Additive Manufacturing of Smart Parts with Embedded Sensors for In-Situ Monitoring in Advanced Energy Systems

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Outline

• Introduction

• Technical Progresses and Accomplishments

• Summary

• Future Work
Demands

• Sensors and instrumentation are needed in advanced energy systems for
  – Advanced process control/optimization
  – Health status monitoring of key components
  – System maintenance and lifecycle management

• Sensors need to survive and operate in the high-T, high-P and corrosive/erosive harsh environments for a long time
Traditional Approach

- Traditionally, sensors are attached to or installed onto the component after the structure is fabricated.
- **Costly and complicated sensor packaging** are required before installation.
- **Poor survivability and reliability** of the sensors.
- **Discrepancy** between the sensor reading and the actual status.
- **Potential performance compromise** of the host materials/structures.
Opportunities

• Smart parts – widely used and proven successful in civil engineering for structural health monitoring (SHM)

• Provide the real-time information of the component and system

• Reduce the complexity in sensor packaging and installation

• Increase the robustness and reliability of the system
Objectives

• **Main Objective:** Demonstrate the new concept of sensor-integrated “smart part” achieved by additive manufacturing and embedding microwave and photonic sensors into critical components used in advanced energy systems

• **Specific objectives**
  – Robust, distributed and embeddable microwave photonic sensors
  – Additive manufacturing techniques for rapid fabrication of “smart parts” and sensors embedment
  – Multifunctional transition layer between the embedded sensor and host material for sensor protection and performance enhancement
  – Models to correlate the sensor readings with the parameters of interest
  – Sensor instrumentation for in situ and distributed measurement
  – Feasibility tests and performance evaluation
Project Elements/Overview

• Performers: Missouri S&T, Clemson, University of Cincinnati

• Interdisciplinary team
  – Hai-Lung Tsai (PI), Professor of Mechanical Engineering, Missouri S&T, Modeling and AM of metal parts
  – Ming Leu, Professor of Mechanical Engineering, Missouri S&T, AM of ceramic parts
  – Hai Xiao, Professor of Electrical Engineering, Clemson University, Sensors and Instrumentation, test and evaluation
  – Junhang Dong, Professor of Chemical Engineering, University of Cincinnati, Sensor protections

• Success criteria:
  – Demonstrate concept and capability in simulated laboratory environments
Development of robust, distributed and embeddable sensors and instrumentation

Approach: Fully distributed microwave photonic fused silica and sapphire fiber sensors

Hai Xiao
Clemson University
• Three types of fully distributed sensors for embedded applications

1. **Microwave sensors** – uniquely harvest the robustness of high temperature coaxial cables

2. **Incoherent Optical carrier based microwave interferometry (OCMI) sensors** – can be used to interrogate previously difficult highly multimode fibers (e.g., quart rod and sapphire fiber)

3. **Coherent OMCI sensors** – can reach extremely high resolution
Microwave-Photonics Sensors

- Optical carrier based microwave interferometry (OCMI)
  - Read optical interferometers using microwave
  - Optics as the carrier to perform measurement
  - Microwave as the signal to locate the sensors
  - Can be implemented in either incoherent (make the optical term become zero) or coherence (keep the optical term)

\[
|E|^2 = |E_1 + E_2|^2 = 2A^2 + 2A^2M\cos\left[\Omega \frac{L_{O1} - L_{O2}}{2c}\right] \cos\left[\Omega \left(t + \frac{2W + L_{O1} + L_{O2}}{2c}\right)\right] + 2A^2 \sqrt{1 + M\cos\left[\Omega \left(t + \frac{W + L_{O1}}{c}\right)\right]} \left(1 + M\cos\left[\Omega \left(t + \frac{W + L_{O2}}{c}\right)\right]\right) \int_{a_{\min}}^{a_{\max}} \cos\left(\omega \frac{L_{O1} - L_{O2}}{c}\right) d\omega
\]

J. Huang, et al., Optics Express, 2014.
Quartz rod (800μm dia. Uncladded)

Input

3dB coupler

Path 1

18.7 cm

R1

Large core fiber

Path 2

R2

Output

Fused silica rod 800μm dia.

