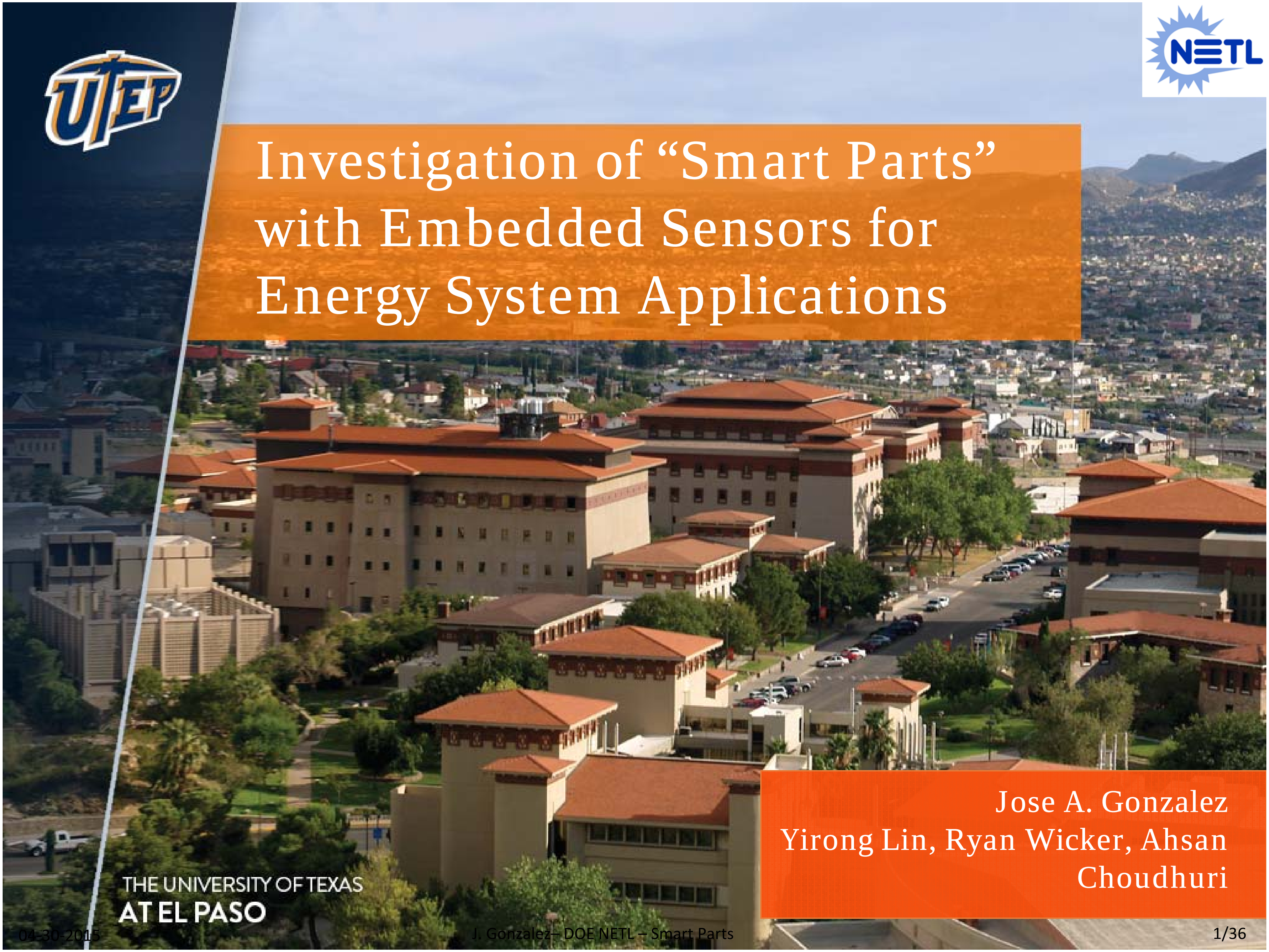
Investigation of “Smart Parts” with Embedded Sensors for Energy System Applications



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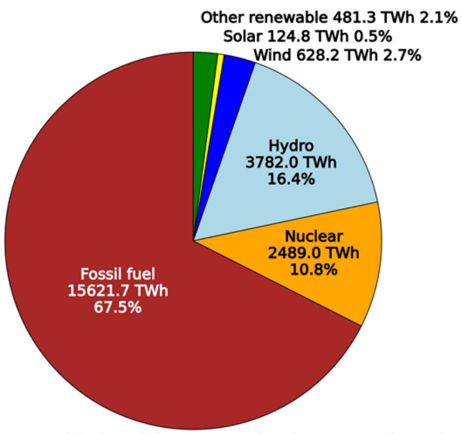
Agenda

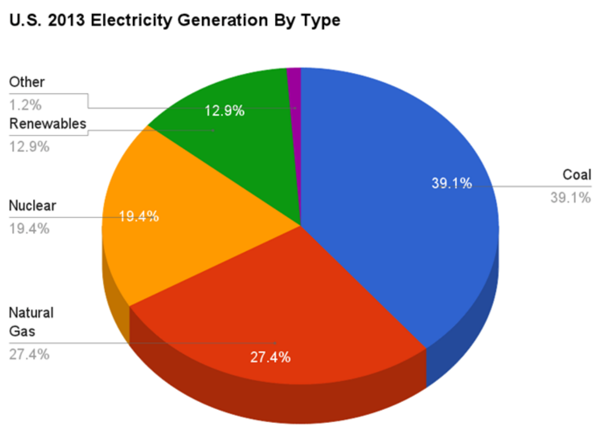
- Introduction and Background
- Objectives
- Technical Approach
- Results
- Summary
- Future Work

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



World Electricity Generation by Source (2013)



Advanced Sensing

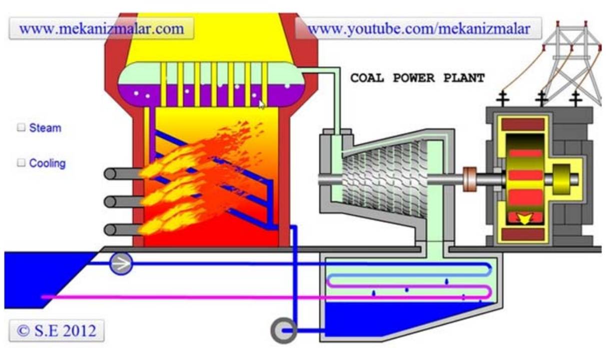
- Harsh high temperature conditions are common to the efficient conversion of fuels and processes for environmental control
- Monitoring/estimating harsh conditions in real time is needed for high system performance and assessing reliability

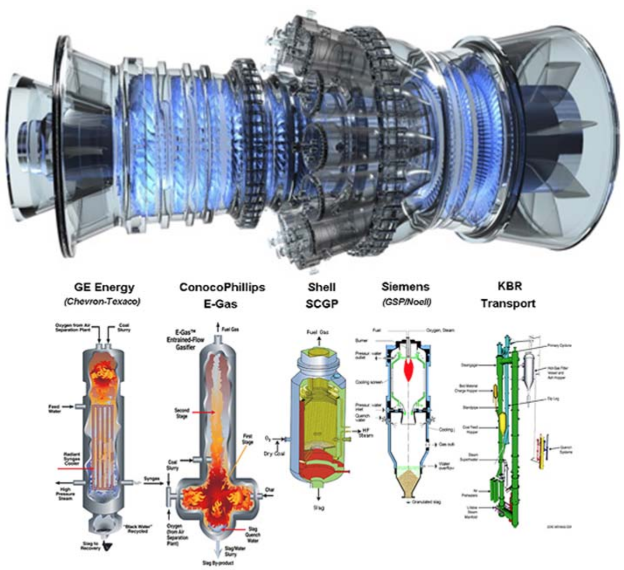
Gasifiers

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

Combustion Turbines

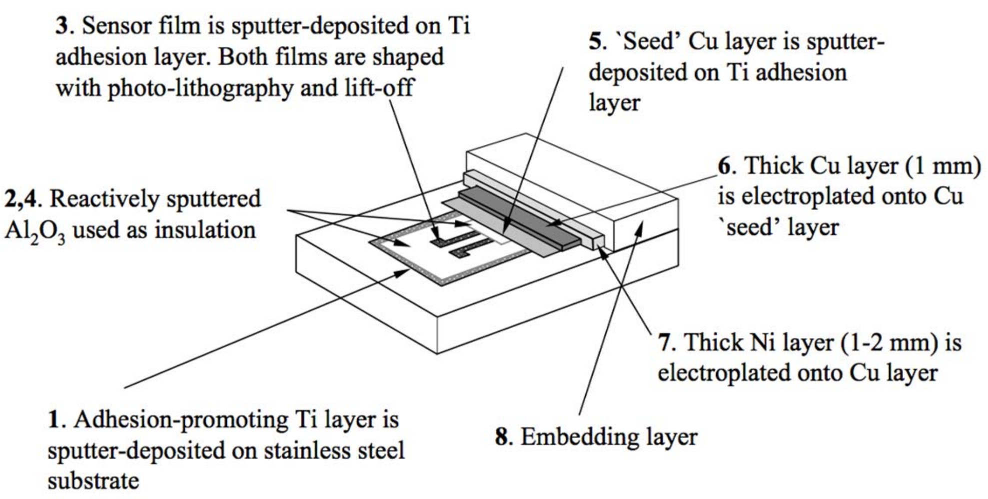
- Up to 1350°C
- Pressure ratios of 30:1
- Thermal shock, highly oxidative
- Complex geometries



