

COE CST Fifth Annual Technical Meeting

**TASK 241. High Temperature,
Optical Sapphire Pressure
Sensors for Hypersonic Vehicles**

PI: William Oates

**PhD Students: Justin Collins,
Harman Singh Bal, Peter
Woerner**

***October 27-28, 2015
Arlington, VA***



Overview

- Team Members
 - William Oates, Justin Collins, Harman Singh Bal, Peter Woerner (FSU)
 - Collaborators: Mark Sheplak & David Mills (UF)
- Motivation
- High temperature experiments
- Theory and modeling of laser machined sapphire
- Conclusions and future work
- Schedule

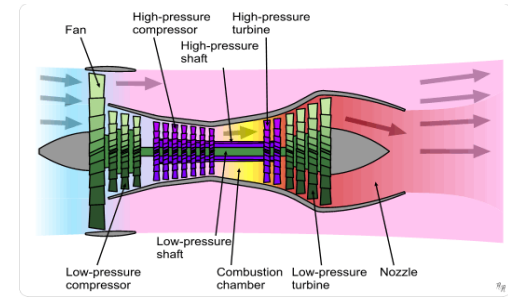
Team Members

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- PI: William Oates, PhD student: Justin Collins (FSU)
- Collaborators: Prof. Mark Sheplak & Post doc: Dr. David Mills (UF)
- Acknowledgements
 - FAA COE-CST
 - Space Florida Matching Funds

Motivation and Overview

- Lack of sensor technology in $>1000^{\circ}\text{C}$ environments

- Hypersonic vehicles
- Gas turbines

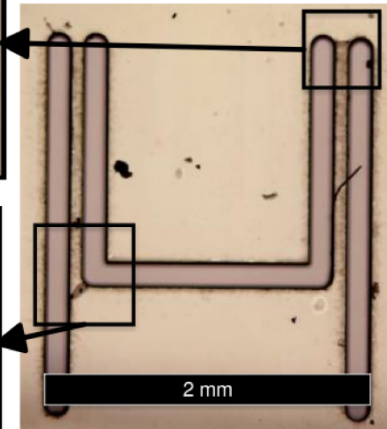
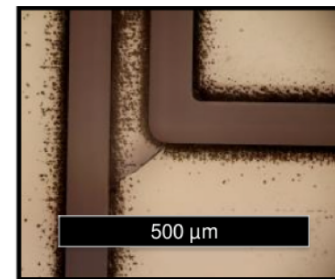
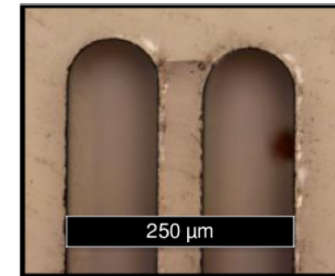
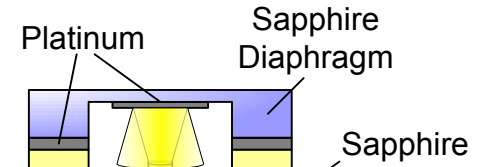


- Pressure sensor technologies

- Capacitive, piezoresistive, optical
- Optical: no EMI, high temperature capability, simple fabrication; packaging/ manufacturing challenges

- Sapphire optical sensing

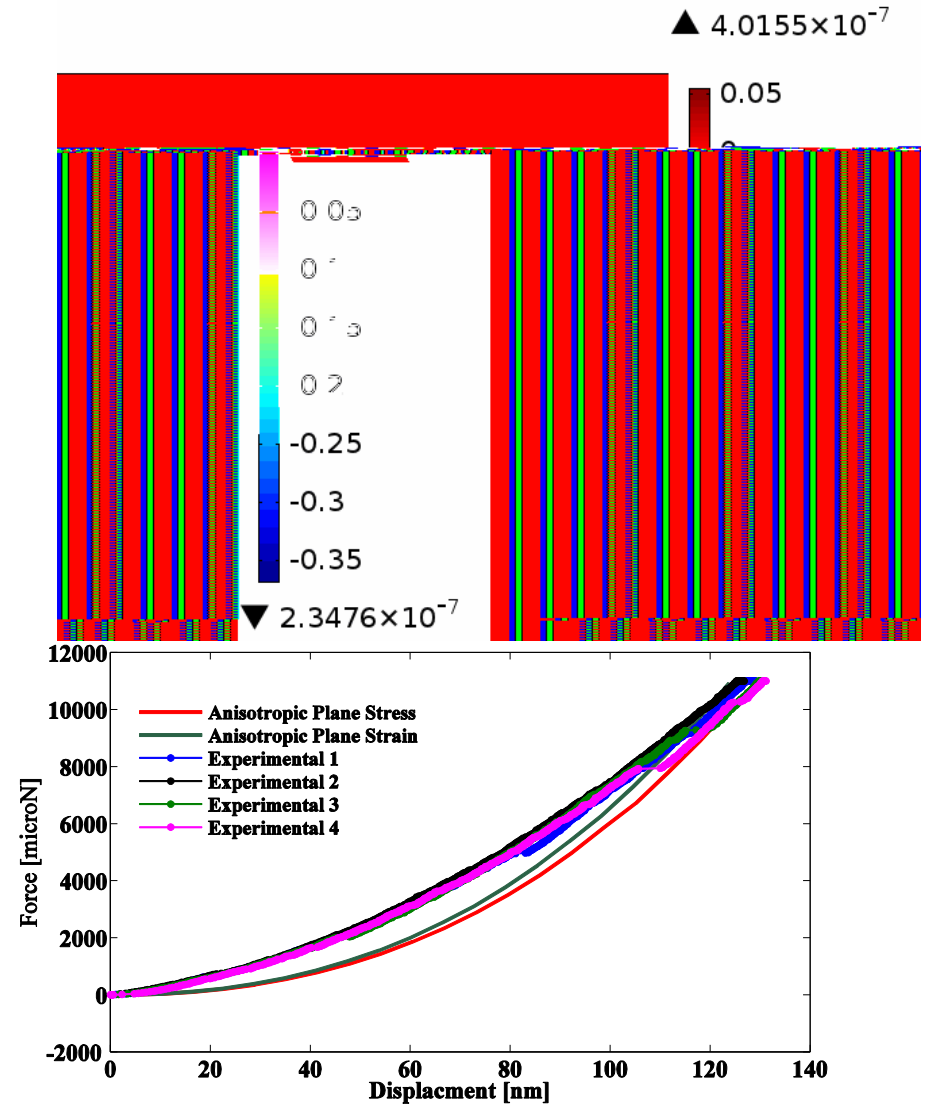
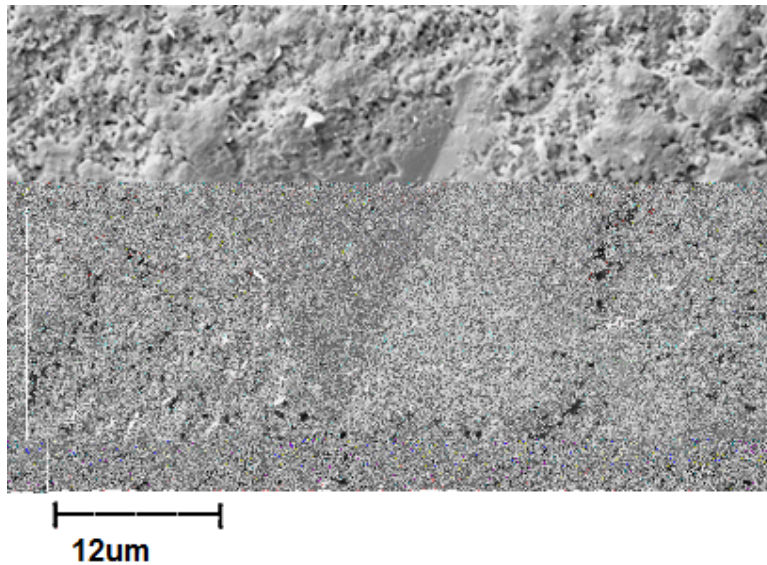
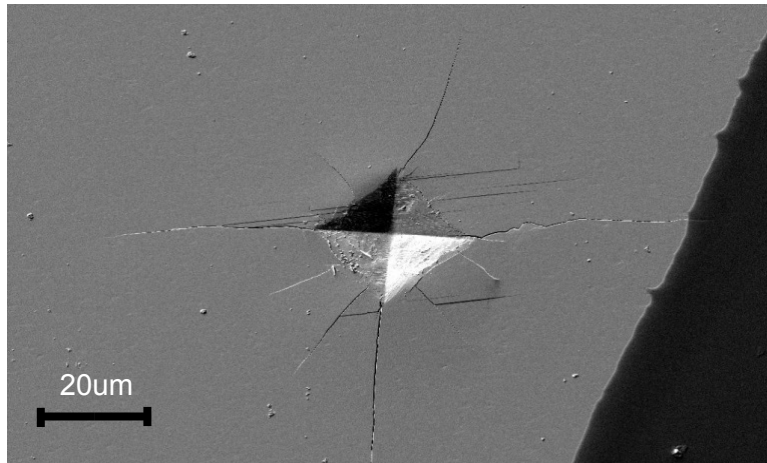
- Laser ablation and spark plasma sintering
- Impact on structural integrity?



