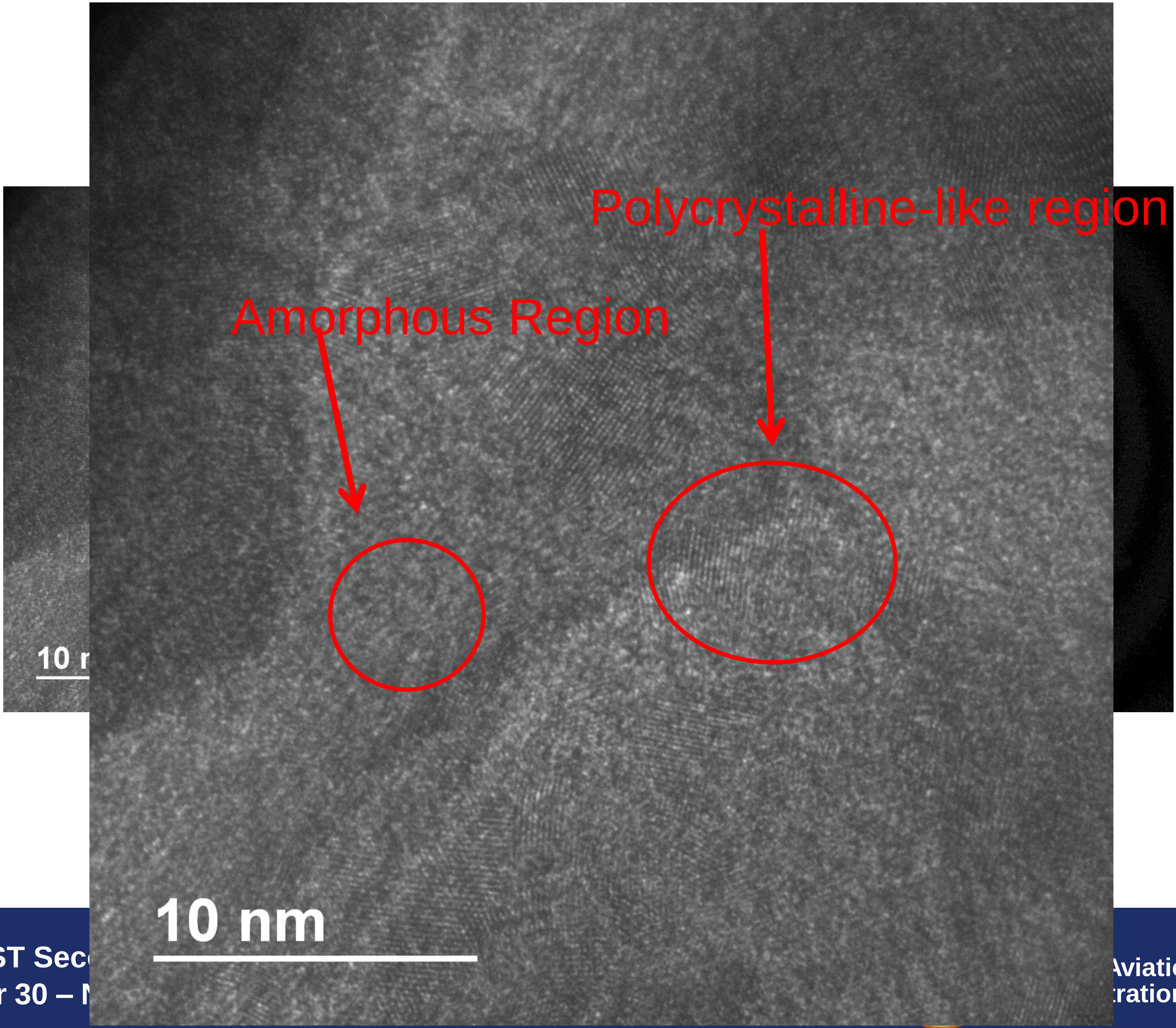
TEM Characterization

- High resolution TEM located at the NHMFL
  - 0.8 Angstrom resolution





TEM Characterization-2



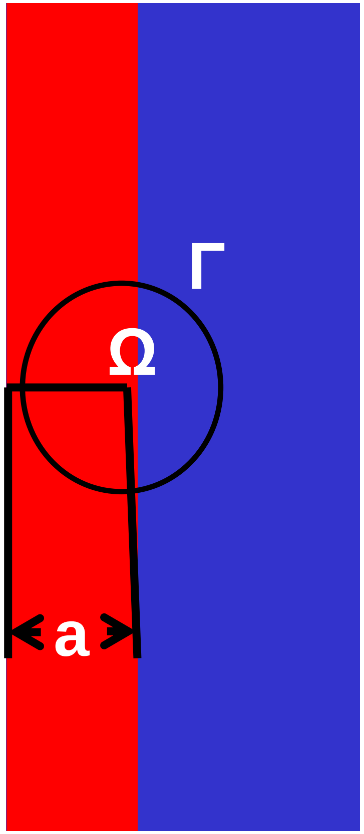
