High-Temperature Sapphire Pressure Sensors for Harsh Environments

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Outline

• Introduction
• Approach
• Proof-of-Concept Device
• Objectives
• Ultrashort Pulse Laser Micromachining
• Laser Ablation Modeling
• Conclusions
Project Overview

• Focus: Development of novel fabrication methods for the synthesis of high-temperature sapphire optical pressure sensors

• Award information
  – Project title: “High-temperature sapphire pressure sensors for harsh environments”
  – Award #: DE-FE0012370
  – Program manager: Sydni Credle
  – Duration: 3 years, beginning Jan 2014

• Project team
  – UF (Project lead)
  – FSU
Motivation

• Development and implementation of advanced energy systems will require novel harsh environment sensors and instrumentation for:
  – Advanced process control/closed loop feedback systems
  – Increased efficiency
  – Reduced emissions & cost

• Applications
  – Coal gasification
  – Advanced gas turbine systems
  – Solid oxide fuel cells
  – Deep oil and geothermal drilling
Motivation

• Sensor operational requirements
  – Temperature: >1000°C
  – Dynamic pressure: up to 1000 psi
  – Atmosphere: corrosive and/or erosive

• Conventional pressure sensor instrumentation is limited to ~500°C

• Temperature mitigation techniques:
  – Stand-off tubes - cause signal attenuation and degradation
  – Water cooling - imparts unknown aerothermal effects on the surrounding flow
Approach

- Transduction mechanisms
  - Capacitive
  - Optical
  - Piezoelectric
  - Piezoresistive

- Benefits of fiber optic transduction
  - DC measurement
  - Immunity to EMI
  - Passive
  - Non-conductive
  - Remote electronics
  - Multiplexing
Approach

- Sensor/optical fiber materials
  - Silicon
  - Silica
  - Silicon carbide
  - Sapphire
  - Diamond

- Benefits of sapphire
  - High melting point (2053°C)
  - Resistance to chemical corrosion
  - Excellent hardness
  - Large transmission window (200 nm – 5 μm)
  - Multimode optical fibers & substrates available
Approach

- Common fiber optic measurement techniques
  - Phase modulation – interferometer
    - High sensitivity
    - Environmental sensitivity
    - Coherent source
    - Single mode fibers

  - Intensity modulation – optical lever
    - Less sensitive to environmental changes
    - Incoherent source
    - Single or multimode fibers
    - Relaxed fabrication/packaging tolerances
    - Multiple send/receive configurations
Proof-of-Concept Device

- **Diaphragm**
  - 8 mm diameter, 50 μm thick
  - Platinum reflective surface
  - Thermocompression bonded to back cavity

- **Configuration**
  - Single send/receive fiber
  - Sapphire/silica fiber connection
  - Reference photodiode

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Proof-of-Concept Device

• Performance issues
  – High stiffness – low sensitivity
  – Large residual stress (~300 MPa) resulted in buckled diaphragm

• Improvements
  – Sensitivity – utilize ultrashort pulse laser micromachining to fabricate thinner diaphragm structures
  – Residual stress – improve thermocompression bond process through additional testing and characterization of bond interface
Technical Objectives

• Implement novel sapphire fabrication processes for fabrication of 3-dimensional structures
  – Subtractive machining: ultrashort pulse laser micromachining
  – Additive manufacturing: thermocompression bonding via spark plasma sintering (SPS) technology

• Characterize and mitigate thermo-mechanical damage imparted by manufacturing processes via statistical modeling of laser pulse-material interactions

• Fabricate, package, calibrate, and demonstrate in the field a high-temperature sapphire dynamic pressure capable of operation up to 1000°C and 1000 psi
Technical Objectives

• Phase I
  – Laser machining process development
  – SPS thermocompression bonding process development
  – Laser machining thermal damage modeling & analysis