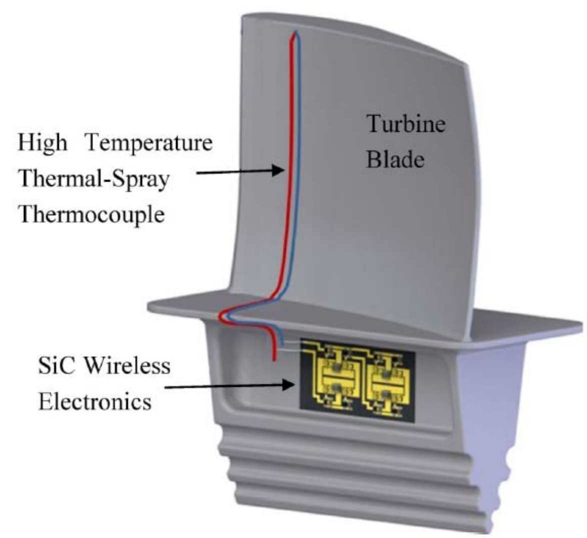


State-of-the-Art

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



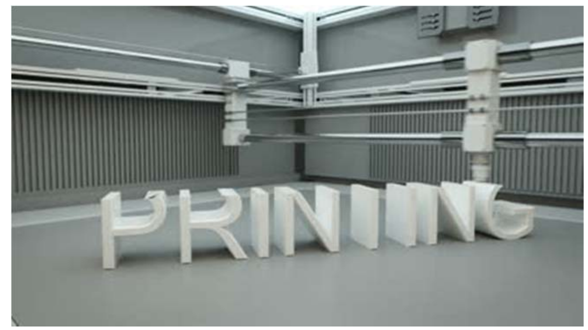
(X. Li, 2001)

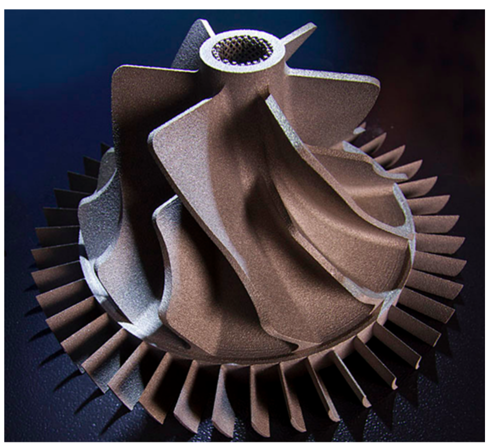


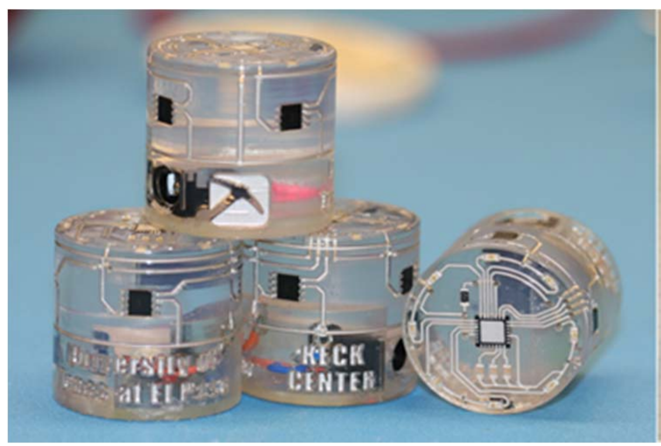
(J. Yang, 2012)

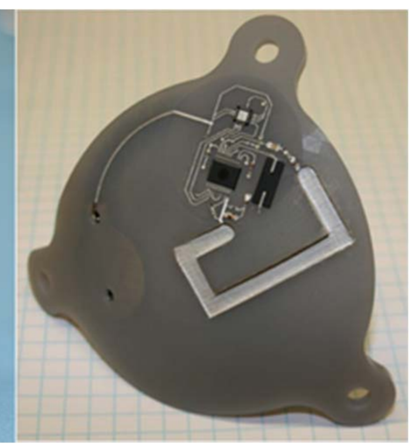
Overview and Rationale

- "Smart parts" with embedded sensor
  - Built-in monitoring capability
  - Accurate sensing at desired location
  - No change required post fabrication
  - Realized by 3D printing technology



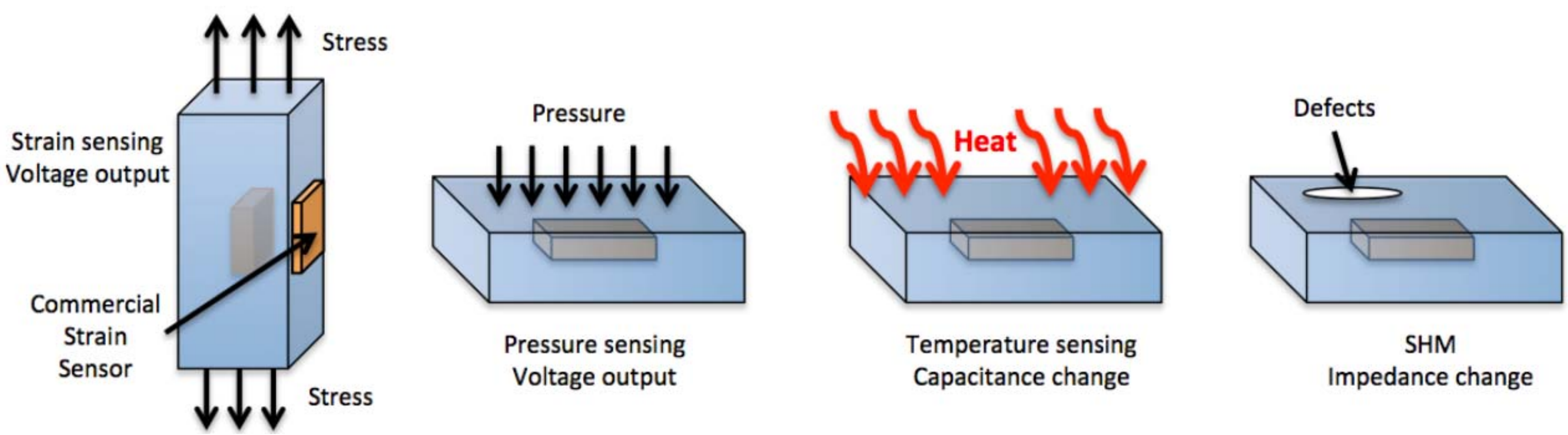






Scope of Work

- Design and fabricate "smart parts" with embedded sensors
  - EBM 3D printing technique for fabrication of "smart parts"
  - Piezoceramic sensors for temperature, strain, pressure, and structural health conditions
- Evaluate the sensing capability of the "smart part" in realistic energy systems

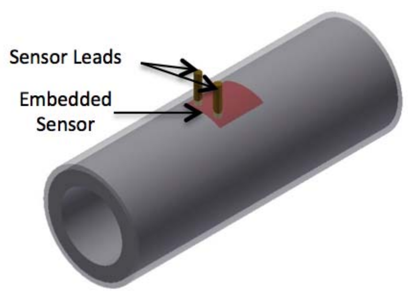


Objectives

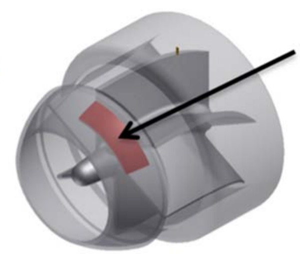
- **Objective 1: Fabricate energy system related components with embedded sensors**
  - Fabrication & evaluation of components without sensor by Electron-Beam Melting (EBM)
  - Manufacturing “Smart Parts” with embedded sensor by EBM

