Investigation of “Smart Parts” with Embedded Sensors for Energy System Applications

Ahsan Choudhuri, Ph.D.
Ryan Wicker, Ph.D.
Norman Love, Ph.D.
Jorge Mireles, M.S.
Yirong Lin, Ph.D.

Department of Mechanical Engineering
The University of Texas at El Paso
Agenda

- Introduction and Background
- Objectives
- Technical Approach
- Results
- Summary
Motivation

- Highly efficient and environmentally benign power and fuel systems require:
  - Critical Sensing in modern power plants and energy systems
  - Higher efficiencies in energy conversion
  - Lower emission for near-zero emission power plants
  - Enhanced material systems safety
Advanced Sensing

- Harsh high temperature conditions are common to the efficient conversion of fuels and processes for environmental control
- Monitoring/estimating harsh conditions in real time is needed for high system performance and assessing reliability

**Gasifiers**
- Up to 1600°C
- Up to 1000 PSI
- Erosive, corrosive, highly reducing

**Combustion Turbines**
- Up to 1350°C
- Pressure ratios of 30:1
- Thermal shock, highly oxidative
- Complex geometries
State-of-the-Art

- Integrated thermocouples bonded to turbine blades
- Temperature measurement enabled
- Signal is sensitive to harsh environments
- Up to 1400 °C for short time

(X. Li, 2001)  
(J. Yang, 2012)
Ultrasonic Sensor Embedding

Ultrasonic Operation

- Normal Force
- Sonotrode
- Work Pieces
- Weld Region
- Ultrasonic Vibration

Cracking
- Laser deposited stainless steel
- Electroplated nickel

Delamination
- Electroplated nickel
- Stainless steel substrate

Cracking
- Laser deposited stainless steel
- Stainless steel substrate
Multi-step Fabrication

Multi-material fabrication using EBM

Fabrication of electro-mechanical system
Overview and Rationale

• “Smart parts” with embedded sensor
  – Built-in monitoring capability
  – Accurate sensing at desired location
  – No change required post fabrication
  – Realized by 3D printing technology
# Timeline

<table>
<thead>
<tr>
<th>Objective</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q 1</td>
<td>Q 2</td>
<td>Q 3</td>
</tr>
<tr>
<td><strong>Objective 1</strong></td>
<td><strong>Task 1: Fabrication Characterization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Task 2: &quot;Smart Parts&quot; Fabrication</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Objective 2</strong></td>
<td><strong>Task 3: Mechanical Evaluation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Task 4: Sensing Demonstration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Objective 3</strong></td>
<td><strong>Task 5: &quot;Smart Tube&quot; Testing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Task 6: &quot;Smart Premixer&quot; Testing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Task 7: Modification to Fabrication</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Progress Report</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Final Report</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Team Description and Assignment

• Ahsan Choudhuri/Norman Love
  - Smart Parts testing
  - Smart Parts case study
  - High temperature assessment

• Ryan Wicker/Jorge Mireles
  - Smart Parts 3D printing
  - Sensor embedding processing

• Yirong Lin
  - Materials characterization
  - Sensing demonstration
  - Smart Parts testing
Scope of Work

• Design and fabricate “smart parts” with embedded sensors.
  – EBM 3D printing technique for fabrication of “smart parts”
  – Piezoceramic sensors for temperature, strain, pressure sensing.

• Evaluate the sensing capability of the “smart part” in realistic energy systems.

\[ i_p = \frac{dQ}{dt} = Ap \frac{dT}{dt} \]
Design of the Fabrication Process

- “Stop and Go” process, first of its kind
- 3D Printing manually interrupted
- Sensor embedded during fabrication at desired location
Objectives

• **Objective 1: Fabricate energy system related components with embedded sensors**
  – Fabrication & evaluation of components without sensor by EBM
  – Manufacturing “Smart Parts” with embedded sensor by EBM

