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

William Oates

Date of Presentation

COE CST

Center of Excellence for Commercial Space Transportation

Overview

- Team Members
- Motivation
- Background
  - Structure property relations
- Experimental Work
  - SEM Characterization
  - TEM Characterization
- Modeling
  - Coupling dislocation evolution with fracture mechanics
- Summary and future work
- Contact Information

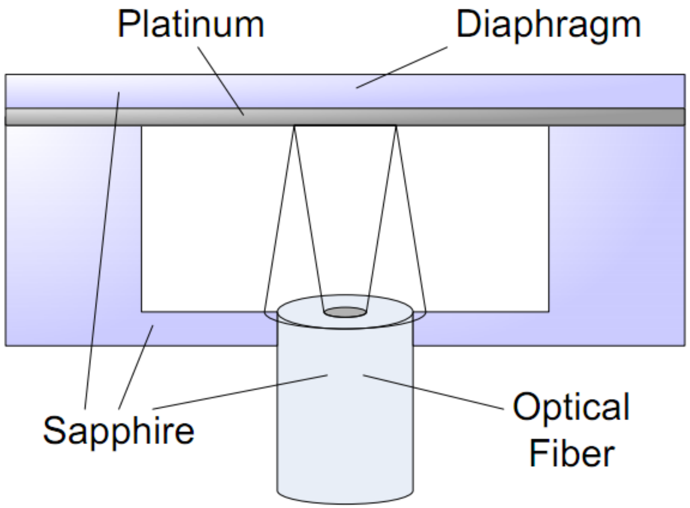
Team Members

- Mark Sheplak (UF)
- Justin Collins (FSU), David Mills (UF), Daniel Blood (UF), Tony Smitz (UNC Charlotte)

Motivation

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

Kulite Pressure Transducer

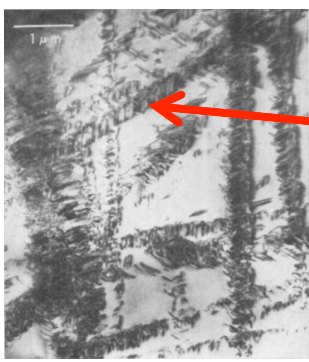


Structure-Property Relations

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

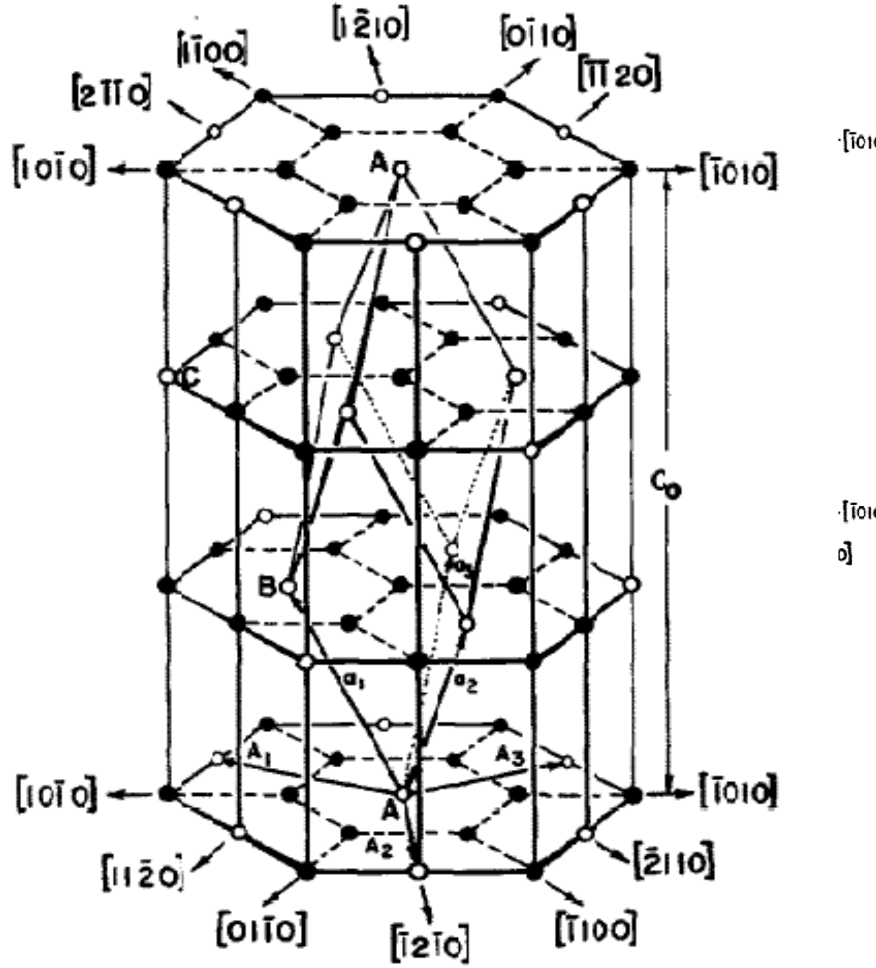
$$\sigma_{ij} = c_{ijkl}\varepsilon_{kl}$$