Theoretical Fracture Analysis

Eshelby stress tensor

J-Integral

$=$ $-$

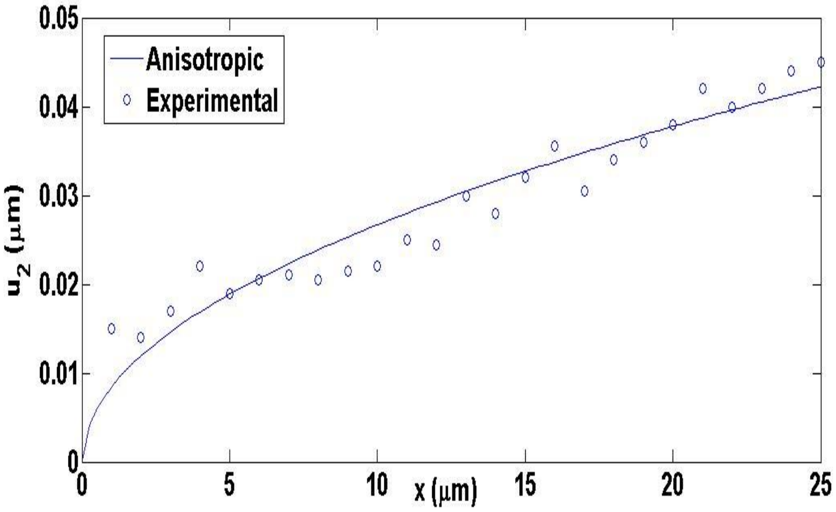
When this condition occurs a crack propagates.