• **Objective 2: Evaluate the mechanical properties and sensing functionalities of the “smart parts” with embedded piezoceramic sensors**
  – Evaluation of interfacial shear properties
  – Characterization of the sensing capability

• **Objective 3: Assess in-situ sensing capability of energy system parts**
  – Short & long term testing to determine sensor reliability
  – Cyclic and constant loading to determine the sensing repeatability and stability
Electron Beam Melting
by Oakridge National Lab
Fabrication

- Powder Material: Ti-6Al-4V
- Mask Plate and Start Plate: Stainless steel
- Layer Thickness: 50 µm
Sensor assembly in “Smart parts”

- Insert part (Ti-6Al-4V)
- Alumina plate
- Piezoceramic sensor
- Electrode (Ti)

Exploded View
Characterization

**Before EBM**

- **Alumina Plate**
- **Ti Electrodes**
- **Piezoelectric Sensor**

**After EBM**

- **Alumina Plate**
- **Ti Electrodes**
- **Piezoelectric Sensor**
Sensor Packaging Design

- Insert part (Ti-6Al-4V)
- Housing
- Electrode
- Piezoceramic sensor
- Bottom part (Ti-6Al-4V)
Sensor Packaging Fabrication

- Machinable Alumina
- Injection Modeling
- 3D printing
- 3D printing + Ceramic spray
Smart parts Fabrication (1st run)

Before Fabrication

Final Part
Force Sensing
Compression Force sensing

10 Hz

15 Hz

20 Hz

25 Hz
Mechanical Property Testing

**Control**
- Elastic Modulus: 110 GPa

**Stop and go**
- Elastic Modulus: 100 GPa

**Graphs**
- Stress vs. Strain for Control and Stop and go processes.

**Images**
- Material microstructure images showing 1st and 2nd built samples.

**Notes**
- Build paused mid-way through fabrication.
- 30mm gauge length.
Interfacial Property Enhancement
Experimental Setup

Tensile bars were fabricated to test mechanical properties after interrupting the fabrication process.

Fabrication was stopped at gauge’s midpoint, the machine was allowed to fully cool and the process was restarted.

Fabricated tensile bars.
Interfacial Property Enhancement
Experimental Setup

- Single Melt
- Double Melt
- Triple Melt

![Bar chart showing UTS, Young's Modulus, and Tensile Strain for Single Melt, Double Melt, and Triple Melt.](chart.png)
Fracture Surface

Single Melt

Double Melt

Triple Melt
Joint Microstructure


(a) Adjacent fabrication

(b) Standard part fabrication

(c) Interface

(d) Ti-6Al-4V
Smart Tube Fabrication

Assembled Bottom Section

Masking plate
Pressure Sensing

- Force sensing with embedded sensor demonstrated
- 1, 5, 10 Hz of dynamic force was used
- 0.04, 0.011 and 0.0064 (V/kN) of sensitivity was achieved
- Lower sensitivity caused by sensor packaging clearance and force loading directions
Sensed temperatures of 198 °C, 178 °C, and 150 °C for 7.6 cm, 15.2 cm and 30.5 cm long tube sections.
Selective Laser Melting Demo
CAD Drawing of Smart Injector

- Thermal soak-back sensing
- Allows for operation at lower safety factors
- Higher temperatures and higher efficiencies
Design of Smart Injector
Fabrication

Fabrication of insert part

Fabrication of bottom part

Fabrication of entire part

Sensor assembly

Final smart part
Fabricated Smart Injector

- The smart injector was fabricated using selective laser melting (SLM) technology
- The electrode wires are visible in the injector
- PZT and LiNbO$_3$ sensor material is embedded inside the injector
- The injector was cut off from the build plate after finishing preliminary sensor testing
Surface Roughness Comparison between SLM, EBM, and Machining

Cost:
- EDM Machined: $6,000, 2 months
- SLM 3D printing: $1,500, 2 days
Preliminary Temperature Sensing Setup of the 3D printed injector

\[ \dot{q} = Ap \frac{dT}{dt} \]

\[ C(T) = \frac{\varepsilon_0 \varepsilon_r(T) A}{t} \]

\[ i_p = \frac{dQ}{dt} = Ap \frac{dT}{dt} \]
In-situ Sensing Demonstration Procedures

Pre-test
• Prove that each valve is working properly
• Make sure all readings are correct from pressure and temperature transducers and flow meters (ambient or zero)
• The line will be pressurized and Snoop will be used on each connection to check for leaks.