Sheplak's group

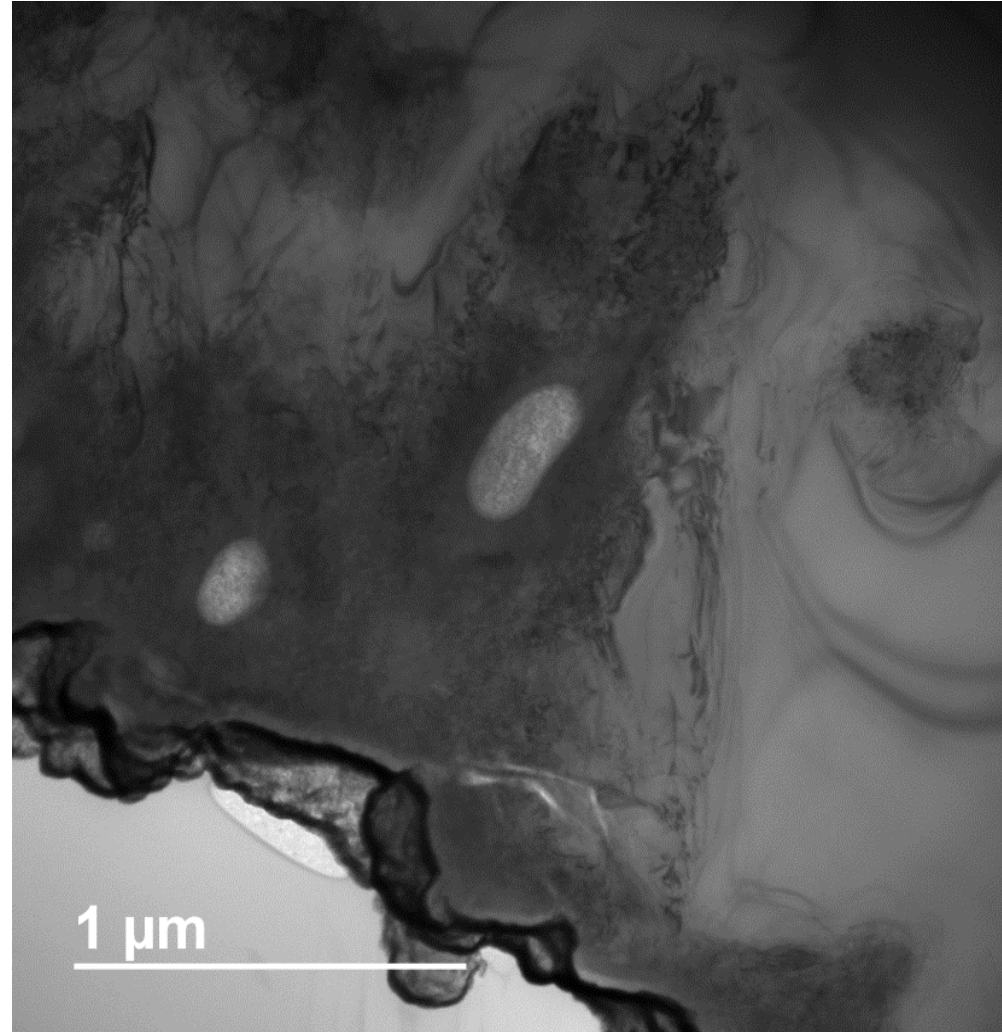
<http://www.nasa.gov/centers/ames/research/2007/faq-shuttleentry.html>
http://en.wikipedia.org/wiki/File:Turbofan_operation.png

Nanomechanics of Sapphire



Nanoscale Laser Damage

- Laser machining (UF—Sheplak's group)
 - 10 picosecond pulsed laser
 - Varying fluence and frequency rates
- Transmission electron microscopy (TEM)
 - National High Magnetic Field Laboratory
 - Presence of laser induced dislocations