- Melting temperature 2030 ℃



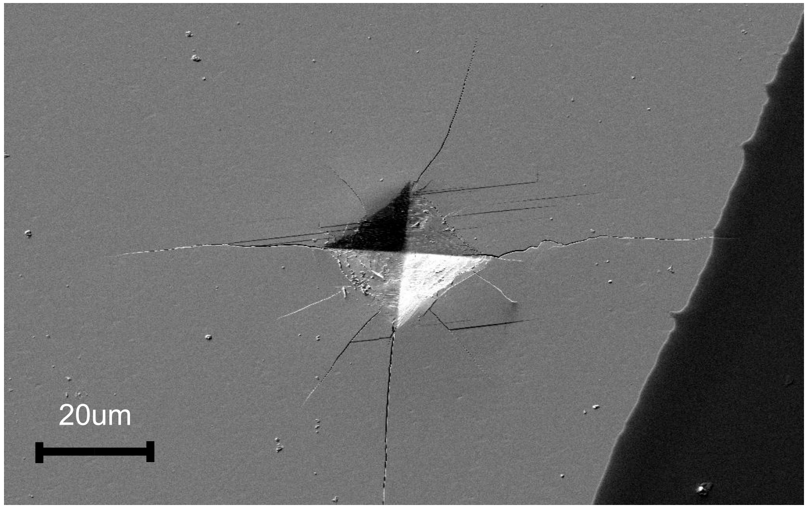
Basal half loop dislocation

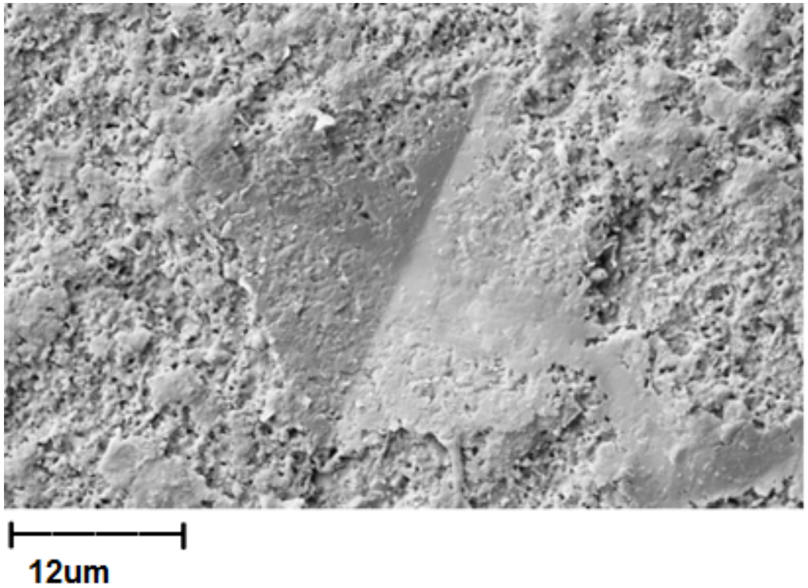
Hockey, Journal of the American Ceramic Society, May 1971, Vol. 54, No. 5



Toughness Induced Laser Machining

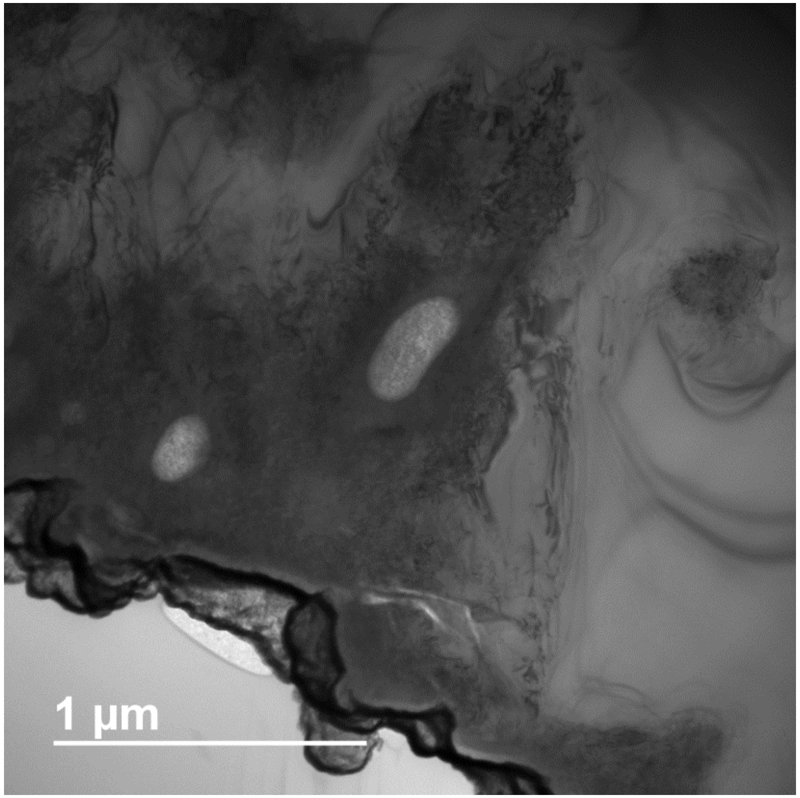
- Vicker's indentation characterization
- No visible cracks in laser machined specimens
- Laser machining parameters
  - 10 kHz rep rate, 10 mm/s scanning speed, 3.8 J/cm^2 fluence, 3um stepover