Measuring pressure drop across the system (Cold flow testing)
• Pressure drop testing will be performed on each line using Nitrogen. Then we will know how much pressure on the tank will be needed to satisfy the desired chamber pressure

Hot firing test
• The test will begin by setting the k-bottles to the indicated pressure indicated in the test matrix and setting LabVIEW to the automated sequence.
Smart Fuel Injector Testing Setup

Multi-purpose Optically Accessible Combustor (MOAC)

Bunker
• Designed primarily for LOX/Methane combustion research
• Capability to simulate up to 50 lb thrusters
• Square chamber, inner dimensions 80x80x150mm
• Wide side quartz windows for optical access and laser diagnostics
• Modular injector/converging section
• Stands 20 bar as maximum pressure

Modeling of the Surface roughness vs Pressure drop
Schematic and bunker diagram
Pressure drop and flow rate test of machined injector
Flow rate and pressure drop results of machined injector

Methane Line (Manufactured)

Air Line (Manufactured)
Pressure drop and flow rate test of 3D printed injector
Flow rate and pressure drop results of 3D printed injector

**Methane Line**

- ΔP vs Mass Flow Rate (lbm/s)

**Air Line**

- ΔP vs Mass Flow Rate (lbm/s)
Insertion of 3D printed injector
Leak test using helium
Spark electrodes fabrication and testing
Torch igniter assembly

Bending

Sparker

Air

Methane
Hot fire testing of CH$_4$ and air using a 3D printed injector

Stoichiometric equation for combustion of CH$_4$ and air:

$$\text{CH}_4 + 2(\text{O}_2 + 3.76\text{N}_2) \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 7.52\text{N}_2$$

Molecular weight of CH$_4$ = 16.043 g/mol
- C = 12.011 X 1 atom X 1 mole
- H = 1.008 X 4 atom X 1 mole

Molecular weight of 2(\text{O}_2 + 3.76\text{N}_2) = 274.66 g/mol
- O = 15.9994 X 2 atoms X 2 moles = 64
- N = 14.007 X 2 atoms x 7.52 moles = 210.66 g/mol

O/f = \frac{17.52}{274.66} = 0.064

Stoichiometric O/F calculated and estimated chamber pressures were used in CEA to calculate the temperatures experienced in the chamber and at the throat as well as the characteristic velocity $c^*$ (cstar). $c^*$ was used to calculate the total flow rate exiting the chamber at the throat as follows:

$$c^* = \frac{P_t A_t}{m}$$

Once the temperature has been calculated from CEA, this can be used to describe the enthalpy change of the combustion and calculate energy, and then finding flow rate of fuel is possible using the following equations:

$$Q = H_p - H_f$$

or

$$Q = (LHV)_{\text{methane}} \cdot \dot{m}_f$$

Flow rates for both the air and fuel are now known and test matrix can be done using these expected flow rates and chamber pressures to begin cold test. The time that the test would take to get to temperature desired is also calculated by the following:

$$\dot{Q} = m_c \cdot c_p \frac{\Delta T}{\Delta t}$$

Test matrix will be followed during the cold testing. Tank pressures will be added once pressure drop is known.
Testing Setup Ready
Publication and Patent


Acknowledgment

• Funding support from DOE-NETL, grant DE-FE0012321

• Maria Reidpath
  – Federal Project Manager, Crosscutting Research, NETL, U.S. DOE

• Robert Romanosky
  – Acting Technology Manager, Crosscutting Research, NETL, U.S. DOE
Thank you

Questions?