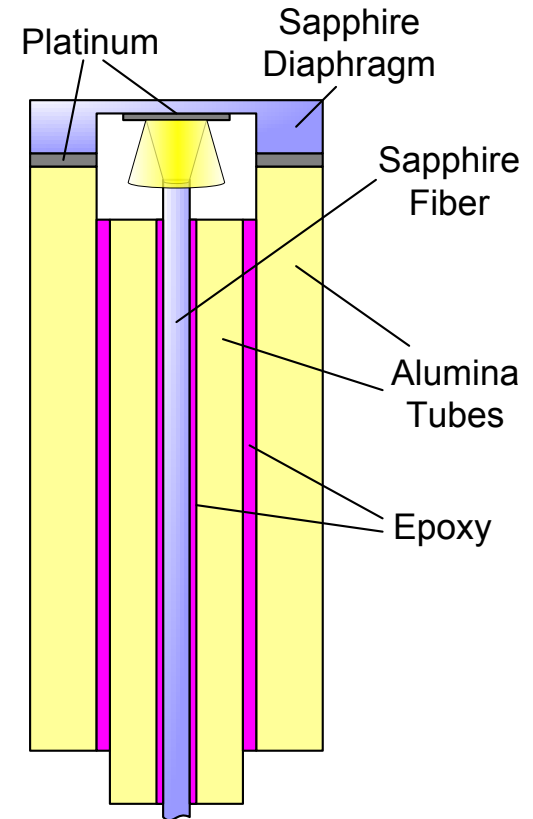
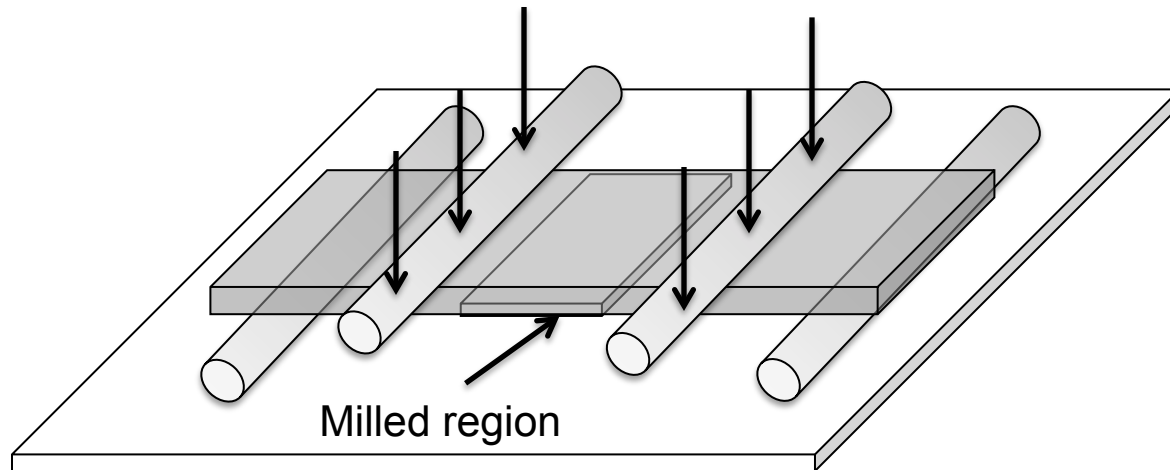
Strength Characterization

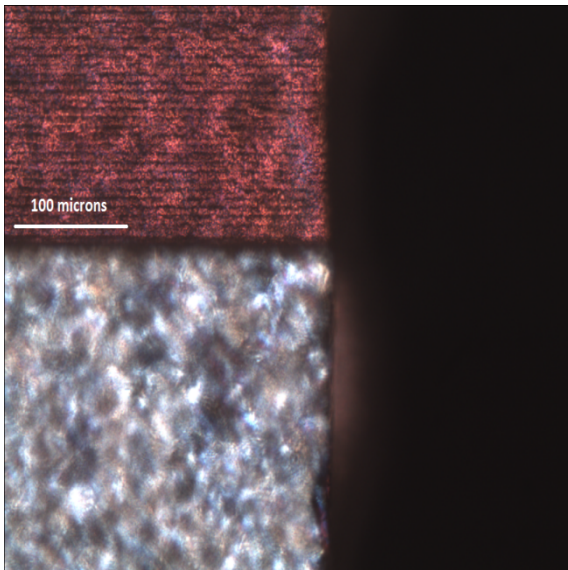
- Sensor reliability

- Target: measure pressure up to 1000 psi @ 750-1600°C

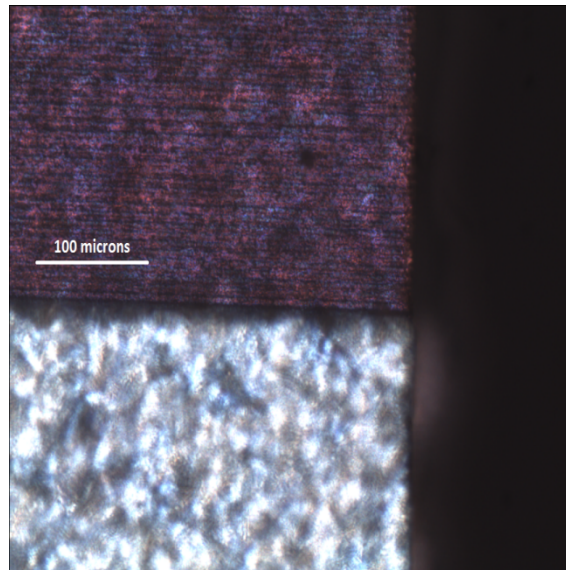
- Thermomechanical flexural testing

- 4-point bending
- Laser machined sapphire ($16 \times 6 \times 0.1 \text{ mm}^3$)
 - Milled center region—20 μm depth