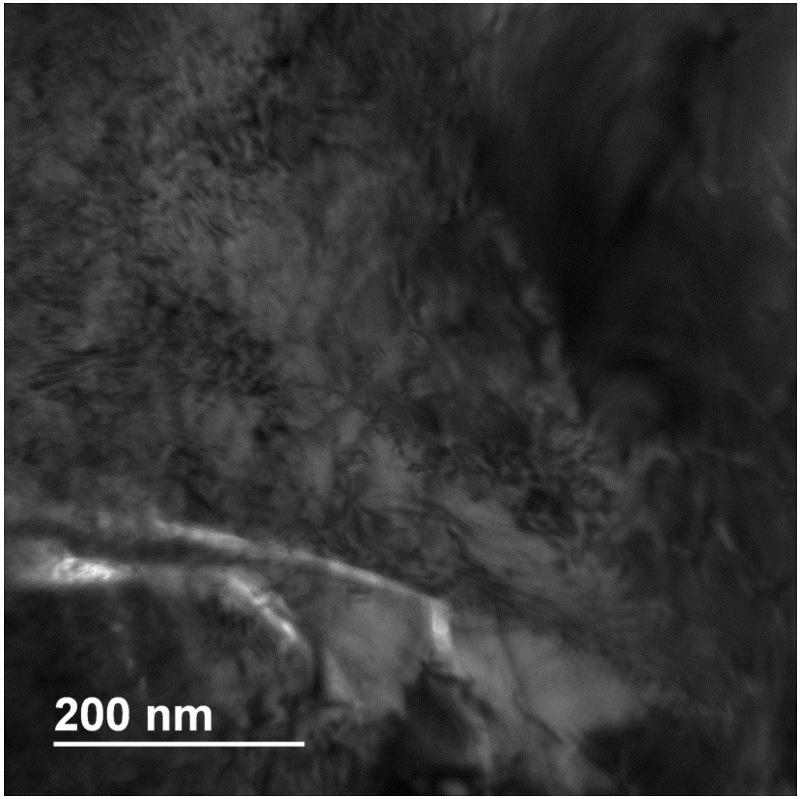




TEM Characterization

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





Coupling Dislocation Theory and Solid Mechanics

Linear Momentum Balance

PDE Governing Dislocation Mechanics

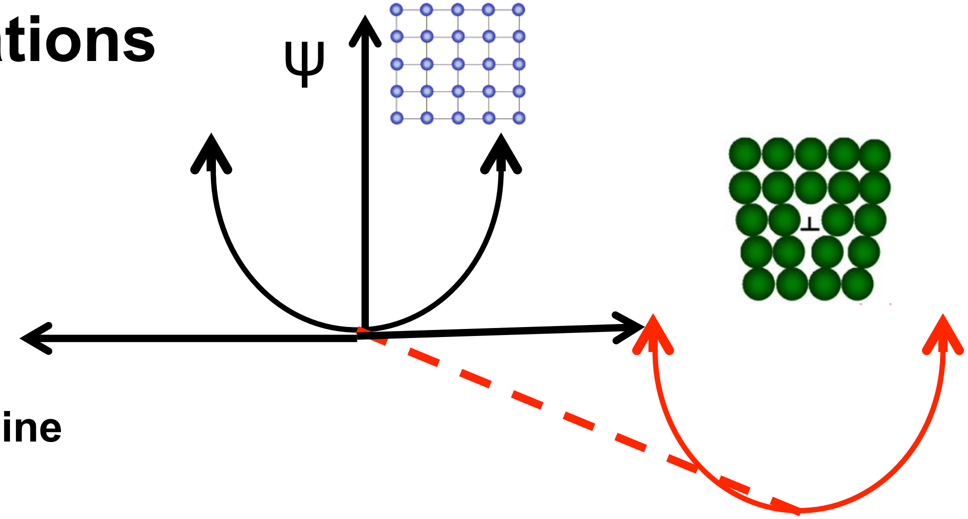
Energy to formulate dislocations

=

Where

Single Crystal

Polycrystalline



FEM Model of Single and Polycrystalline

Polycrystalline	Single crystalline
	

Fracture Analysis

Stroh's Formalism

Equilibrium

Constitutive Relation

Boundary Condition

Generalized Displacement Potential

J-Integral

Eshelby stress tensor

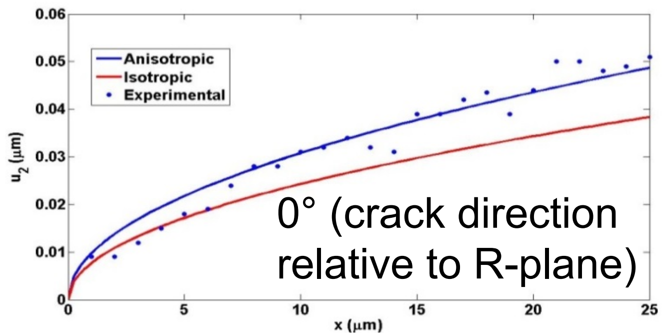
J_1 (direction of the crack)