• Phase II
  – Sensor design & fabrication
  – High-temperature packaging

• Phase III
  – Room- and high-temperature characterization
  – Hot jet testing
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Pulsed Laser Micromachining

- Ultrashort pulse laser micromachining
  - Classification based on relation between thermal diffusion depth, \( d \), and optical penetration depth, \( \delta \)
  
  \[
  d = 2\sqrt{at} \quad \delta = \frac{2}{\alpha}
  \]

  - \( d < \delta \), material removal is dominated by photochemical processes and is considered ultrashort
Pulsed Laser Micromachining

- **Oxford Lasers Micromachining Station**
  - Laser: Coherent Talisker Ultra (DPSS)
  - Pulse duration: 10-15 ps nominally
  - Wavelength: 355 nm
  - Beam diameter: 8.8 µm
  - Max output: 4 W at laser head (20 µJ pulse energy)
  - Beam attenuator from 0 -100%
  - Pulse frequency: up to 200 kHz

- **For sapphire,**
  \[ \delta \approx 72.4 \, \text{µm} \]
  \[ d \approx 24.4 \, \text{nm} \]
  10ps pulse is considered ultrashort
Pulsed Laser Micromachining

- Four key machining parameters of interest:

1. Pulse Spacing (µm)
2. Pulse Repetition Rate (Hz)
3. Pulse Fluence (J/cm²)
4. Cut Passes – Number of times the cut path is repeated
Gentle vs. Strong Ablation

- Transition from gentle to strong ablation is dependent on the number of laser pulses in a given area and the laser fluence.
- Machining parameters:
  - Feature size: 400 μm x 250 μm
  - Laser fluence: 1.2 – 21.5 J/cm²
  - Number of passes: 1-50
- Linear fits to gentle (blue) and strong (red) ablation regimes.
- Threshold laser fluence: ~1 J/cm²
Gentle vs. Strong Ablation

5 Passes

Average Cut Volume Per Pulse ($\mu m^3$) vs. Average Fluence (J/cm$^2$)

- 10 $\mu m$ Spacing
- 7.5 $\mu m$ Spacing
- 5 $\mu m$ Spacing
- 2.5 $\mu m$ Spacing
- 2 $\mu m$ Spacing
- 1.5 $\mu m$ Spacing
- 1.25 $\mu m$ Spacing
- 1 $\mu m$ Spacing
- 0.75 $\mu m$ Spacing
- 0.5 $\mu m$ Spacing
Sidewall Angle

- Machining parameters
  - Fluence: 5.1-25.5 J/cm²
  - Pulse area overlap: 45-99%
  - Number of passes: 50-2000

- Sidewall angle is constant above ~75% pulse area overlap

- Higher fluence and number of passes reduce sidewall angle
Laser Machining Simulation

- **User inputs**
  - Cut program (G code)
  - Process parameters
  - Laser station settings

- **Program outputs**
  - Results table
  - 2D and 3D simulated depth of cut plots
  - 2D velocity plot
  - Input feedrate vs machining time plot

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**Input Process Parameters:**
- Feed rate
- Pulse frequency
- Measured average power
- Attenuation
- Material
- Number of passes
- Focal distance
- Workpiece thickness
- Mesh size

**Input Laser Station Settings:**
- Acceleration profile type
- Jerk rate (if applicable)
- Acceleration rate
- Beam radius
- Laser power consumption
- Electricity rate
- Operator hourly cost
- Machine hourly cost

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- **Start**
  - Generate Cut Program
  - Load Cut Program
  - Measure Average Laser Power

**Laser Station Settings Correct?**
- No
- Yes

**Run Simulation**
Laser Machining Simulation

Input file

Machining parameters

Process modification

Simulation outputs

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<td>Mesh Size (um)</td>
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<th>Modification Method</th>
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<td>Speed</td>
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<td>Tolerance (%)</td>
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<td>Time To Machine (s)</td>
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<td>Laser On Time (s)</td>
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<td>Energy Consumed (W/end)</td>
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<td>Cost of Cut ($)</td>
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<td>Pulse Area Overlap (%)</td>
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<td>Max Realizable Feed</td>
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<td>Avg Depth of Cut (um)</td>
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<td>Min Depth of Cut (um)</td>
<td>5.22e+000</td>
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Part Path Modification