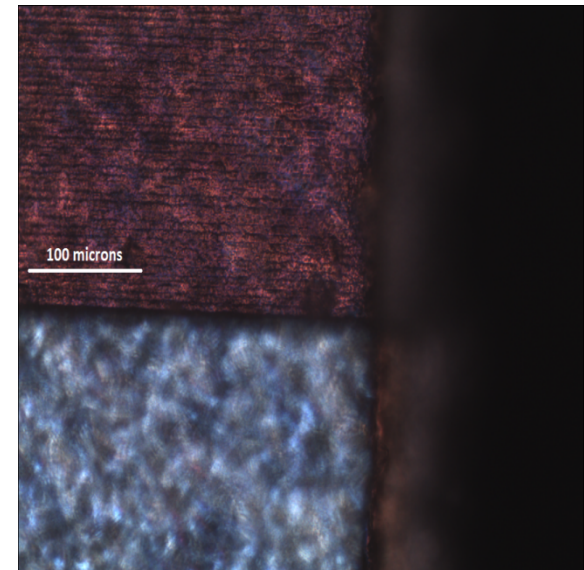




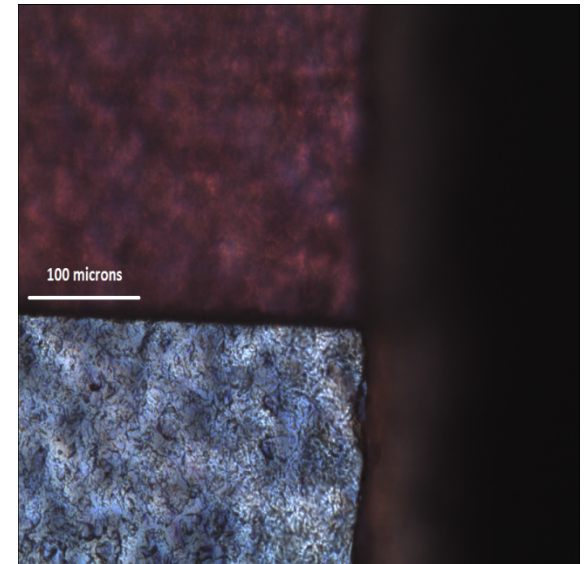
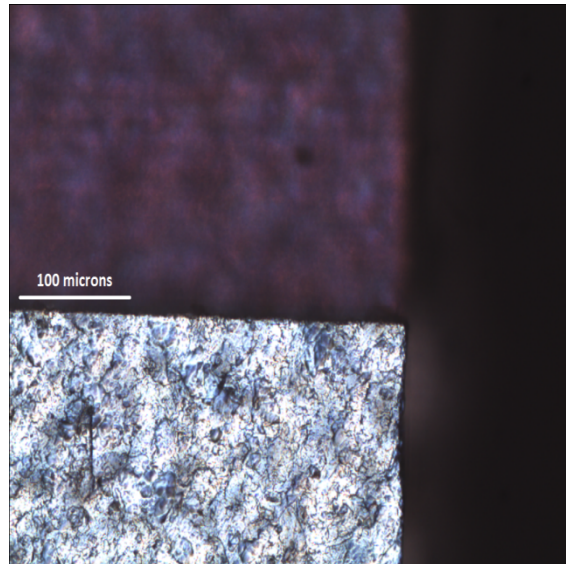
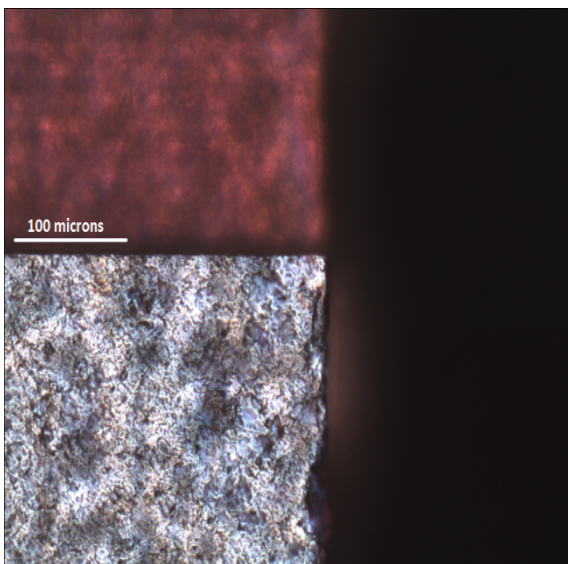
Room Temperature