- **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

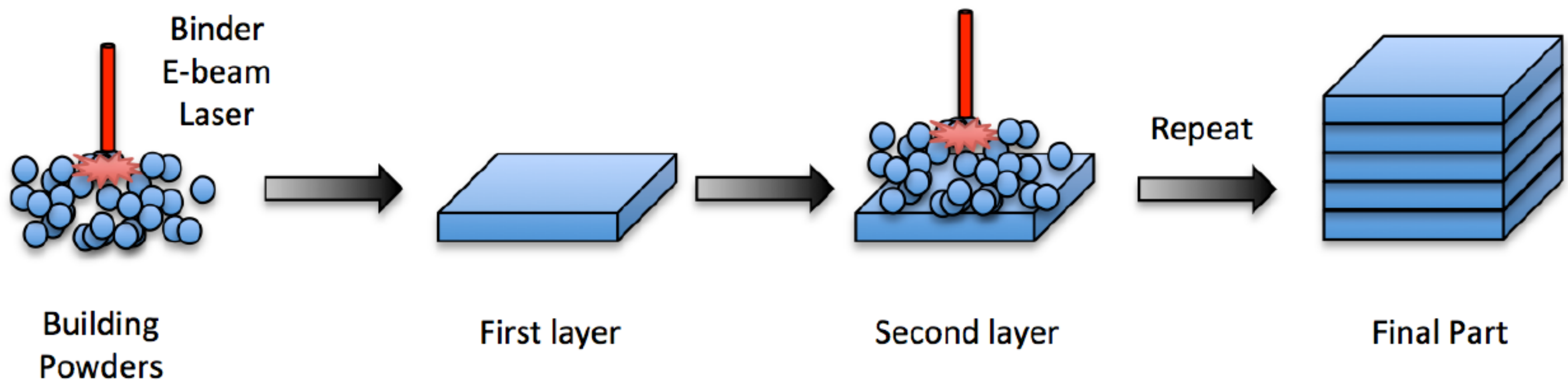


Smart tube with embedded sensor



Additive Manufacturing

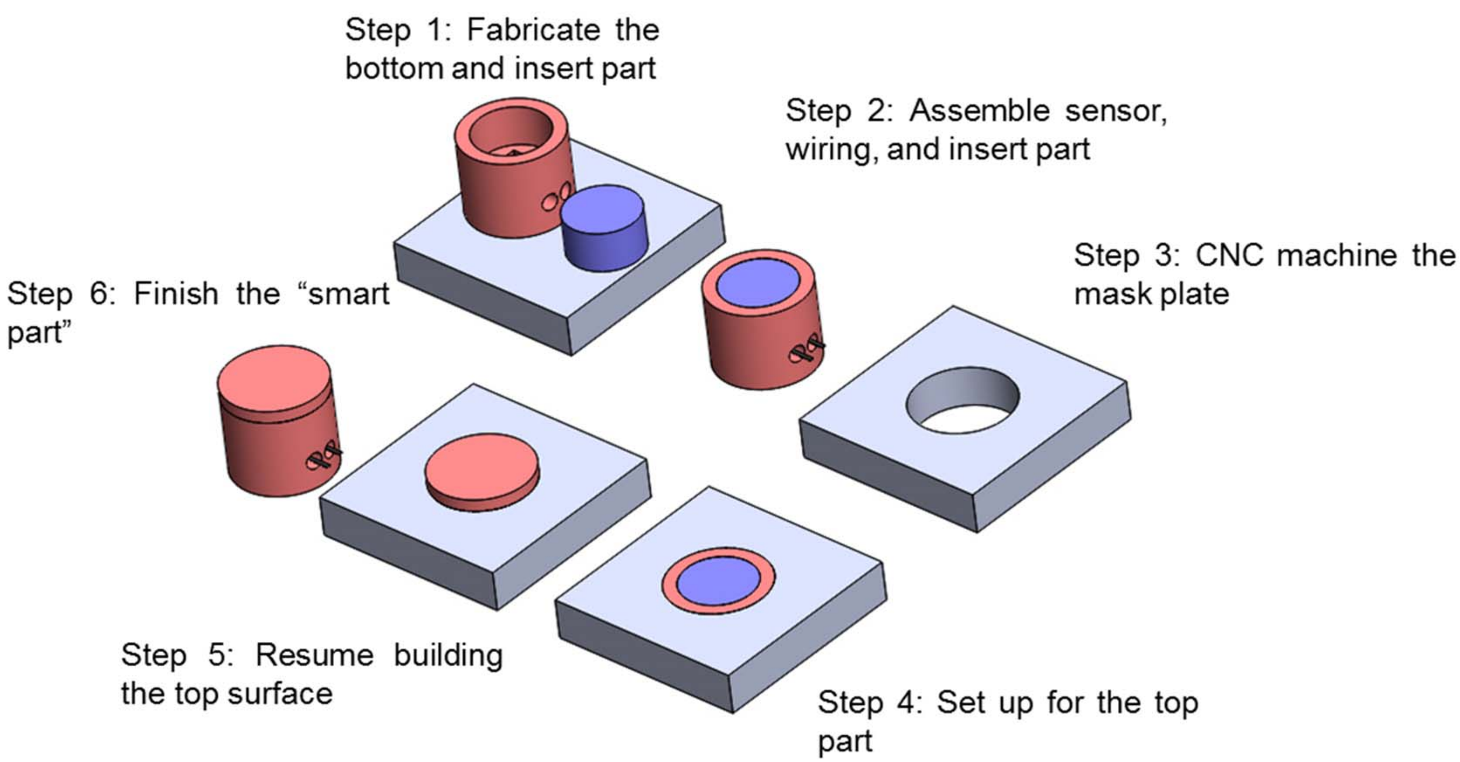
- Additive Manufacturing is a process for creating parts directly from a computer model based on 3D Printing technologies
  - Builds complex, functional parts designed in a 3D CAD program
  - Eliminates variation of properties across scales
  - Wide range of applications: ceramic molds, structural ceramic parts, parts for tooling, ceramic preforms for metal matrix composites, etc.



EBM Demo

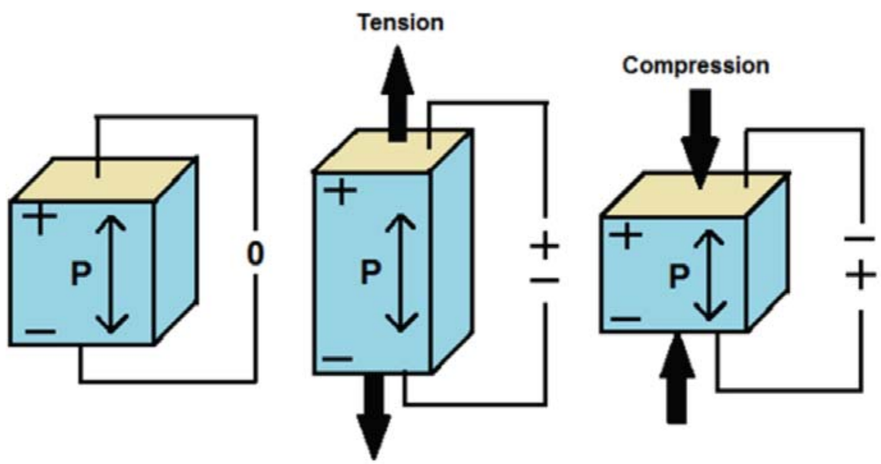
Design of the Fabrication Process

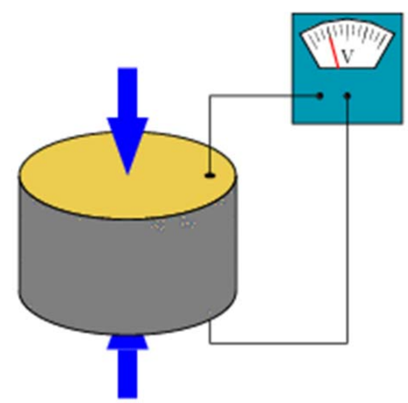
- "Stop and Go" process, first of its kind
- EBM fabricated manually interrupted
- Sensor embedded during fabrication at desired location



Selection of Materials

- Piezoceramic for sensing
  - Piezoelectric elements are used in smart systems due their capability of coupling energy in mechanical, thermal, and electrical domain
  - Most of applications rely on relative magnitudes of voltage, or frequency spectrum of signal modified by sensor
  - $LiNbO_3$, T_c = 1200 °C