Interference fringes

High temperature response

L. Hua., Applied Optics, 2015

Quartz rod can be used to measure strains at high temperatures
Sapphire fiber Michelson OCMI

Excellent fringe visibility > 30dB

Slope ≈ -0.064 MHz/°C

Distributed sensing

- Spatially continuous (no dark zone), fully distributed sensing.
- High spatial resolution (<1cm)
- High sensitivity (~με)
- Flexible gauge length (1cm – 100m)
- Long reaching distance (~km)
- Can be implemented using various fibers including sapphire and quartz rods

Coherent OCMI System

- Use a coherent light source
- Arrange the interferometers within the coherent length of the source
• Use both real and imaginary part of the signal (quadrature)
• Resolution reaches 10nε using an interferometer with a length of 10cm.
Incoherent and Coherent OCMI

- **Incoherent OCMI** – use incoherent (i.e., broadband) optical source
  - Large dynamic range
  - Resolution is limited, about $10^{-5}$ - $10^{-6}$

- **Coherent OCMI** – use coherent (i.e., narrow bandwidth) optical source
  - Limited dynamic range
  - Resolution can be extremely high, about $10^{-8}$ - $10^{-9}$

- The two can be combined into a single system with two optical sources to achieve a high resolution in a large dynamic range.
  - Sensing Range (Spatial resolution): 100 km (1m), 2 km (2cm)
Develop a multifunctional transition layer between the embedded sensor and the host material for sensor protection

Approach: Design and select ceramic and metal materials based on structural and chemical potteries

Junhang Dong, University of Cincinnati
Summary of Accomplishments

- Silica fiber optic sensors packaged in the ceramic host capillary tubes are fully functional at high temperature (tested up to 1000°C) with good stability.

- Silicalite layers directly grown on the sapphire fibers may be used both as fiber cladding and sensor protection (up to ~900°C).

- MgAl2O4 layers can be used as sapphire cladding for operation up to 1250°C.
**Results:** Stainless steel has been identified as the most stable metal among the candidates (Ti/Pd, Al, Cu, etc.) and demonstrated to be stable when coated with ceramics at 1000°C for >100h.
Sensor Protection by ceramic adhesive in sintered SS capillary tube

**Stainless steel hosted fiber unit:**

Fused silica optical fibers as a packaged sensor unit for direct installation in “smart bricks”. Porous ceramic adhesion layers (e.g. alumina and zirconia based materials) used to fix the fiber with the host capillary tube.

EDS line scan across the SS/alumina interface/fiber interfaces indicated no significant solid state reaction or diffusion at 1000°C over extended period.
Results: pre-packaging of fibers in ceramic capillary tubes (e.g. porous zirconia and α-alumina) has been demonstrated using ceramic adhesion and tested at 1000°C stable over extended periods.
Packaging of Fiber Optic Sensor in Host Ceramic (or SS) Capillary Tubes
**Results:** The fibers pre-packaged in the host tubes have been verified to be optically functional for signal generation and transmission at high temperatures.
A fused silica LPFG sensor was packaged in a ceramic capillary and connected to a tunable laser for monitoring strain and structure damage at high temperature. The packaged sensor was able to detect the external force induced strain and fracture of the packaged unit that indicate promise for installation in refractory liners for structural health monitoring.
The structures of silicalite-coated-sapphire with an overcoats of ZAlMg (ZrO$_2$-Al$_2$O$_3$-MgO mixture) and ADZ (Zr$_{1-0.75x}$Al$_x$SiO$_4$) are both stable after firing at 1000°C for 200 h according to SEM and EDS examinations – No structural damage or inter-layer element diffusion was found.
Additive Manufacturing of Ceramics

Approach: Multi-extruder freeze-form extrusion based additive manufacturing

Ming Leu
Missouri University of Science and Technology
A new ceramic on-demand extrusion (CODE) system has been developed to fabricate Functionally Graded parts (Configuration 1) and Multi-Material parts (Configuration 2).