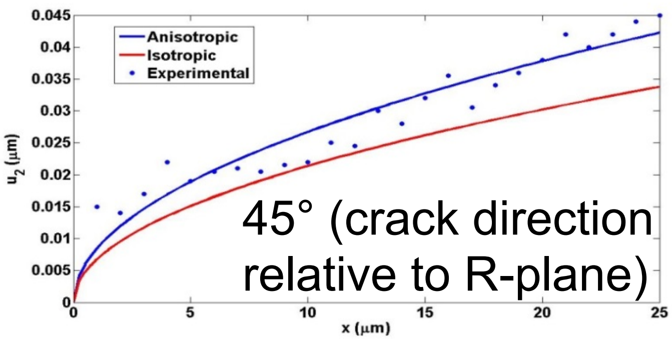
=

When this condition occurs a crack propagates.

Comparison of Fracture Toughness

Experimental





$K_{1c} \cong 2.2\ MPa*m^{1/2}$

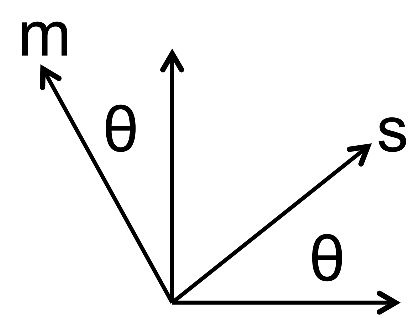
$J_c \cong 11.64\ N/m$

$K_{1c} \cong 2.50$

$\cong 15.25$

Simulation

Crack Tip Driving Force Comparison, J^*	
Θ=0	Θ=45
20.9 N/m	18.84 N/m



Summary

- Laser machining subsurface damage quantified
  - TEM characterization identified dislocations
- Dislocations modeling coupled with solid mechanics
  - Changes in slip system cause change in the crack tip driving force.
- Future work
  - Comparison of slip systems in Sapphire for 3D model.
  - Thermal annealing & laser parameter studies

Acknowledgements

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

Contact Information

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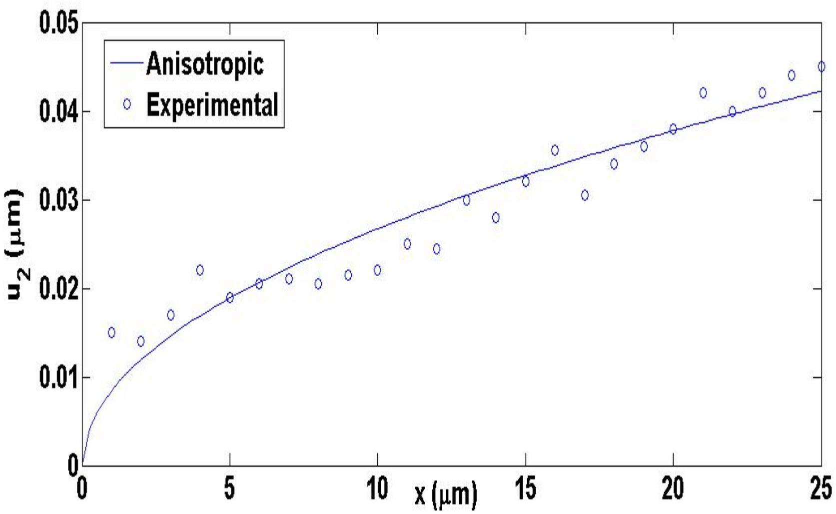
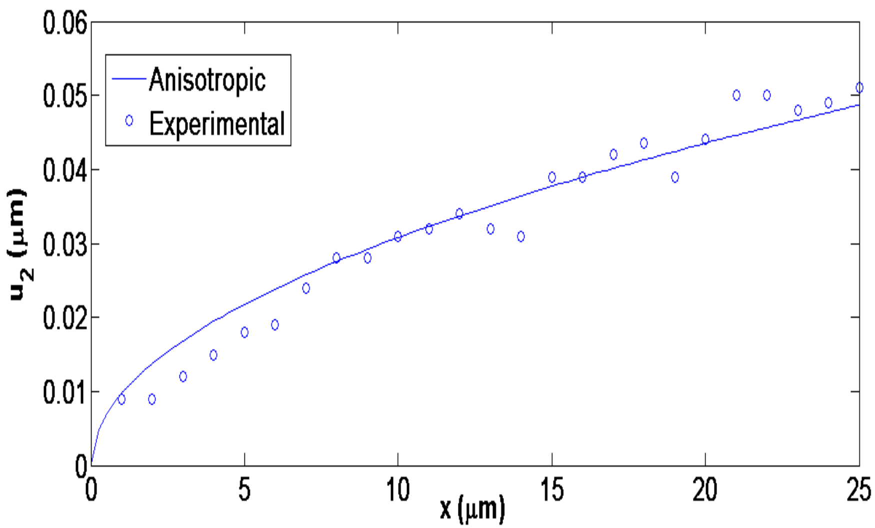
Fracture Toughness