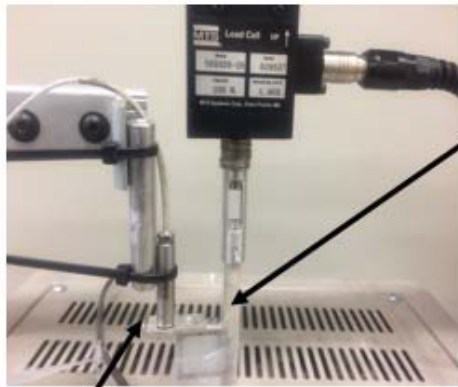
Tested at 950°C



Tested at 1300°C

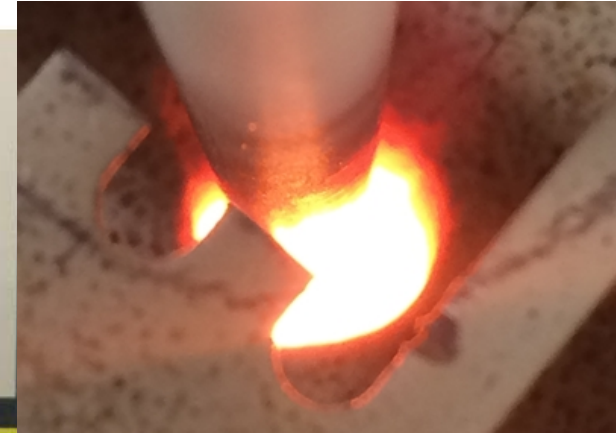


Experimental Set-up

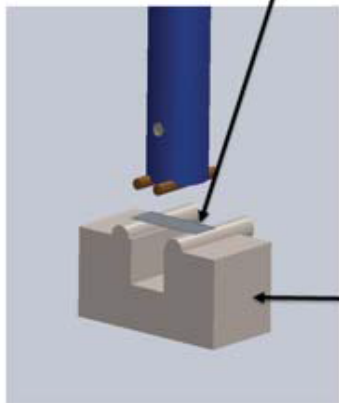


Capacitor Probe

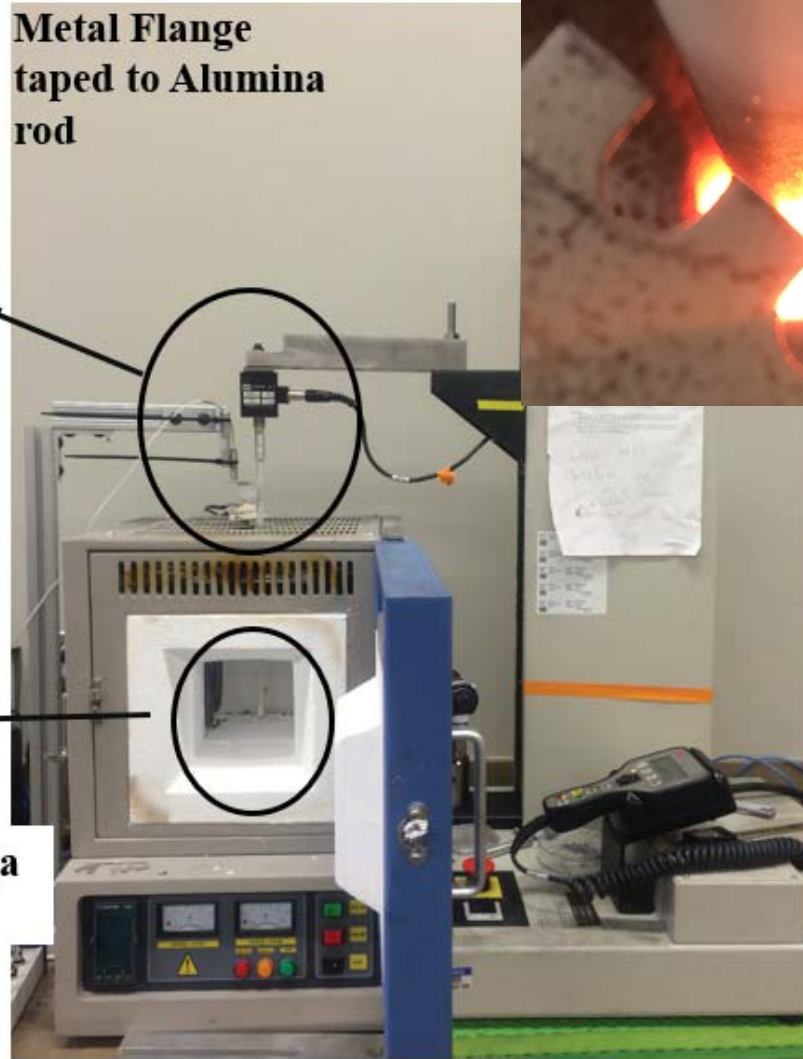
Metal Flange
taped to Alumina
rod



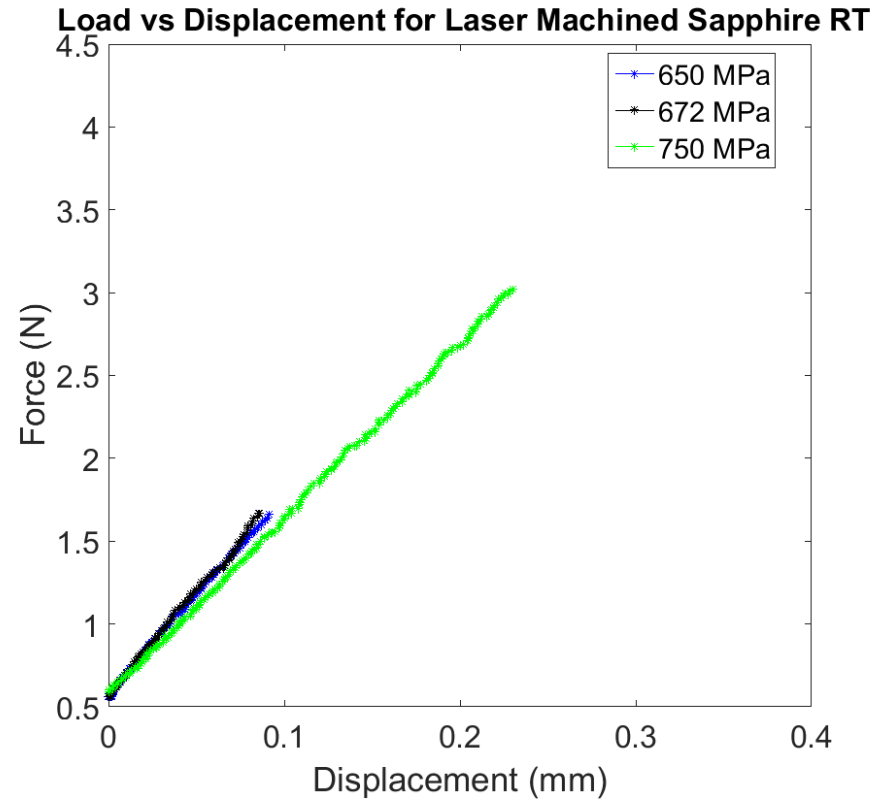
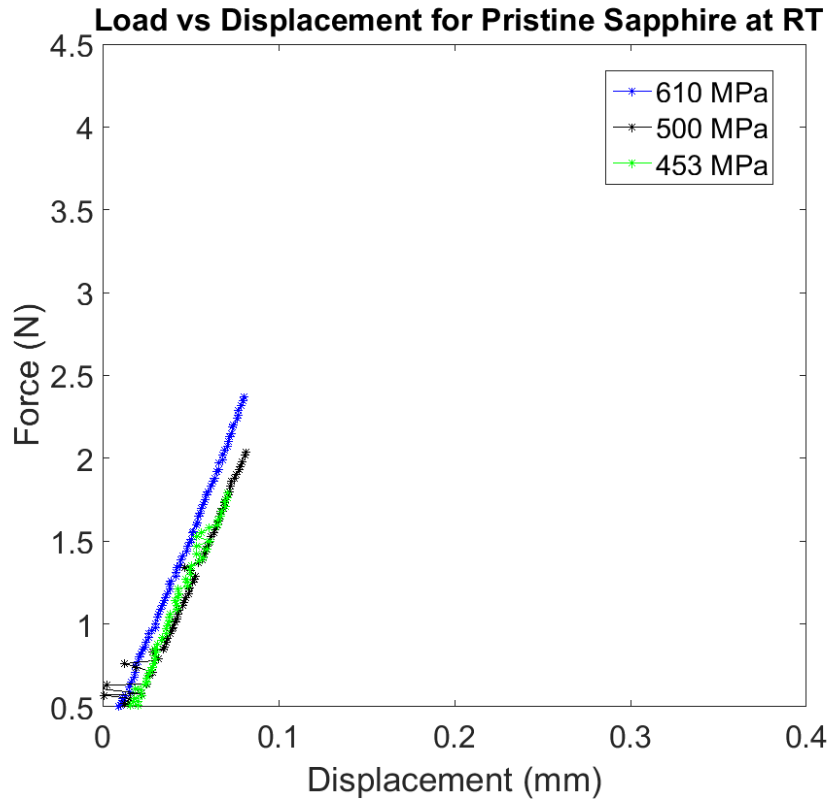
Sapphire Specimen