- Test geometry – overlapping rectangles
  - Creates deeper machined region
  - Goal: add passes in specific areas to create a single region of consistent depth
Part Path Modification Results

- Additional passes in region of single overlap improves the depth uniformity
- Good agreement with simulation including capture of periodic structures in the machined recess

![Simulated and Measured Plots](chart.png)
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Laser Ablation Modeling

- Material physics modeling of laser ablation
  1. Laser input: time dependent Maxwell’s equations
  2. Material evolution: electronic structure balance equation

\[
L = L_F + L_I + L_M
\]

Lagrangian energy formulation

Energy losses to ablation

\[
\Pi_D = -\sum_{\alpha} \frac{1}{2} \beta^\alpha \dot{y}^\alpha_i \dot{y}^\alpha_i
\]

\[y^\alpha_i\] --vector order parameters \((\alpha=1,\ldots,n)\) defining homogenized electronic structure

Laser Ablation Modeling

- One dimensional model approximation
  - Scalar order parameter governing electron density
    \[ \rho(x, t) = \sum_{\alpha} \sqrt{y_i^\alpha (x, t) y_i^\alpha (x, t)} \]
  - Balance law governing \( \rho(x, t) \) obtained from minimization of energy functions
  - Leads to a phase field or sharp interface model driven by electric field (laser) pulses

- Key governing equations
  \[
  \sigma(\rho) \mu_0 \frac{\partial E}{\partial t} = \nabla^2 E
  \\
  \beta(E) \frac{\partial \rho}{\partial t} = a_0 \nabla^2 \rho - \frac{\partial \psi}{\partial \rho} - \gamma(E)
  \]
  Electromagnetic equation
  Phase field based order parameter model
  Multi-well energy
Model Validation

- Ablation of material predicted as a function of picosecond pulsed laser excitation
- Laser intensity dependence model parameters identified via Bayesian statistics

Model Analysis – Parameter Sensitivity

Electromagnetic equation

\[ \sigma(\rho) \mu_0 \frac{\partial E}{\partial t} = \nabla^2 E \]

Phase field based order parameter model

\[ \beta(E) \frac{\partial \rho}{\partial t} = a_0 \nabla^2 \rho - \frac{\partial \psi}{\partial \rho} - \gamma(E) \]

• Critical parameters considered

\[ \sigma(\rho) = \sigma(\rho; \sigma_1, \sigma_2) \]

Electric conductivity:
- \( \sigma_1 \) (room temperature)
- \( \sigma_2 \) (excited state)

\[ \beta(E) \]

Inverse electronic mobility parameter

Region of finite machined depth giving potentially valid numerical correlation with laser ablation experiments
Bayesian statistics applied to quantify reduced order model uncertainty

- Kinetic parameter ($\beta$) found to increase approximately linearly with picosecond pulsed laser intensity
- Illustrated in terms of the probability of $\beta$ given a machined depth $d$

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Summary

• Laser machining process for the sapphire-UF laser system characterized

• Simulator developed and validated based on empirical data

• Laser ablation model developed
  – Coupling among laser excitation and electronic structure evolution
  – Uncertainty and sensitivity analysis conducted on a reduced order model approximation
  – Parameter dependence on laser intensity identified
Future Work

- Quantification of laser damage via four point bend testing at elevated temperatures
- Extension of the laser ablation model to include effects of sub-surface laser damage on strength and fracture
- Fabricate high-temperature plane wave tube for dynamic pressure calibration
- Sensor fabrication
- High-temperature package development
- Packaged sensor calibration & hot jet testing
Questions?