- $K_{1c} \cong 2.2\ MPa*m^{1/2}$
- $J_c \cong 11.64\ N/m$

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

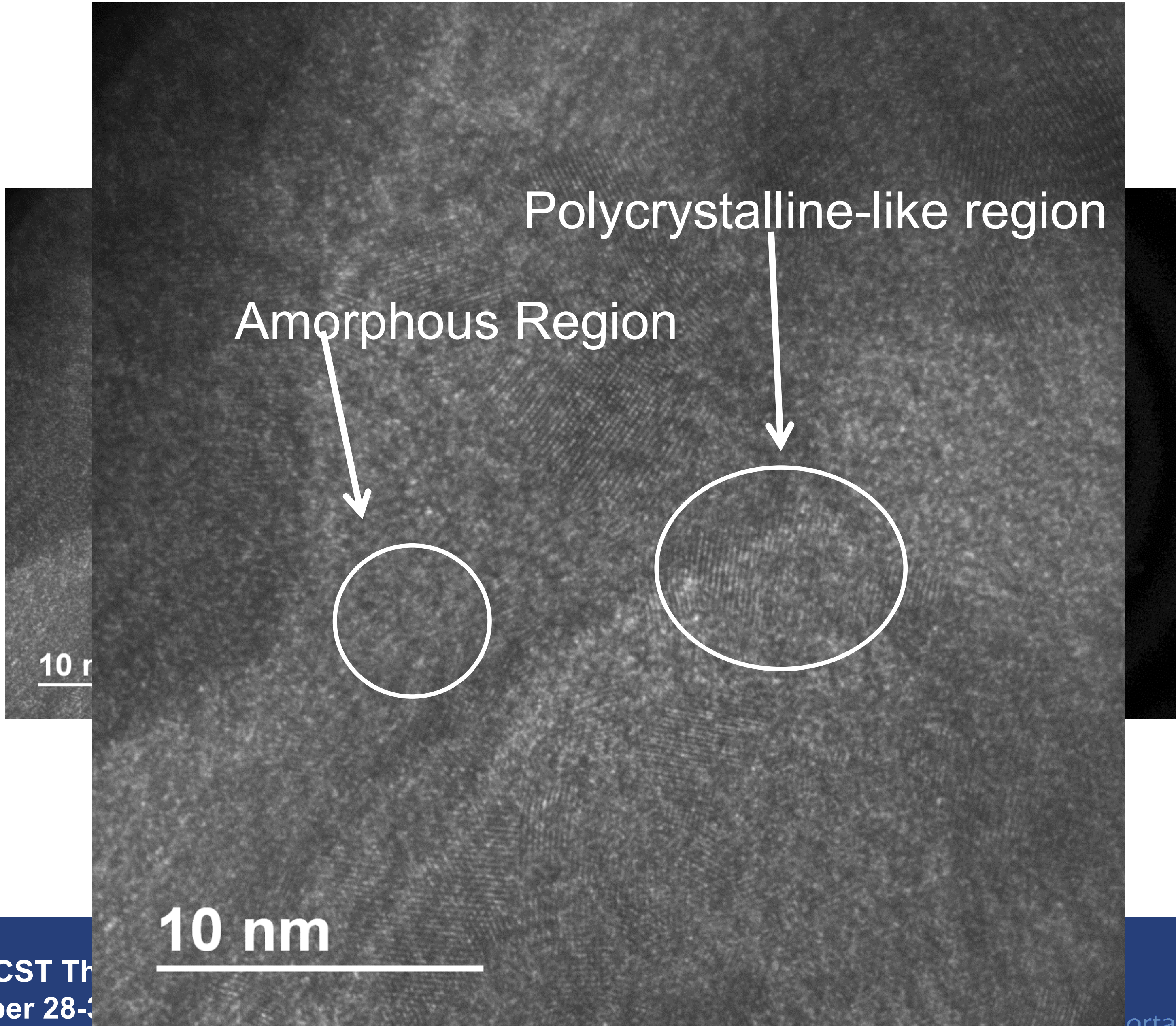


Indentation at ~0



Indentation at ~45°

TEM Characterization-2

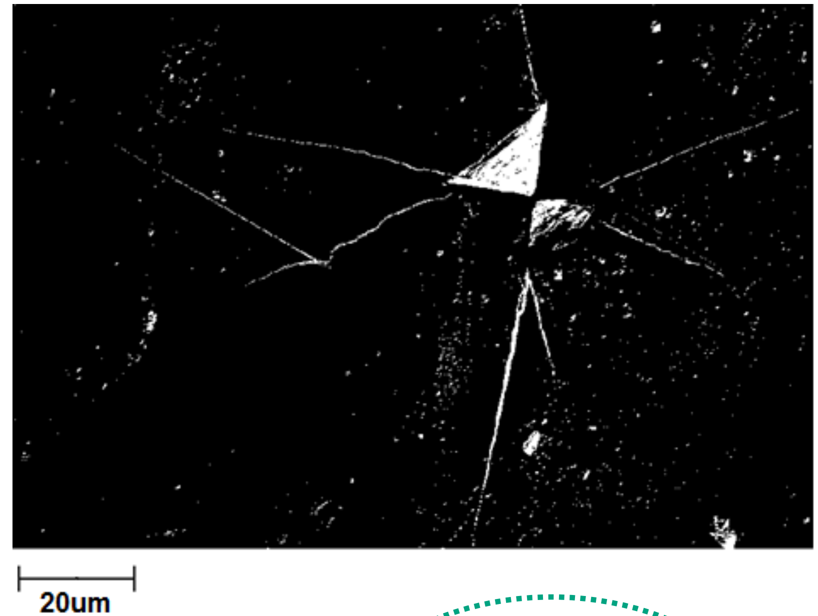


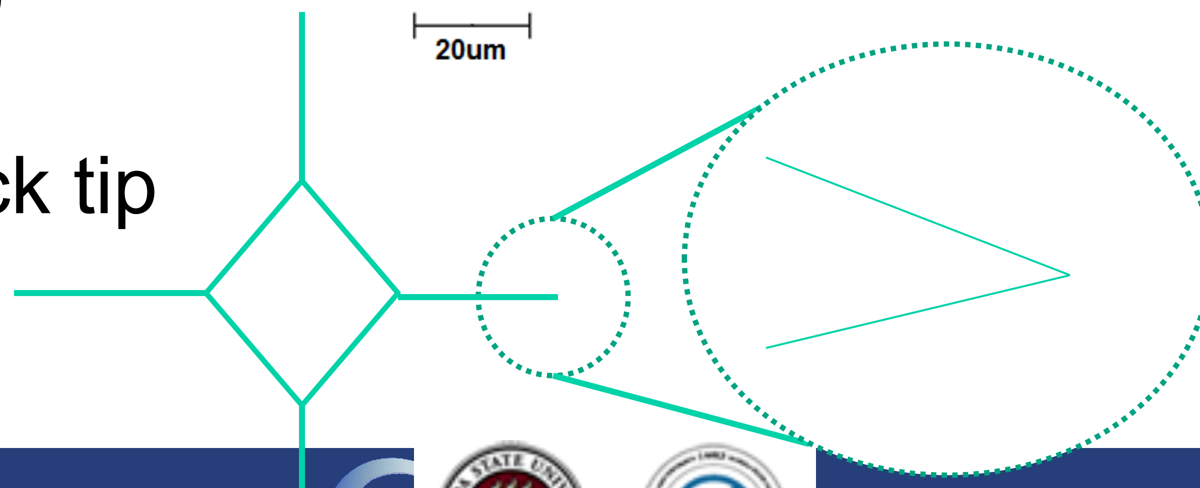
Anisotropic Fracture Stroh's Formalism

- Equilibrium
  - $\nabla \cdot \sigma = 0$