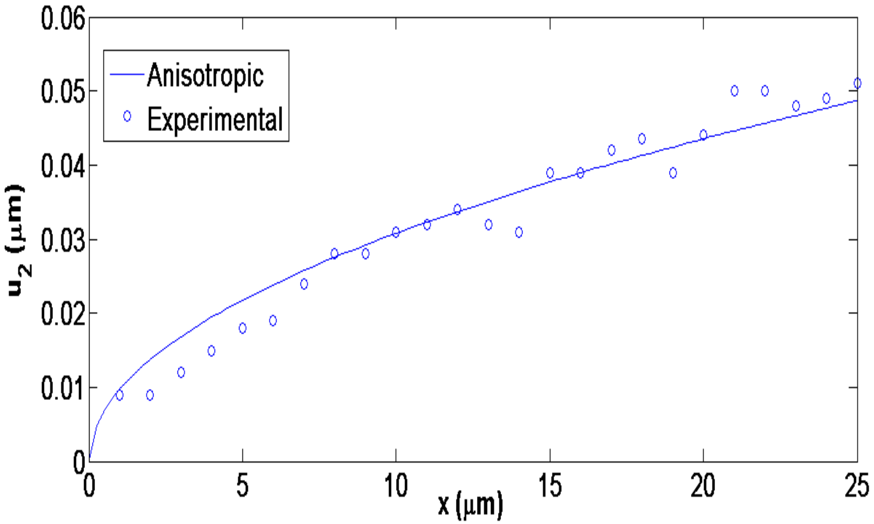
Fracture Toughness

- ○ $K_{1c} \cong 2.2$ –
- ○ $\cong 11.64$ –

- $K_{1c} \cong 2.50$ –
- $\cong 15.25$ –

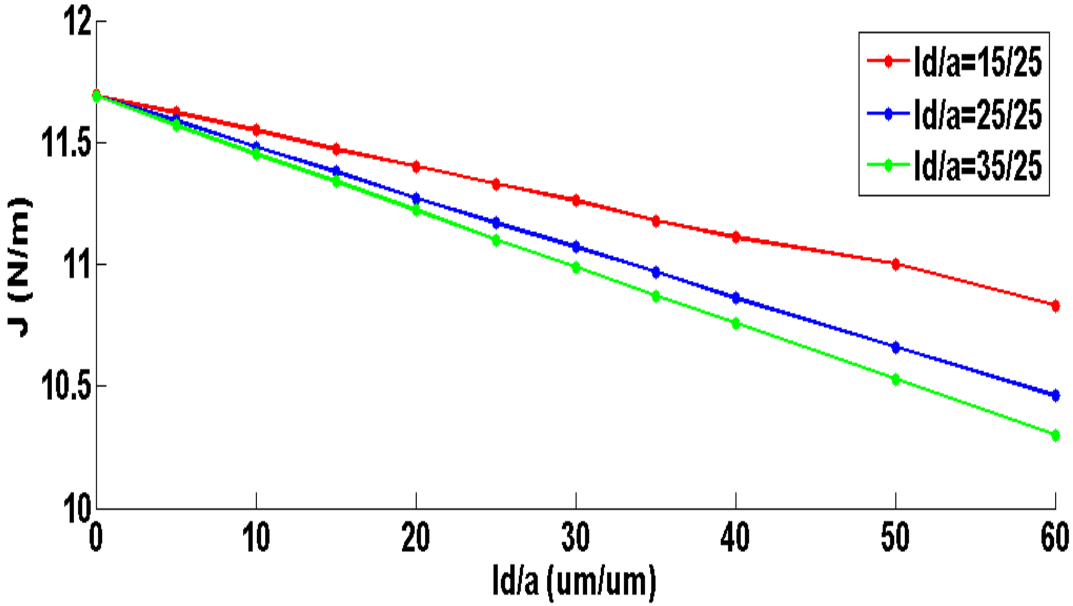


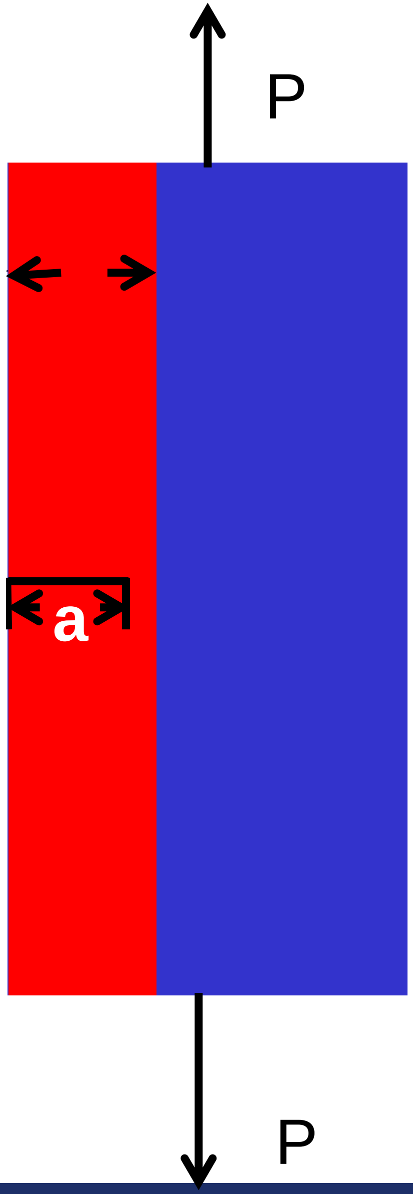
Indentation at ~0



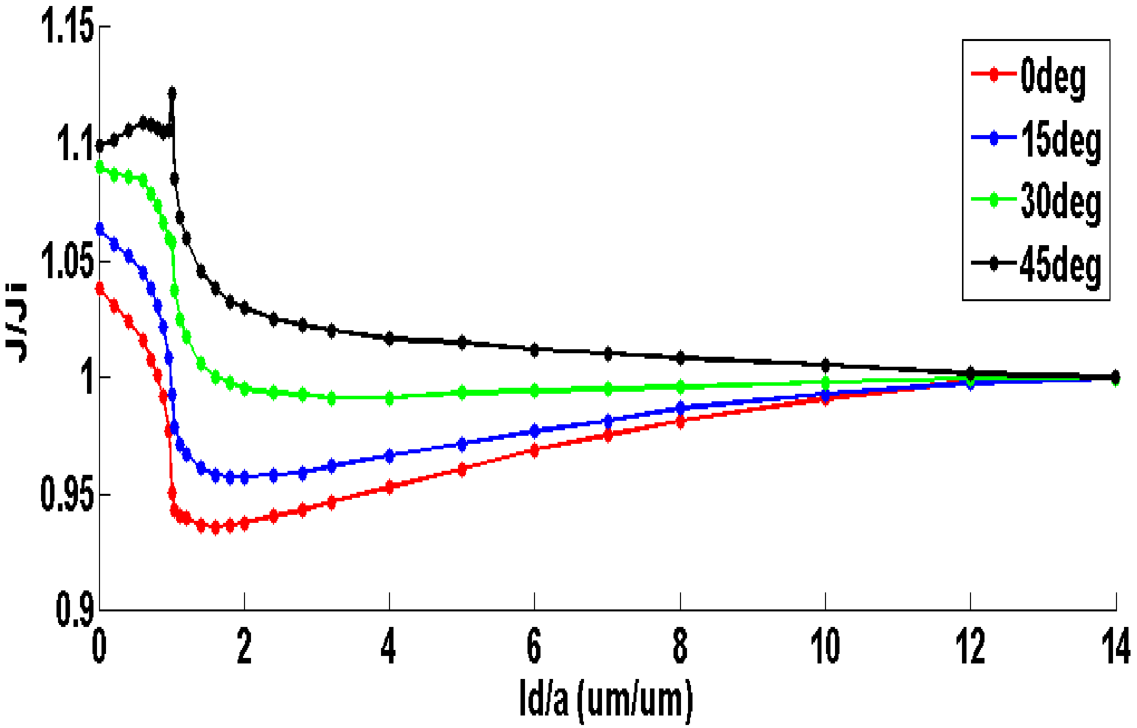
Indentation at ~45°

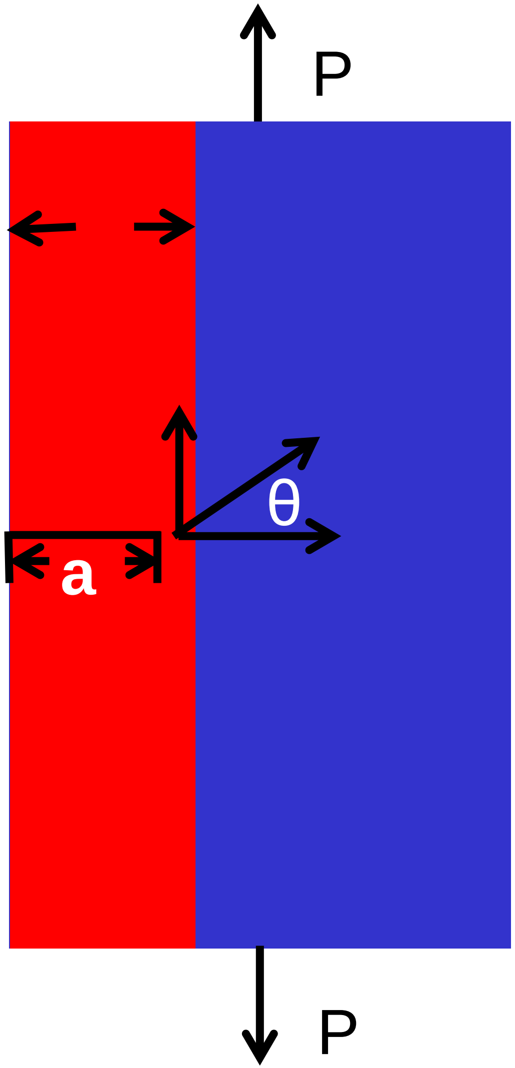
Theoretical Work-Residual Strain





Theoretical Work-Isotropic to Anisotropic





Summary

- Laser machining subsurface damage quantified
  - TEM characterization identified dislocations
  - Amorphous and polycrystalline-like behavior also observed
- Anisotropic fracture toughness
  - Significant dependence on crystal anisotropy
- Future work
  - Thermal annealing & laser parameter studies
  - Transition to pressure sensing characterization