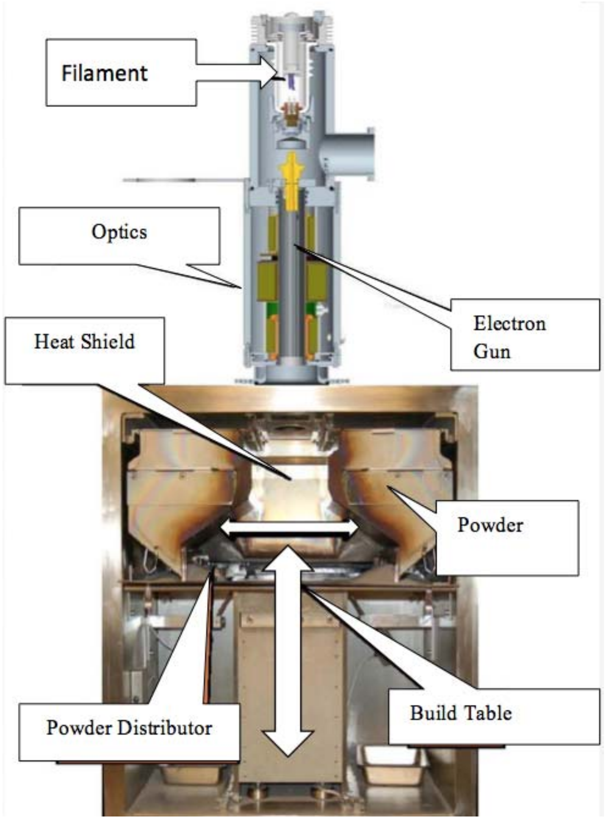




Fabrication

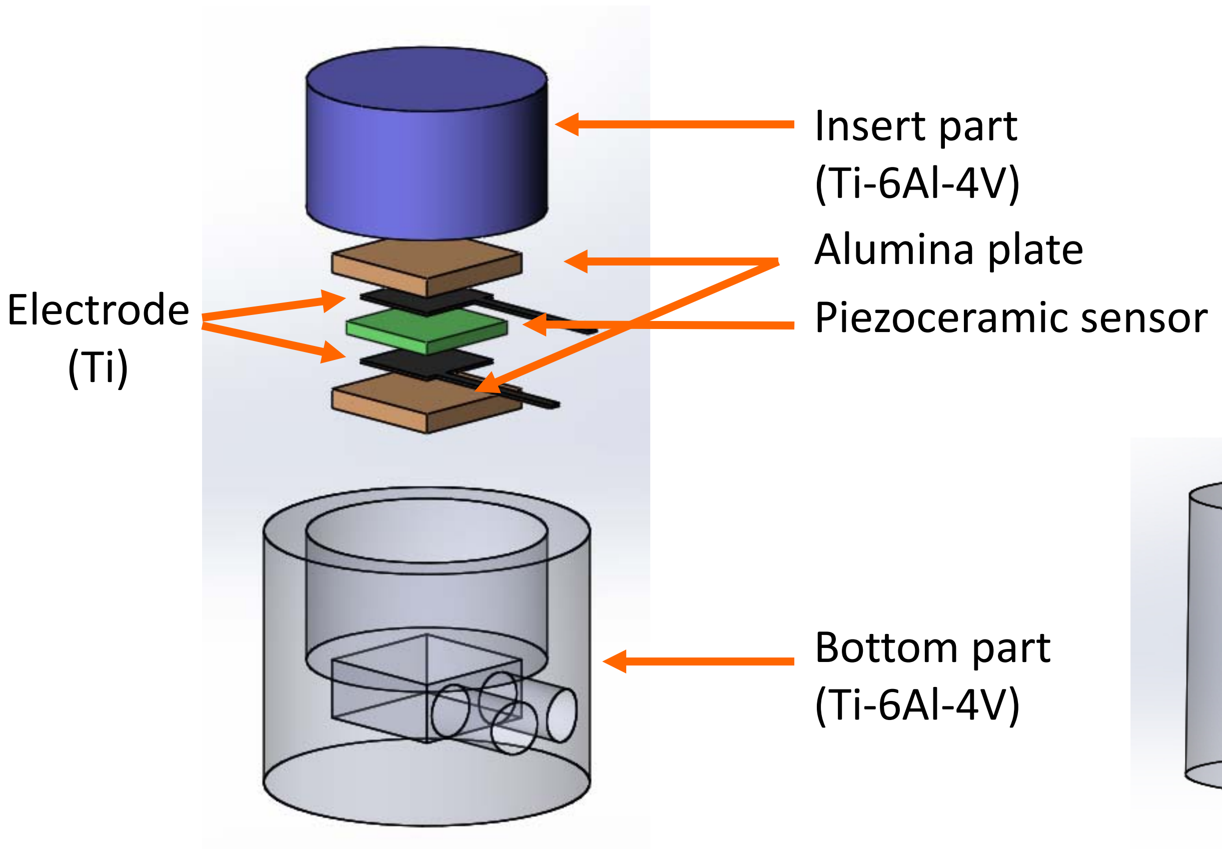
- Powder Material: Ti-6Al-4V
- Mask Plate and Start Plate: Stainless steel
- Layer Thickness: 50 µm

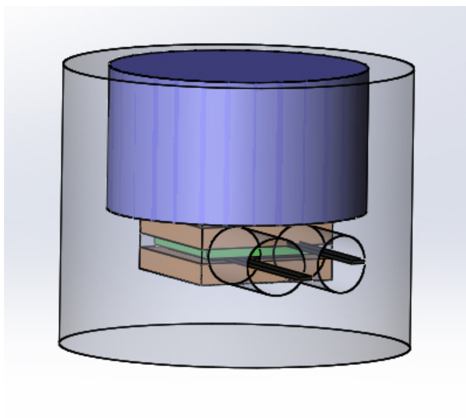
Arcam EBM



Cross-section view

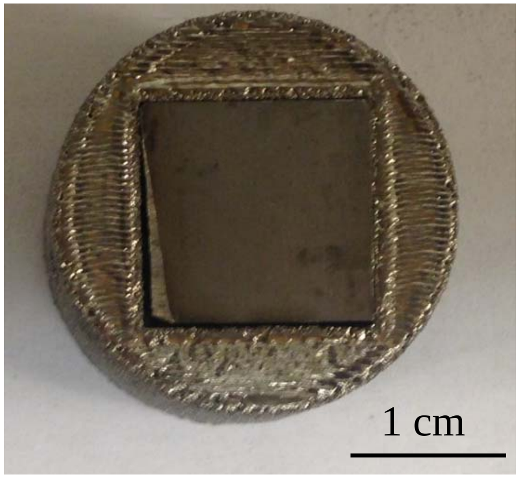
Sensor assembly in "Smart parts"





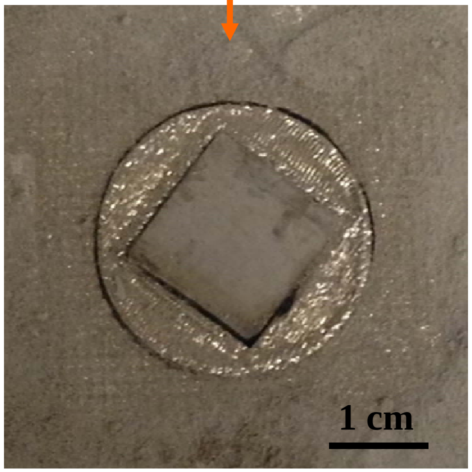
Exploded View

Fabrication Results



Bottom part

Mask Plate

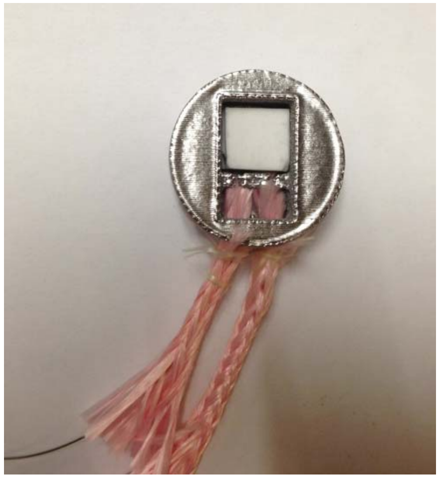


Part press fitted into the mask plate (150 mm × 150 mm)

Misalignment of 435 µm

Final “smart parts”