- Constitutive Relation
  - $\sigma_{ij} = C_{ijks} u_{k,s}$
- Boundary Condition
  - $t_i = \sigma_{ji} n_j$
- Generalized Displacement Potential
  - $u_i = 2\sum_{j=1}^{3} Re\{A_{ij} f(z_j) q_j\}$

SEM Characterization

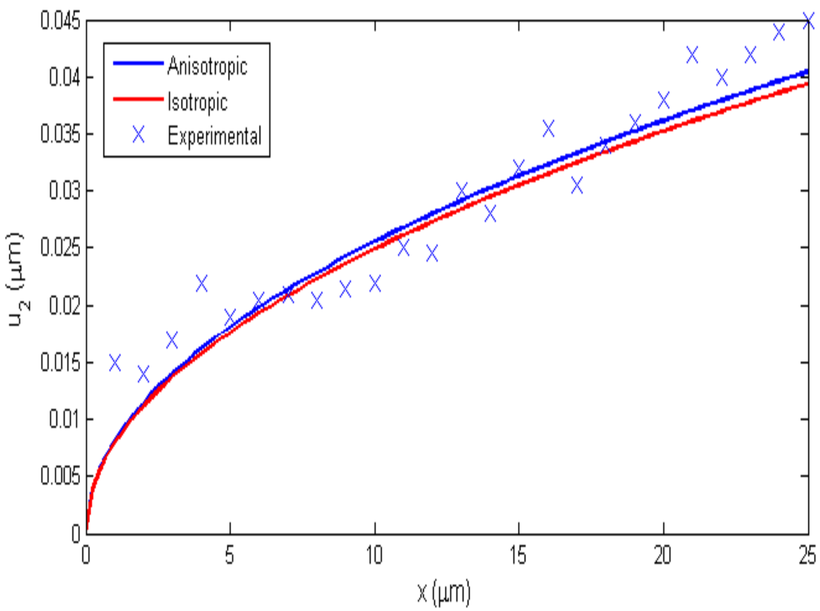
- Fracture characterization
  - Virgin vs. laser machining
- Crack opening quantified
  - Intrinsic crack tip toughness measured