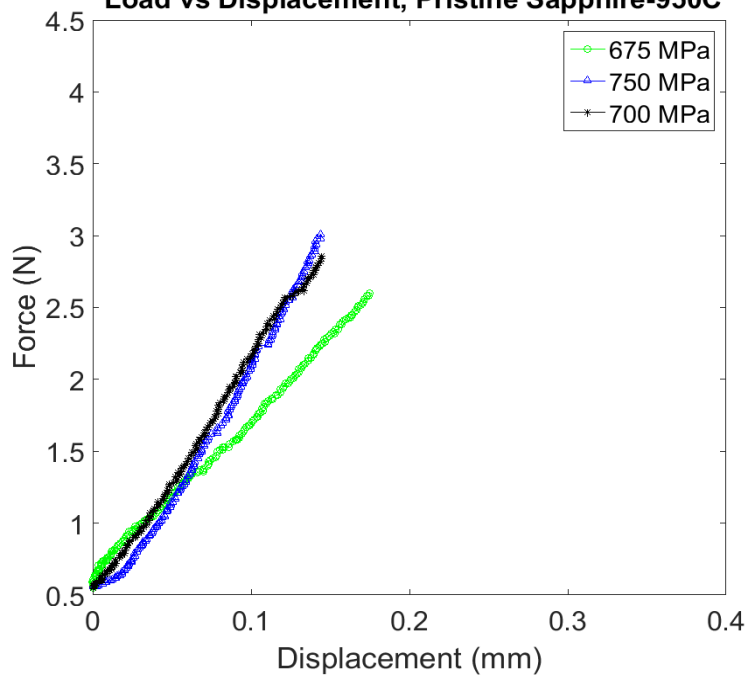
Alumina
Block



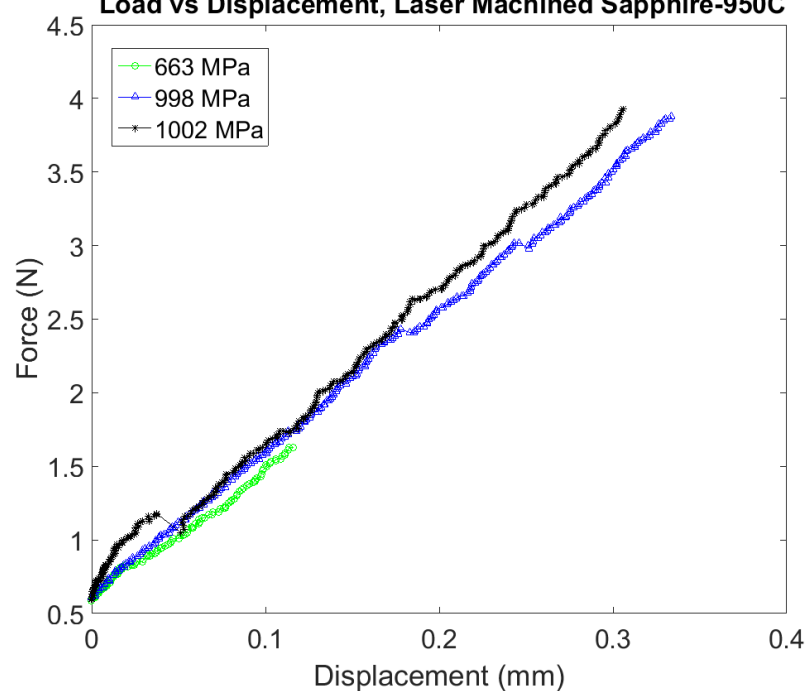
Experimental Results



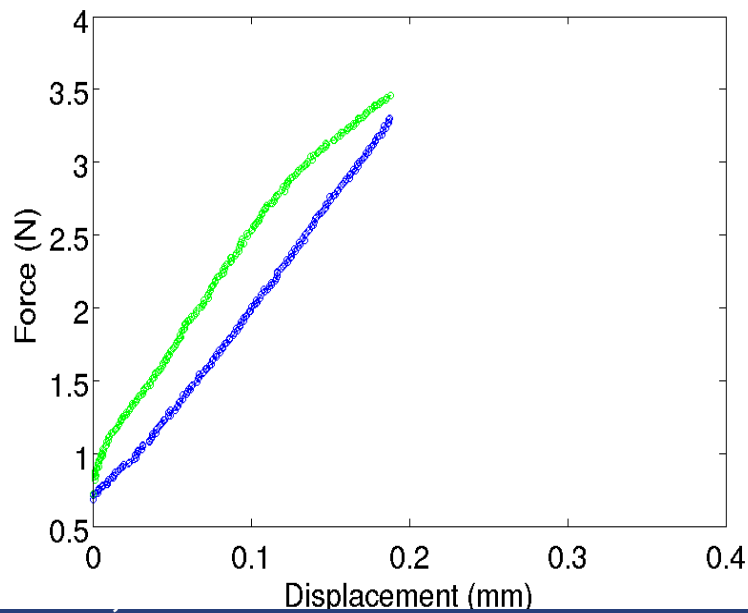
Load vs Displacement, Pristine Sapphire-950C



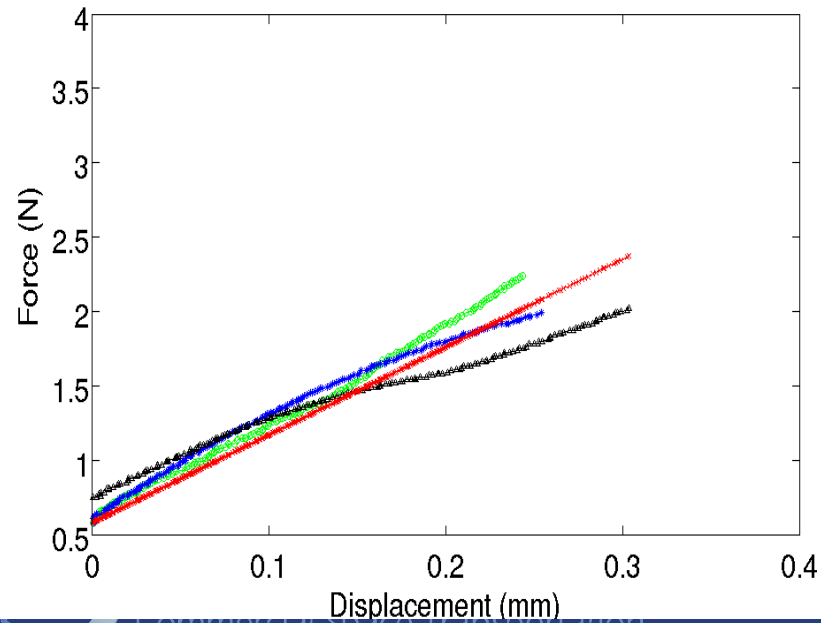
Load vs Displacement, Laser Machined Sapphire-950C