Acknowledgements

- National High Magnetic Field Laboratory
  - Dr. Yan Xin
  - NHMFL-Applied Superconductivity Center
- FAA
- FAMU-FSU College of Engineering
- University of Florida
  - Mark Sheplak, David Mills, Daniel Blood, Tony Smitz (UNC Charlotte)

Contact Information

- Justin Collins
  - Research Assistant
  - Email: justin.collins.eng@gmail.com
- William Oates
  - Associate Professor
  - Email: woates@eng.fsu.edu
  - Phone: (850) 645-0139
  - Fax: (850) 410-6337

Quad Chart

Major Milestones Past

- Fracture toughness of laser machined sapphire experimentally characterized
- Higher toughness observed in laser machined specimens
- Origin of increased toughness explored through scanning electron microscopy (SEM) comparisons with anisotropic fracture mechanics theory

Major Milestones Present

- Transmission electron microscopy (TEM) used to identify potential toughening mechanism: dislocation formation, residual strain, and/or amorphous zone formation
- Toughening found to depend on thermal annealing: T>1200°C, indentation cracks formed similar to virgin material
- Theories based in laser damaged zone near a crack tip implemented to illustrate differences in crack tip driving forces

Major Milestones Future

- Quantify differences in micro and nanostructure after thermal annealing using TEM
- Design and implement sapphire-based pressure transducer in a thermo-mechanical loading environment

Budget

FY12	FY13	FY14	FY15	FY16	FY17
$93k	$86k	$0k	$0k	$0k	$0k

Cost matching:
134k

Funding Requirements – Five Years

- Gross received thru October 31, 2012
- Gross requested for five total years broken out by year