Design A



Assemble of parts

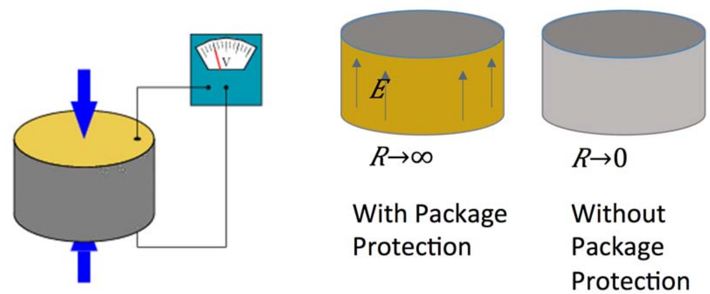
After 2nd Fabrication of parts (top view)

After 2nd fabrication of parts (side view)

Dissemble of the top parts

Important Notes:

- Top part fell off



Design B

Assemble of part
(Top View)

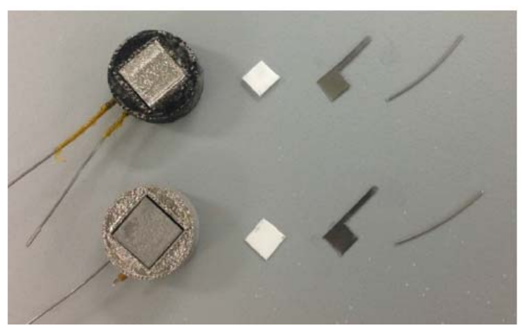
Assemble of part
(Side View)

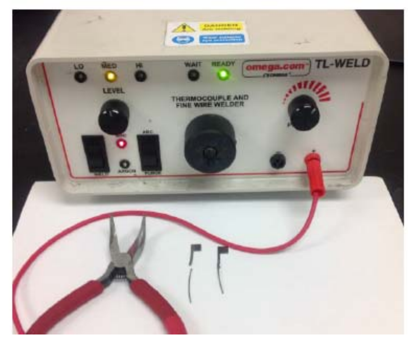
2nd fabrication of part
(Top View)

Build part (Side View)

Important Notes:

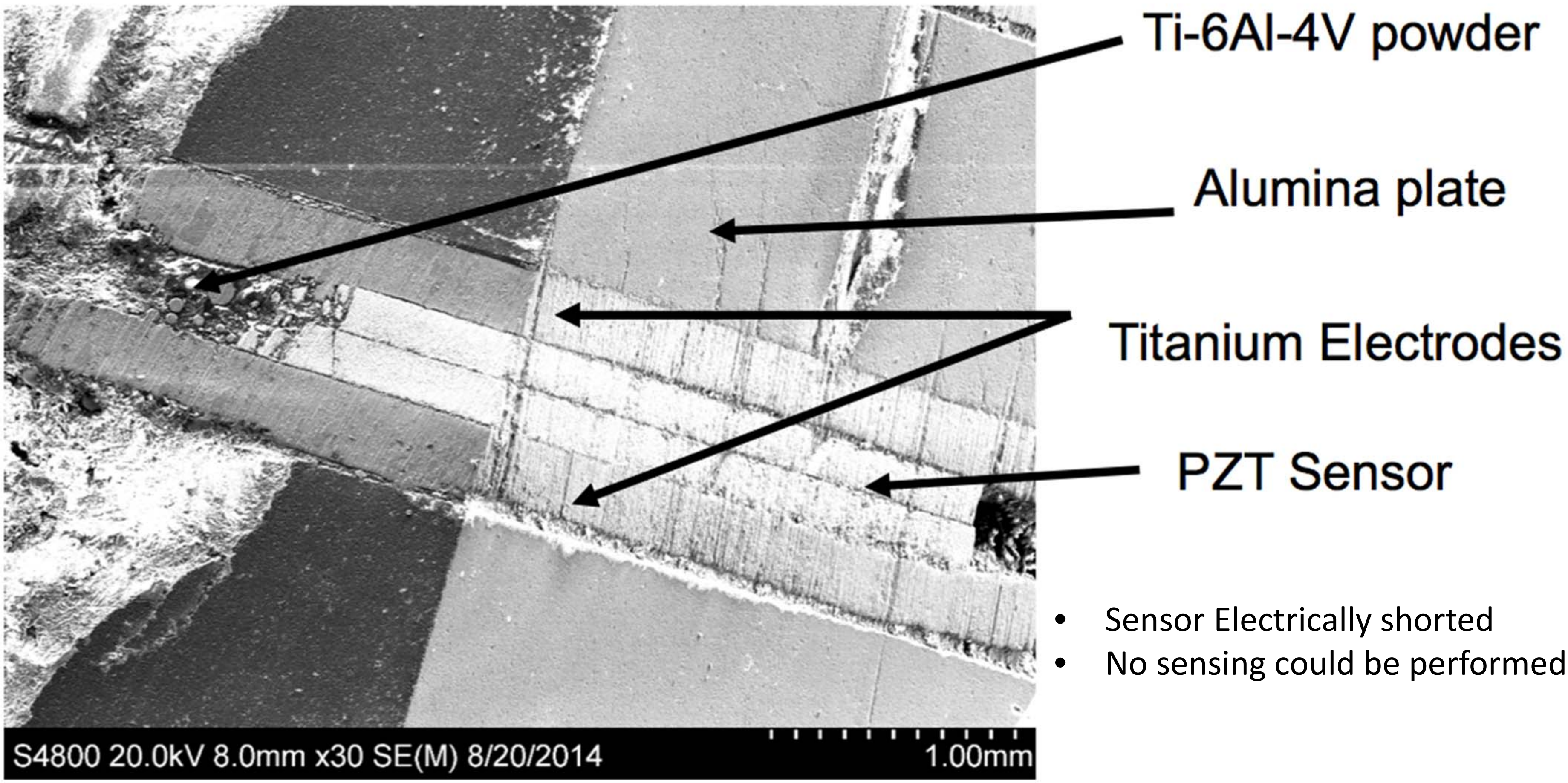
- A misalignment of 1.15 mm was obtained due to the centering of the beam offset





Fabricated parts

Alumina cloth to seal the sensor assembly from metal powder

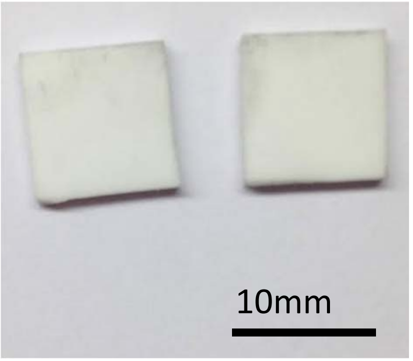


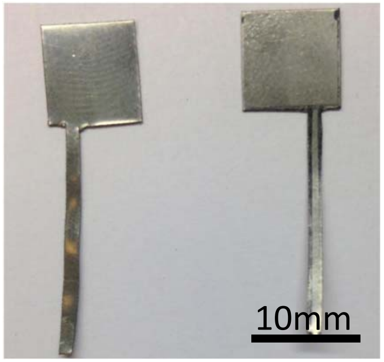
- Sensor Electrically shorted
- No sensing could be performed

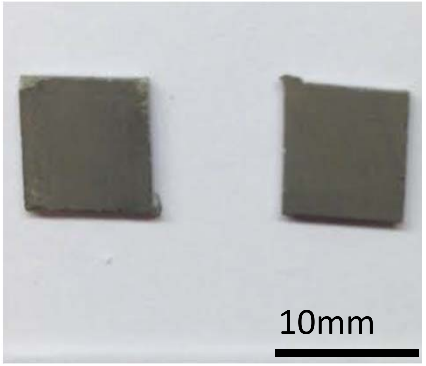
Characterization

Before EBM

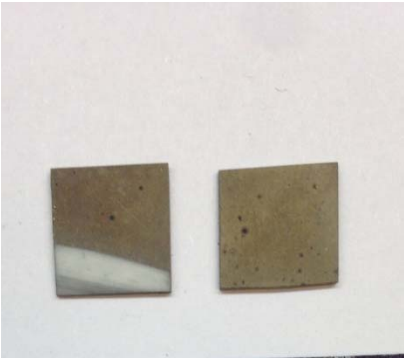
Alumina Plate | *Ti Electrodes* | *PZT Sensor* | *Alumina Sleeve*