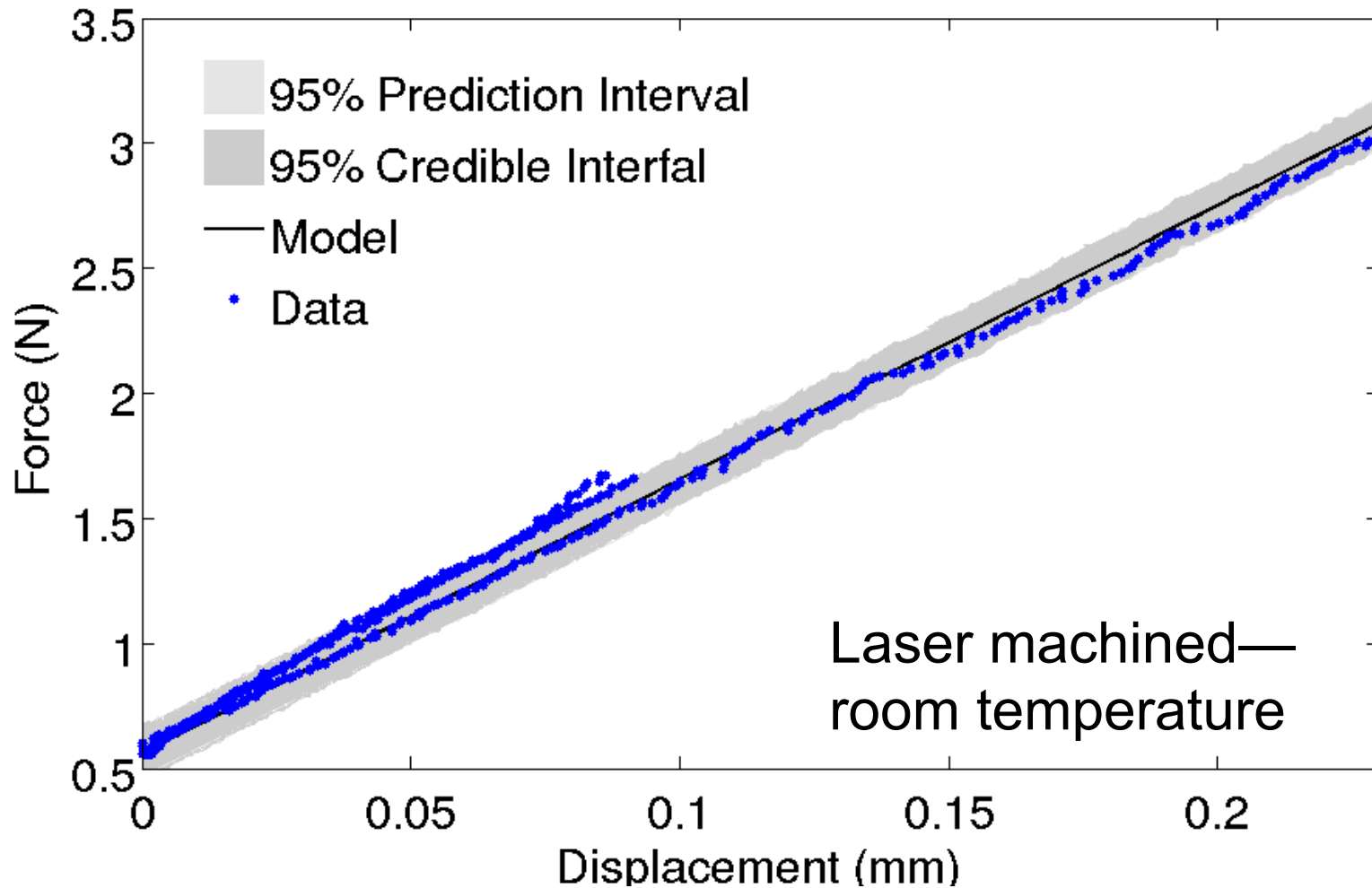
Load vs Displacement, Pristine Sapphire-1300C