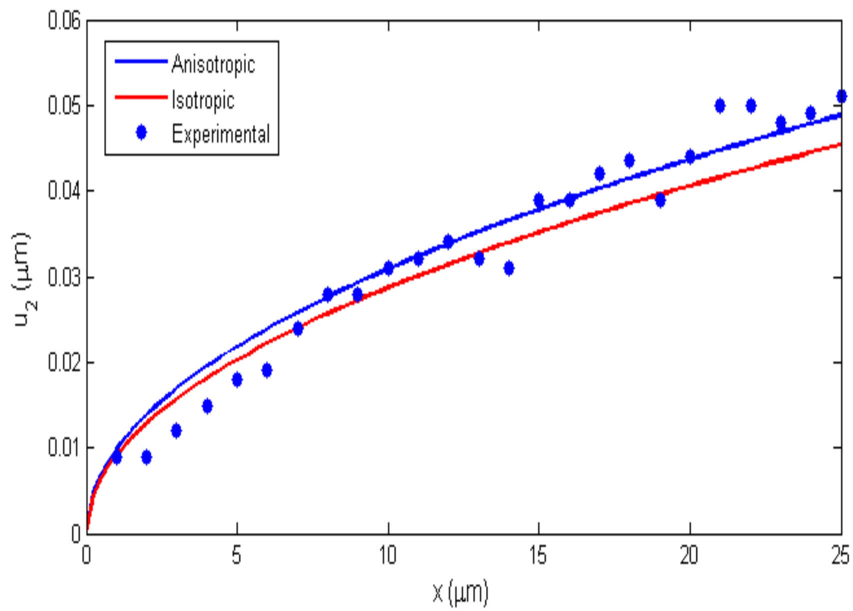




Fracture Toughness

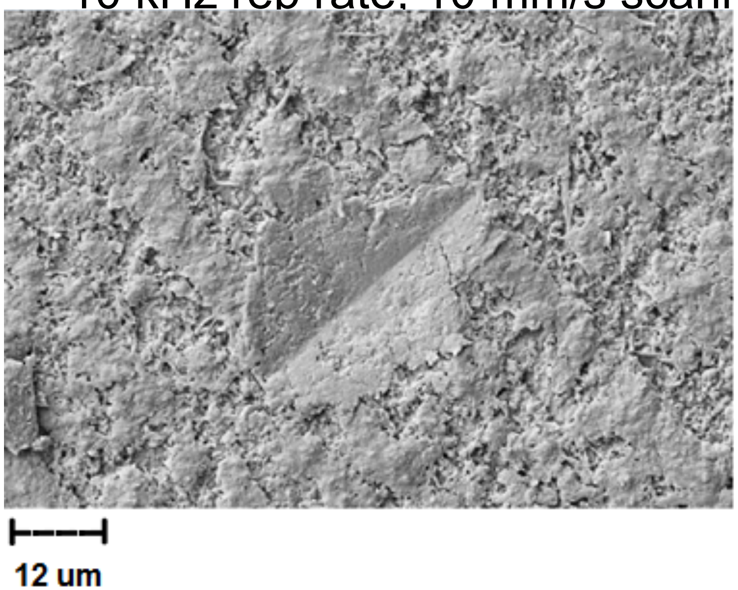
- $K_{1c} \cong 2.3\ MPa*m^{1/2}$
- $G_c \cong 11.65\ N/m$

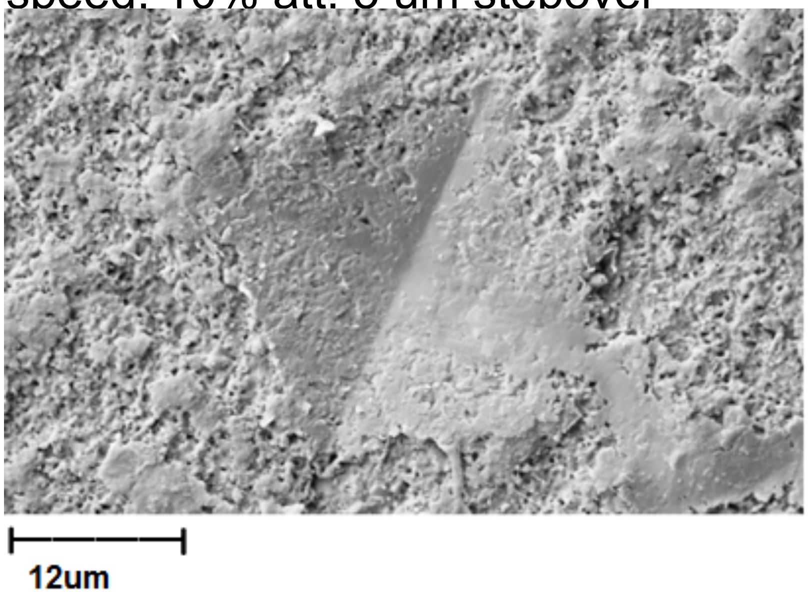




Toughness Induced Laser Machining

- Preliminary Vicker's indentation characterization
- No visible cracks
- Laser machining parameters
  - 10 kHz rep rate, 10 mm/s scanning speed, 10% att, 3 um stepover