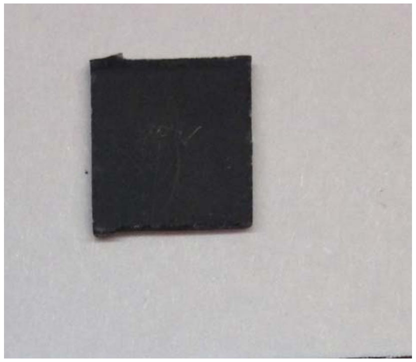




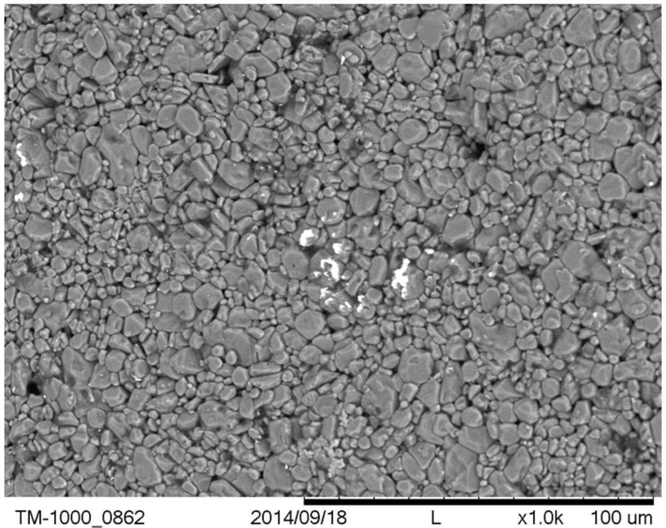


After EBM

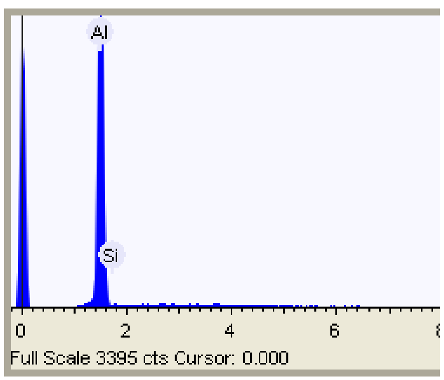




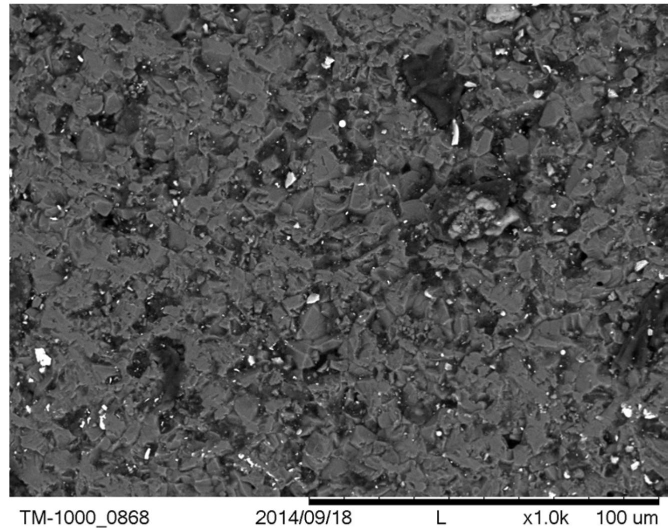

EDS on Alumina Plates(Before EBM)



Element	Weight %
Aluminum	98.5
Silicon	1.5

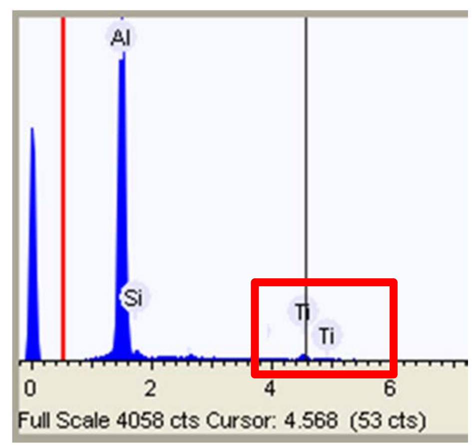


EDS on Alumina Plates(After EBM)



Element	Weight %
Aluminum	89.3
Silicon	3.6
Titanium	4.2

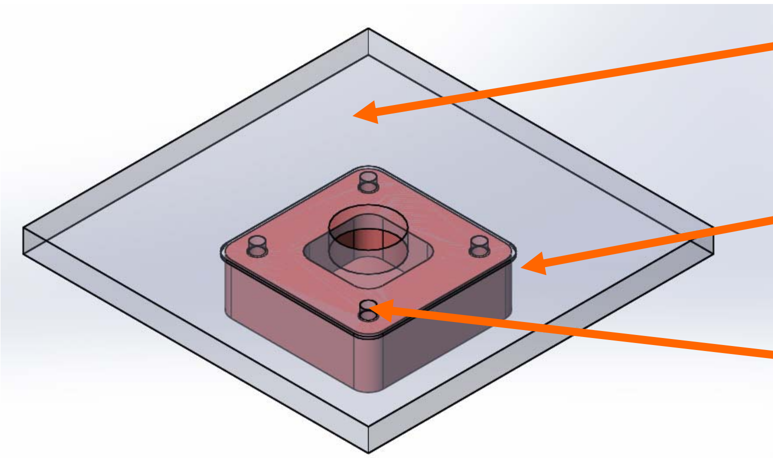
Titanium detected on alumina plate

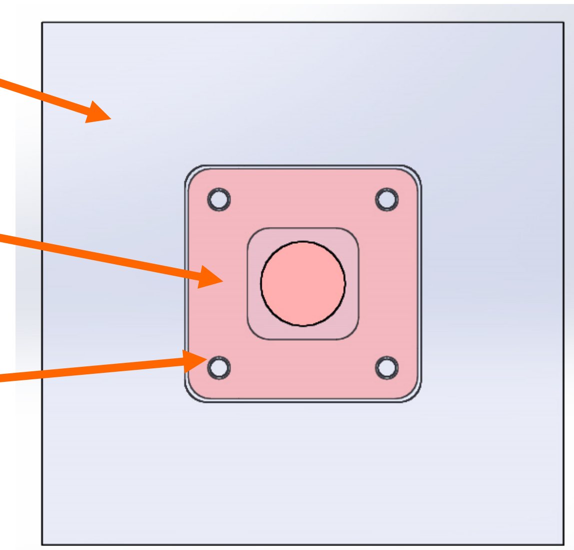


Vaporization temperature of different materials

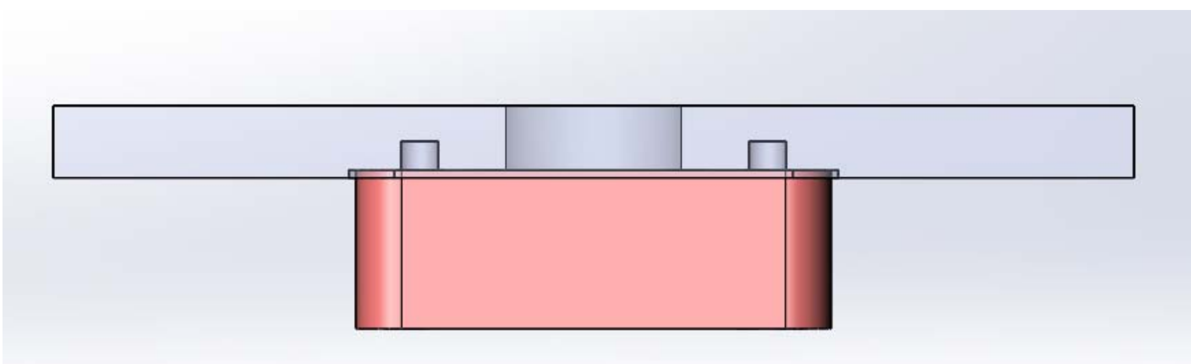
Element	Vaporization Temperature (C) At Pressure (Torr)				
		10^{-4}	10^{-3}	10^{-2}	10^{-1}
Copper		1035	1141	1273	1432
Gold		1190	1316	1465	1646
Iron		1195	1310	1447	1602
Platinum		1744	1904	2090	2293
Titanium		1250	1384	1546	1742
Tungsten		2767	3016	3309	
Yttrium		1362	1494	1650	1833
Niobium		2355	2539		
Nickel		1257	1371	1510	1679

Mask plate fabrication with isolation cup





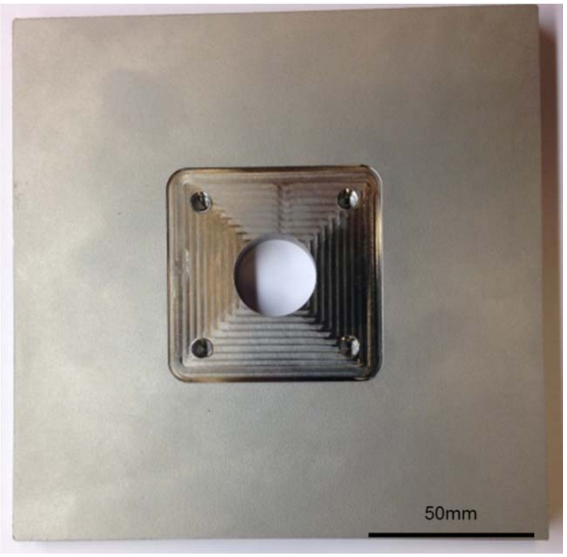
Mask plate along with the bottom section