Building envelope: 250 x 250 x 150 mm³
Positioning resolution: 1 μm
Positioning accuracy: 18 μm over 300 mm travel
Fabricating Parts with Support Material

**Printing**

(a) CAD model
(b) Support structure being printed
(c) Overhanging structure being printed
(d) Part having been printed completely (surrounded by oil)

**Post processing**

(a) Parts after 1st step sintering (1100 °C)
(b) Support structures being dissolved
(c) Cleaned parts (after support removal)
(d) Final sintered parts
Sample Parts Fabricated with the CODE System

Zirconia gears:
400 μm layer
98.5% Density

Alumina disks:
400 μm layer
vs.
200 μm layer

Alumina turbine blower housing
400 μm layer, 97.5% density

Good circularity

D1: Mean = 29.3 mm, Std.Dev. = 0.07 mm
D2: Mean = 63.7 mm, Std.Dev. = 0.05 mm
Additive Manufacturing of Metals

Approach: Foil-Based Dual-Laser Additive Manufacturing Technology

Hai-Lung Tsai
Missouri University of Science and Technology
Laser-Foil-Printing AM Technology

- System Design, Hardware and Software Implementations, and Integration.
As-Fabricated Metallic Glass Samples
Sensor-Embedded Parts Fabrication

3D models for sensor embedding.

Curved sensors to be embedded in the printing process.

Sensors are embedded in the parts.
Thermal Stress-Strain Modeling of Embedded Sensors

Pressure Caused Stress-Strain Distribution

Temperature Caused Stress-Strain Distribution
Additive Manufacturing and Test of Sensor Embedded Parts

Approach: Fully distributed microwave photonic fused silica and sapphire fiber sensors

Hai Xiao
Clemson University
An advanced manufacturing system integrates both additive and subtractive manufacturing

- Multiple dispensers based 3D printing
- Multiple extruders based paste 3D patterning
- CO$_2$ laser based 3D heating and sintering
- ps and fs lasers based 3D fine cutting
- Computer controlled motion stages and CAD fusion capability
- Ceramic, metal and plastic and composites
Micro dispensers

- Direct printing by dispensed sol-gel and laser in situ sintering
Extrusion based 3D printing

Printing ceramic block

(2cm*2cm*6mm)

(1.8cm*1.8cm*5mm)

<table>
<thead>
<tr>
<th>Shrinkage</th>
<th>Parts only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrinkage in length</td>
<td>&gt;10%</td>
</tr>
<tr>
<td>Shrinkage in width</td>
<td>&gt;10%</td>
</tr>
<tr>
<td>Shrinkage in height</td>
<td>&gt;20%</td>
</tr>
<tr>
<td>Volumetric shrinkage</td>
<td>&gt;32.5%</td>
</tr>
<tr>
<td>Relative density (Archimedes principle)</td>
<td>88%</td>
</tr>
</tbody>
</table>
Direct laser sintering of ceramics

- **Surface**

  ![Surface Images]

  A. 1.0 mm/s  
  B. 1.5 mm/s  
  C. 2.0 mm/s

- **Cross sections**

  ![Cross Section Images]

  A. 1.5 mm/s  
  B. 2.0 mm/s  
  C. 2.5 mm/s  
  D. 3.0 mm/s  
  E. 3.5 mm/s
3D printing sensors inside the part

800 µm hexagons
Embedded cable for strain test

- Embedded Coaxial Cable

Ceramic tube (~7mm)

~3mm air gap

Titanium tube

Base extrusion

Graph with series data:

- Series 1
- Series 2
- Series 3
- Series 4
- Series 5
- Series 6
- Series 7
- Series 8
- Series 9
Embedded Coaxial Cable Sensor

High temperature test of the smart part embedded with a metal-ceramic coaxial Cable (MCCC) Sensor
Embedded Coaxial Cable