Backup Slides

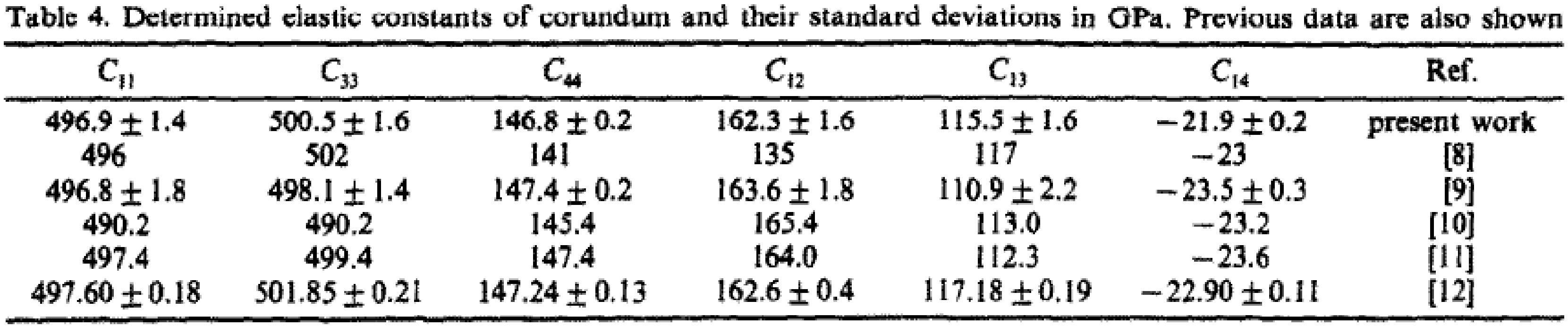
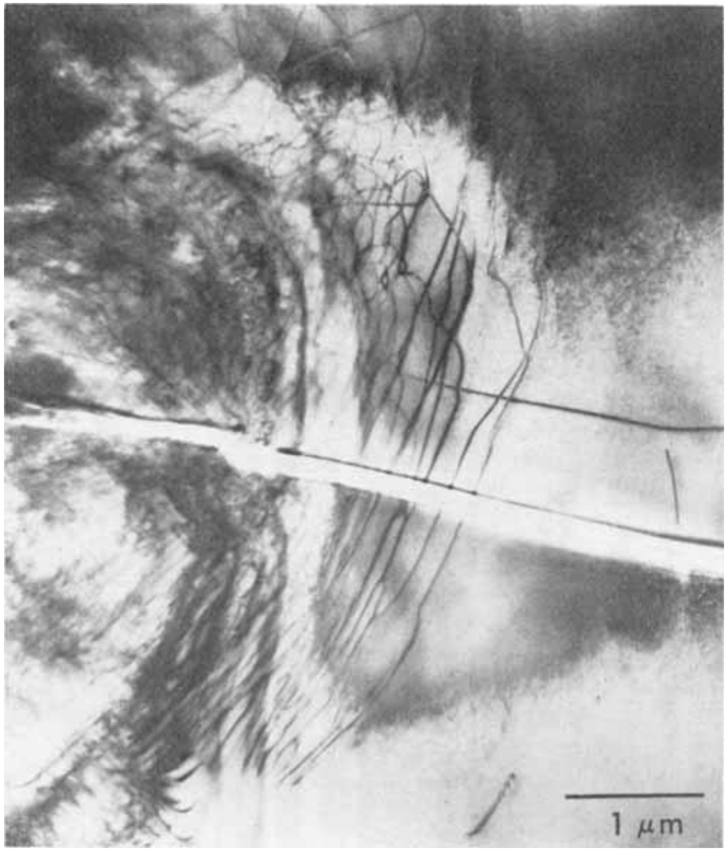


Table 4. Determined elastic constants of corundum and their standard deviations in GPa. Previous data are also shown

C_{11}	C_{33}	C_{44}	C_{12}	C_{13}	C_{14}	Ref.
496.9 ± 1.4	500.5 ± 1.6	146.8 ± 0.2	162.3 ± 1.6	115.5 ± 1.6	−21.9 ± 0.2	present work
496	502	141	135	117	−23	[8]
496.8 ± 1.8	498.1 ± 1.4	147.4 ± 0.2	163.6 ± 1.8	110.9 ± 2.2	−23.5 ± 0.3	[9]
490.2	490.2	145.4	165.4	113.0	−23.2	[10]
497.4	499.4	147.4	164.0	112.3	−23.6	[11]
497.60 ± 0.18	501.85 ± 0.21	147.24 ± 0.13	162.6 ± 0.4	117.18 ± 0.19	−22.90 ± 0.11	[12]

Dislocation Mechanics

- Basal dislocations associated with a 100-g indentation on a (0001) basal plane section
- Specimen polished with abrasive paper.
- How does laser machining affect the properties of sapphire? Are dislocations induced during the process?



FEM Analysis