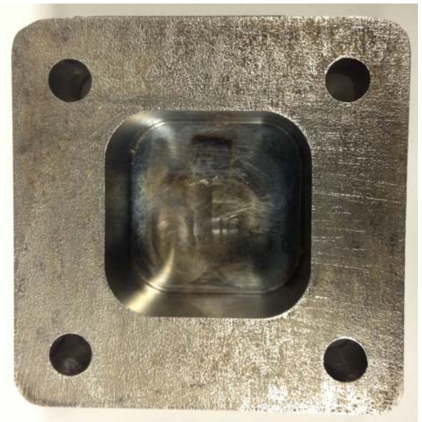
Front view

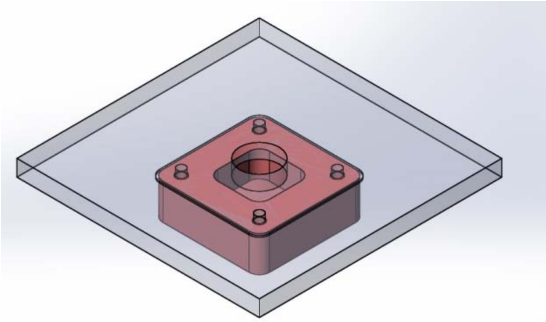
Addition of isolation cup to start plate

- Mask plate was machined using CNC
- Bottom cap made of 304 Stainless Steel
- Bolts: 316 Stainless Steel socket head cap screws
- Used to avoid metal powder from entering in sensor box



Machined Mask Plate

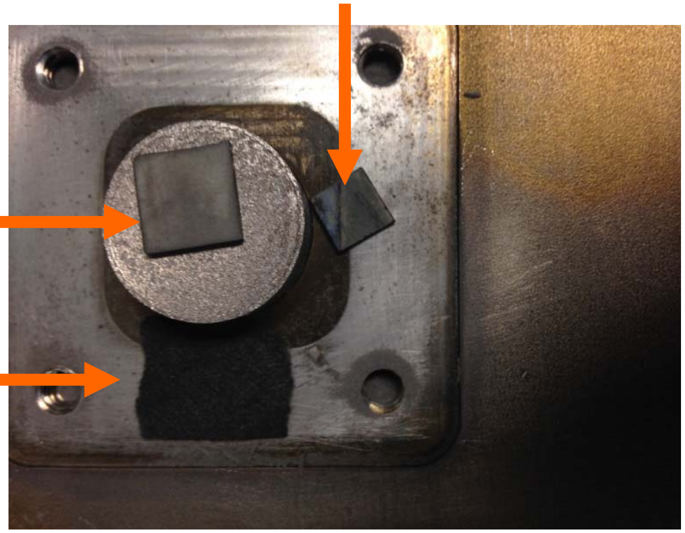




Isolation Cup

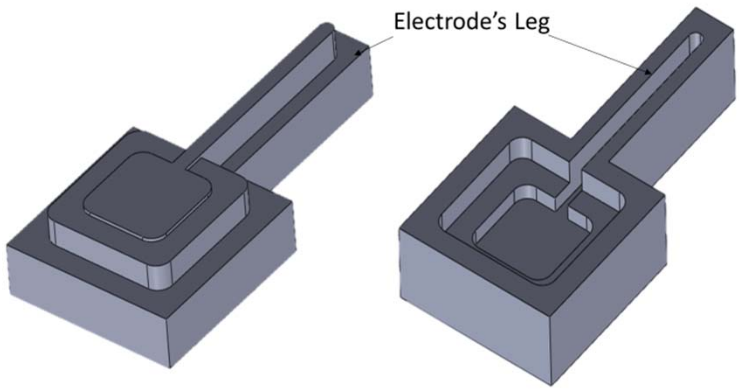
Sensor components within isolation cup

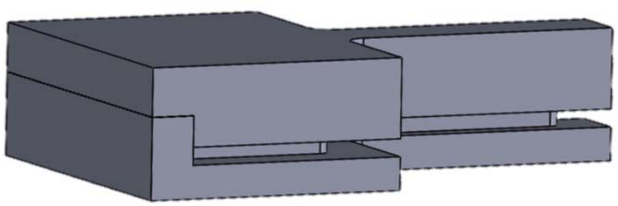
- **NO ELECTRODES PRESENT**
- Alumina cloth, alumina plates, PZT, and sleeves were present within isolation cup during build
- Metal coating was **still visible** on parts