Load vs Displacement, Laser Machined Sapphire-1300C

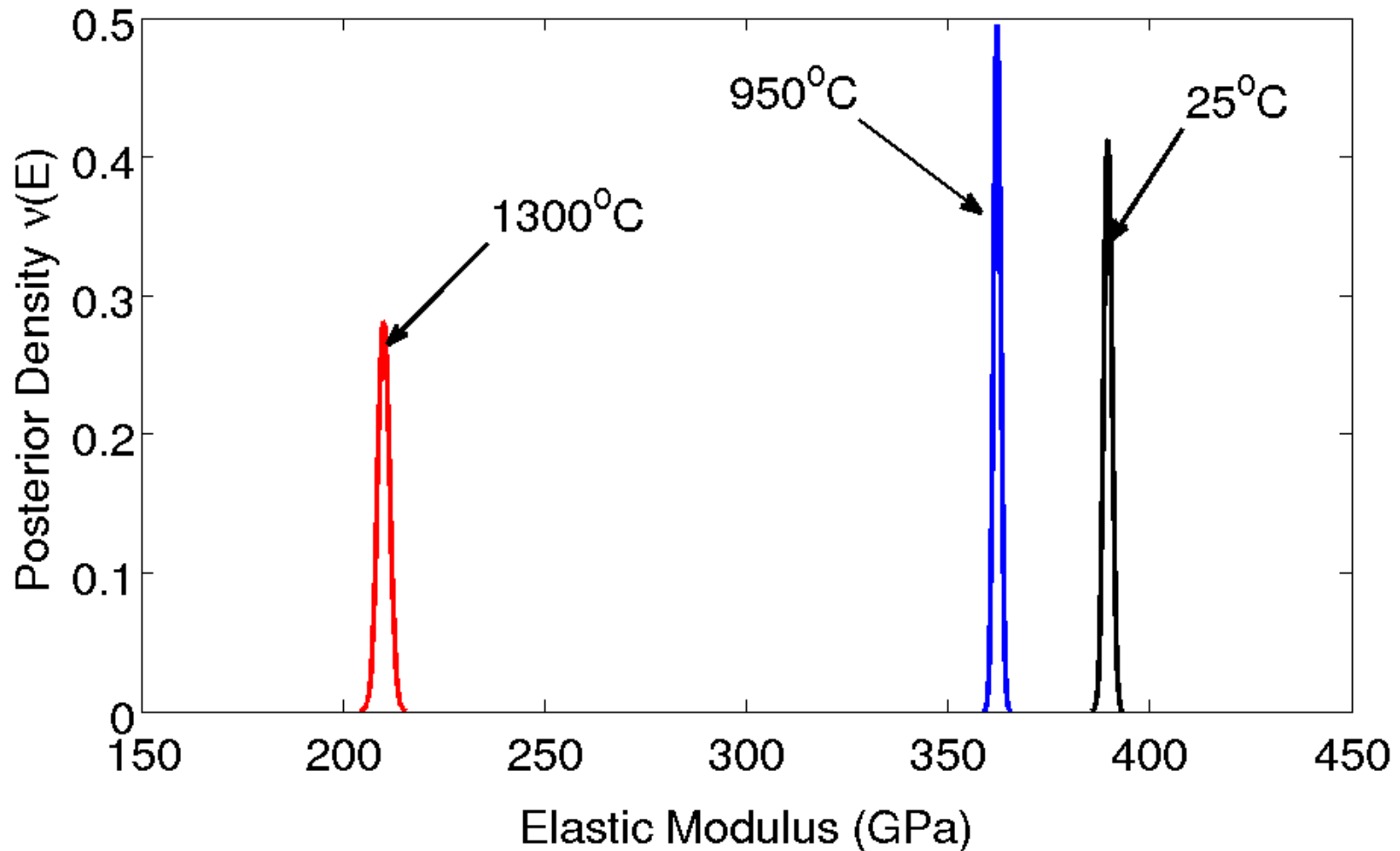


Bayesian Uncertainty Analysis



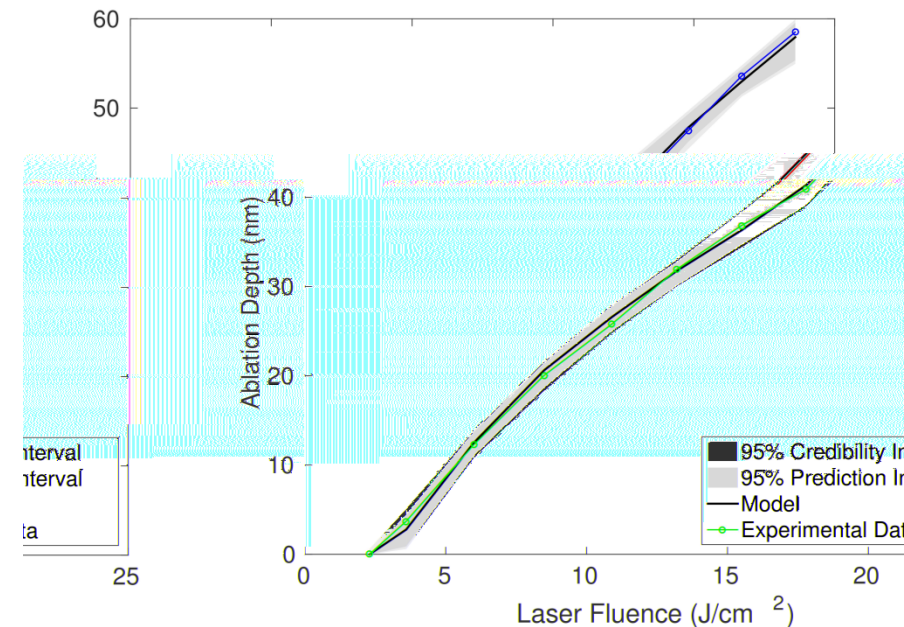
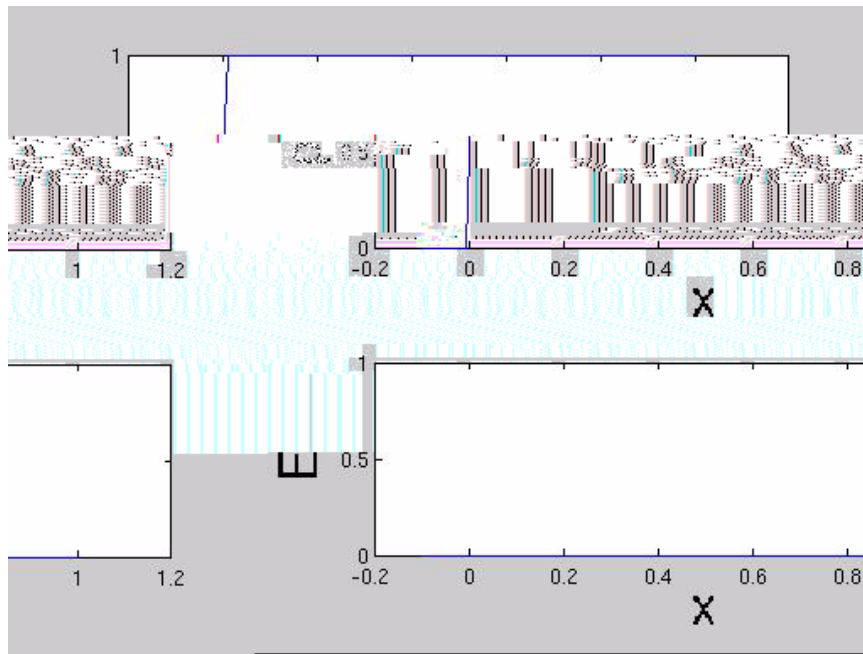
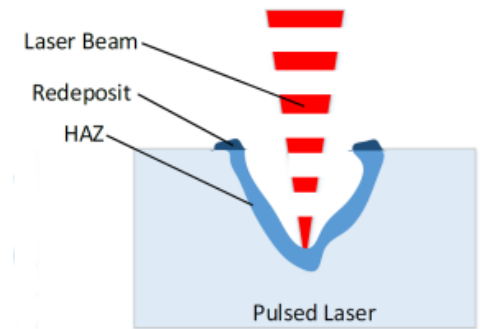
Uncertainty of Elastic Modulus

Laser machined specimens



Overview of Laser Ablation

- Multiphysics model developed
- Validated using Bayesian statistics in light of data from the University of Florida
- Model couples electromagnetics of light with electronic structure evolution



Conclusions and Future Work

- Mechanical properties of laser machined sapphire quantified
 - Theory and experimental fracture analysis (prior research)
 - Laser and nanomechanical dislocation measurement and modeling (prior research)
 - Experimental high temperature strength characterization (current efforts)
 - Light-matter interactions and thermomechanical reliability predictions (current efforts)
- Next Steps
 - Dissemination of results
 - Rigorously understand laser machined surface properties
 - System integration and hot jet testing

TASK 241. High Temperature, Optical Sapphire Pressure Sensors for Hypersonic Vehicles

PROJECT AT-A-GLANCE

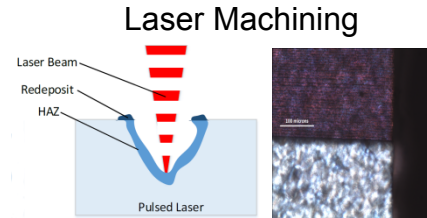
- UNIVERSITY: Florida State University
- PRINCIPAL INVESTIGATOR: William S. Oates
- STUDENT: Justin Collins

RELEVANCE TO COMMERCIAL SPACE INDUSTRY

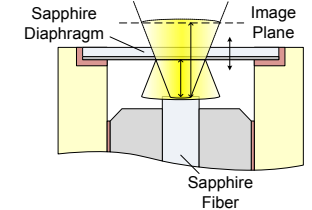
- Development of high temperature sapphire based pressure transducers for structural health monitoring.

STATEMENT OF WORK

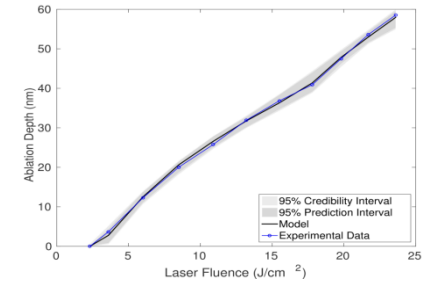
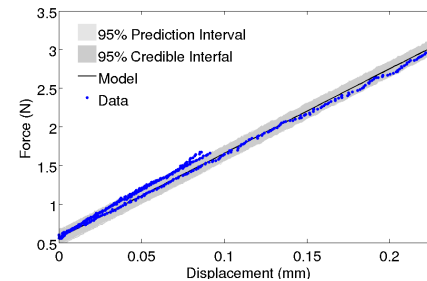
- Implement sapphire based pressure transducer that can operate in high temperature environments (~1000°C to 1200°C)
- Sapphire cannot be manufactured using conventional silicon based chemical etching
- Sapphire based transducer requires a strong understanding of mechanical property changes due to laser micromachining
 - Combined studies of single crystal dislocation mechanics and experimental testing focused on improved sensor reliability and manufacturing methods



Sensor Characterization



High Temp. Strength Measurement Laser Ablation Material Physics



STATUS

- High temperature thermo-mechanical set-up designed and validated
- Modulus and strength of sapphire and alumina characterized from room temperature to 1300°C
- Material physics of laser ablation analyzed over broad range of laser fluence conduction
- Uncertainty in modulus and laser ablation quantified using advanced Bayesian statistics algorithms

FUTURE WORK

- Rigorous assessment of damage evolution during loading and unloading of laser machined sapphire specimens
- Pressure transducer characterization with Univ. of Florida