Summary

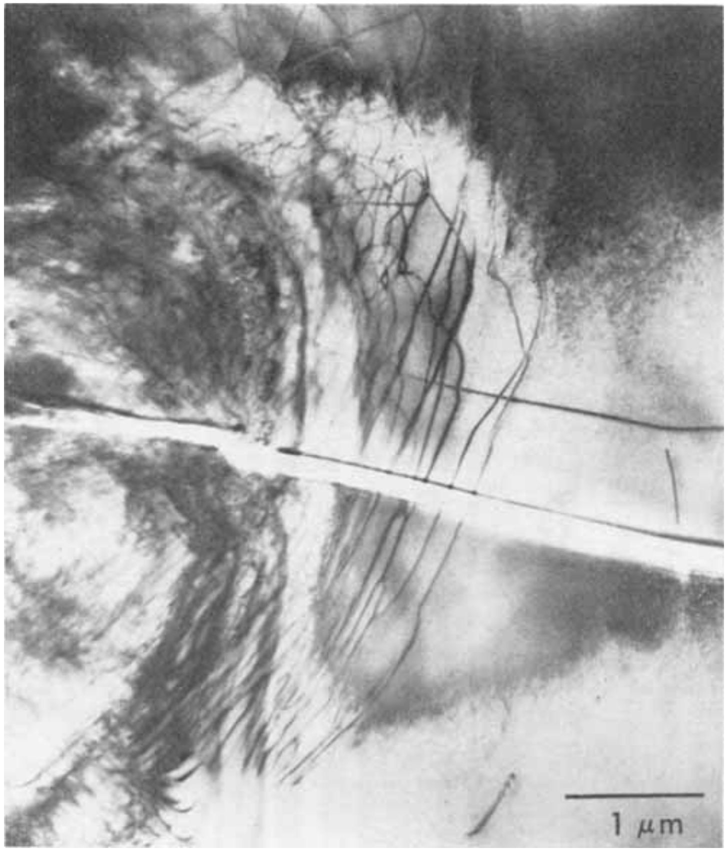
- Correlated crystal structure with anisotropic elastic properties
- Quantified crack tip toughness in virgin sapphire specimens
  - Good correlation with data in literature
- Laser machining effects on fracture
  - Unusual toughness enhancement
- Hypothesis: Laser induced dislocations
  - TEM characterization and dislocation/fracture modeling currently underway

Acknowledgements

- NHMFL-ASC
- FAA
- FAMU-FSU College of Engineering
- University of Florida
  - Mark Sheplak, David Mills, Daniel Blood, Tony Smitz (UNC Charlotte)

Dislocation Mechanics

- Basal dislocations associated with a 100-g indentation on a (0001) basal plane section
- Specimen polished with abrasive paper.
- How does this influenced by laser machining?



Background

- Brittle
- Extremely hard material
  - Ranks a 9 on the Mohs scale
- Melting temperature of 2030°C
- Chemically inert

Introduction

- Crystallographic Structure
  - Hexagonal
  - Rhombohedral

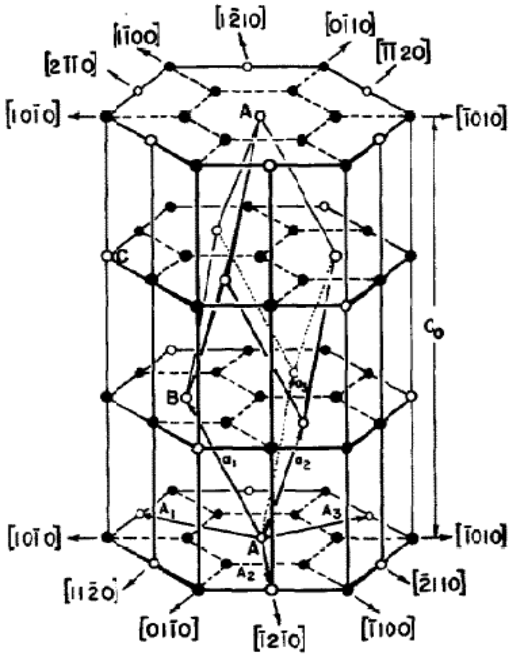


Table 4. Determined elastic constants of corundum and their standard deviations in GPa. Previous data are also shown

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]

Current Work

- Using Stroh's Formulism for 2D anisotropic elastic body.

Stress-strain law $\sigma ij = Cijksuk,s$

Equation of Equilibrium $Cijksuk,sj=0$

Let $ui=aif(z)$

Assume Solution $z=x1+px2$

$$(C1k1+p(Ci1k2+Ci2k1)+p2Ci2k2)ak=0$$