- **Embedded Metal-Ceramic Coaxial Cable (MCCC) Fabry-Pérot Interferometric Sensor**

- Such cable can be operated at 1600°C

Sensitivity = -2.274e-5 GHz/°C
1. Fabricate the channel on the ceramic substrate with designed shape for fiber embedding

- Easy to fabricate by ps-laser with high resolution
- Confining the fiber into the small channel can provide more protection to the optical fiber
- Control the thickness of the ceramic filler by controlling the depth of the channel
2. Place the optical fiber sensor into the channel and filled the channel with the ceramic paste

- Slightly applied tensile stress on two ends of the optical fiber to make sure it was straight and touch the bottom of the channel

Fiber embedded setup

An IFPI was placed inside the channel

Channel was filled with the ceramic paste
3. Use a CO₂ laser to process the filling materials and seal the fiber inside

- **Laser operating parameters:**
  - Laser output power: 9 W
  - Scanning speed: 0.2 mm/s
  - Spot size: 1.1 mm

- **high speed scanning at low power to pre-heat the materials before high power processing**

- **The optical fiber was monitoring by the OSA during the whole embedding process**

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<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Max Output Power</td>
<td>20W</td>
</tr>
<tr>
<td>Operation</td>
<td>Continuous wave (CW)</td>
</tr>
<tr>
<td>Mode Quality</td>
<td>( \text{TEM}_{00}, M^2 &lt; 1.1 \pm 0.1 )</td>
</tr>
<tr>
<td>Beam Diameter before focusing</td>
<td>2.5mm ± 0.5mm</td>
</tr>
<tr>
<td>Beam Diameter after scanner</td>
<td>~1.0 mm</td>
</tr>
<tr>
<td>Wavelength</td>
<td>10.6 μm</td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear (Horizontal)</td>
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</tbody>
</table>
3. Use CO$_2$ laser to process the filling materials to seal the fiber inside

(2) Embed an IFPI optical fiber sensor into the ceramic substrate and seal it by the CO$_2$ laser

- For the IFPI sensor, after laser processing, the spectrum slightly shifted to longer wavelength for about 1 nm
- Known from the cross-sectional image, the channel was filled well but it seems that there were still pores at the part that was close to the optical fiber
4. Test the high temperature stability of the embedded optical fiber sensor

(1) Improved high temperature stability of the embedded optical fiber by laser sintering

- Traditional furnace based sintering, the embedded optical fiber had a huge loss (~45 dB) when the temperature reached 400°C
- Direct laser sintering, though small ripples occurred after 400°C, the transmission spectrum generally maintain straight and only 5 dB loss when the temperature reached 1000°C
4. Test the high temperature stability of the embedded optical fiber sensor

(2) High temperature stability of the embedded intrinsic Fabry-Perot interferometer (IFPI)

- Survived 1000°C and still produced good signals
- Slightly compression of the optical fiber that reduced the cavity length of the IFPI
- Need further improvement and optimization
Manufacturing of smart parts

- Manufacturing of sensor embedded smart parts (a smart ceramic washer)
Embedment and experimental setup

Ceramic block ($\phi = 8$ cm)

Ceramic block ($\phi = 5$ cm)

Ceramic tube to guide fiber

Large size

Small size

Experimental setup
Embedded Photonic Sensor

• Embedded Sapphire Fiber Michelson interferometer

High temperature results
(100-1600°C)

Frequency domain

Frequency response VS temperature

y = -0.039 x + 64.361
Summary of Progresses

- Distributed microwave and photonic sensors and instrumentation have been developed and proven
- Protective coating materials have been identified and successfully coated on silica and sapphire optical fibers
- Additive Manufacturing techniques have been developed for fabrication of metal and ceramic parts
- Smart parts with embedded sensors have been fabricated using advanced manufacturing and preliminarily tested
Future Work

- Manufacture more smart parts
- Comprehensive tests of the smart parts
Acknowledgement

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  - Otis Mills