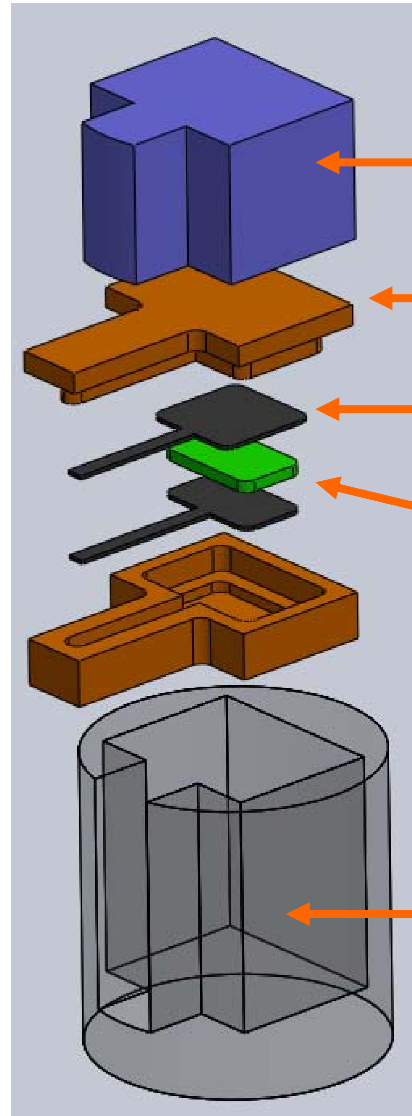


Bottom of start plate after EBM

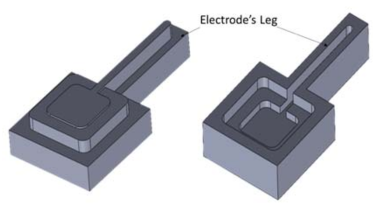
Sensor Packaging Design

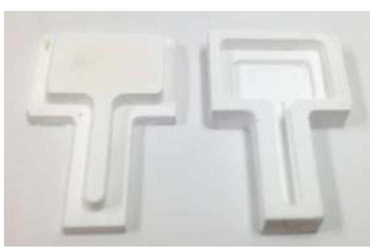






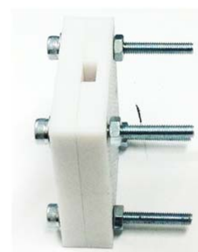
Sensor Packaging Fabrication

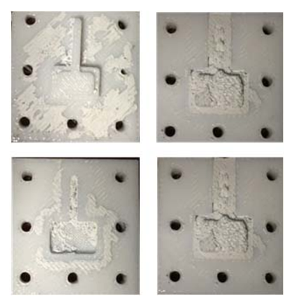




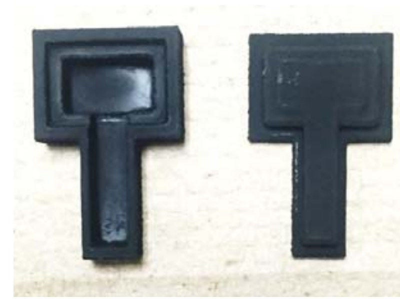
Machinable
Alumina

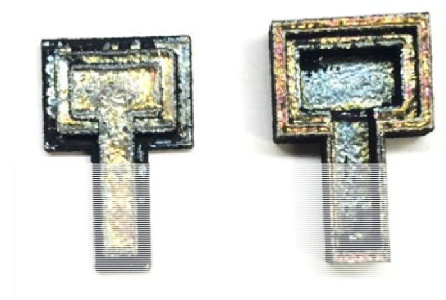
3D printing





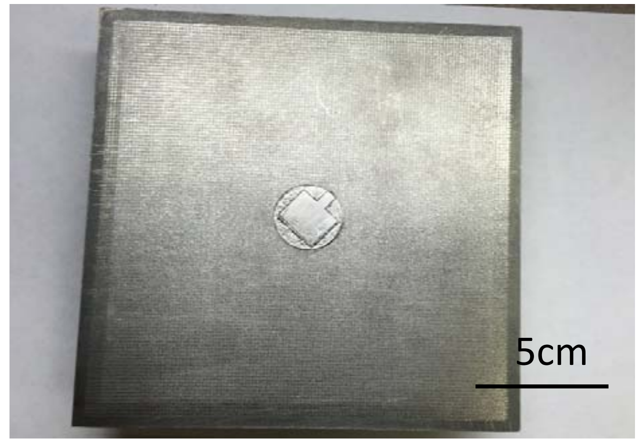
Injection
Modeling





3D printing
+
Ceramic spray

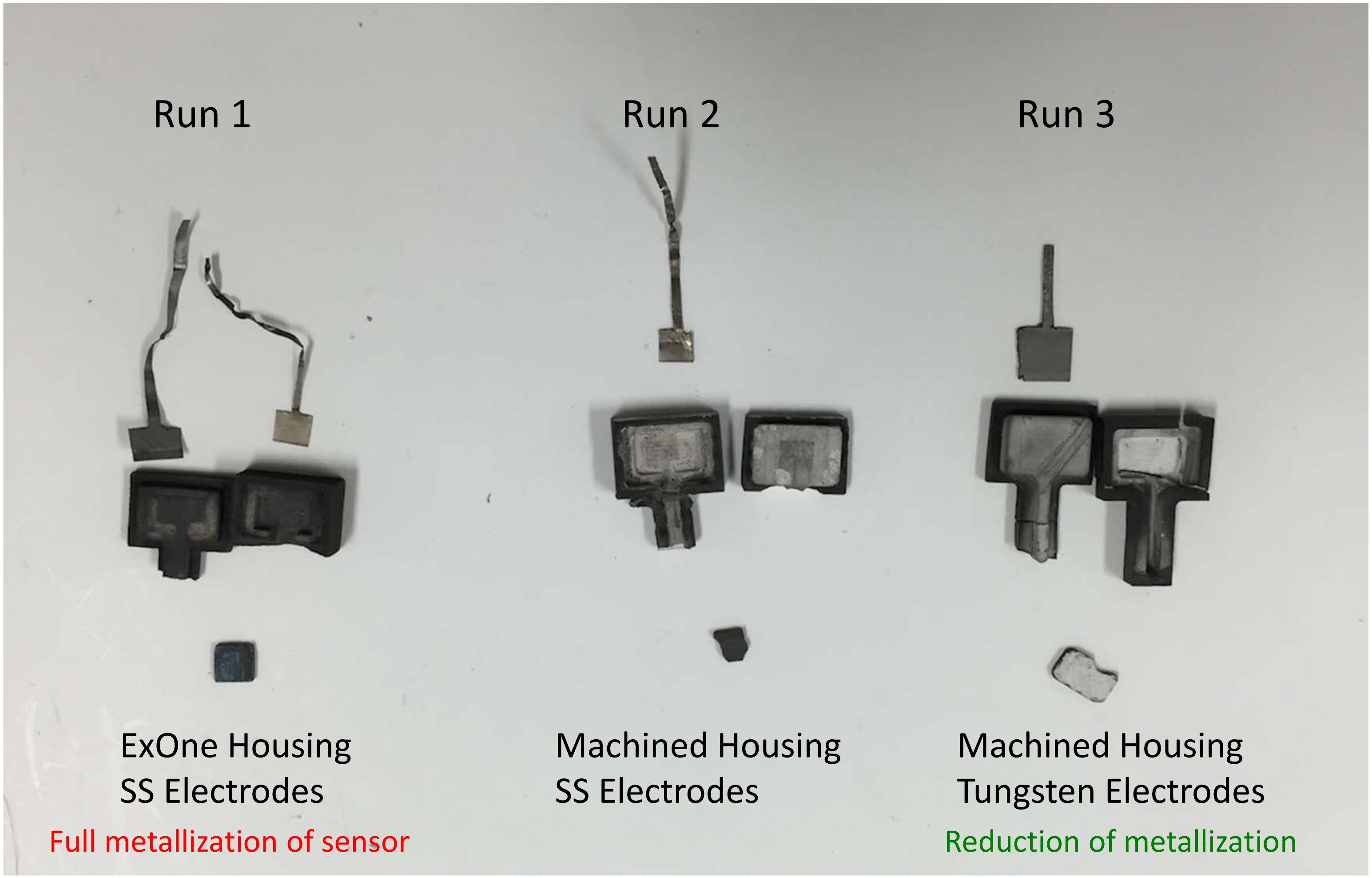
Smart parts Fabrication (1st run)



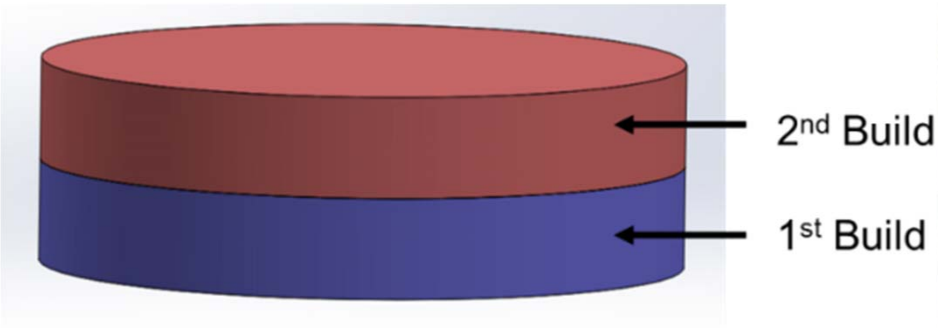
Before Fabrication

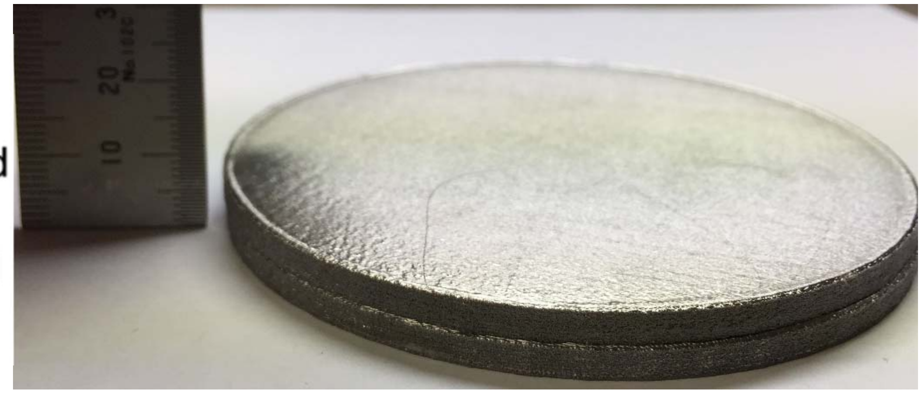
Final Part

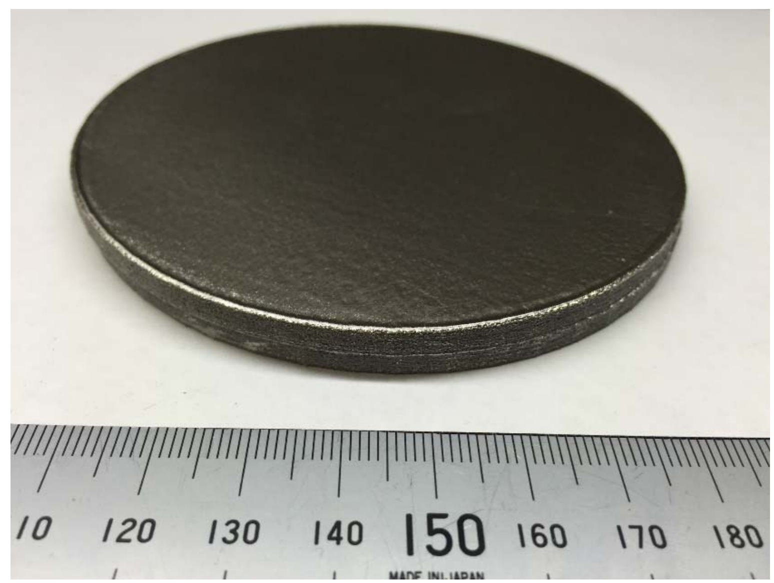
Successfully Fabricated Smart Parts



Modified Stop and Go Process

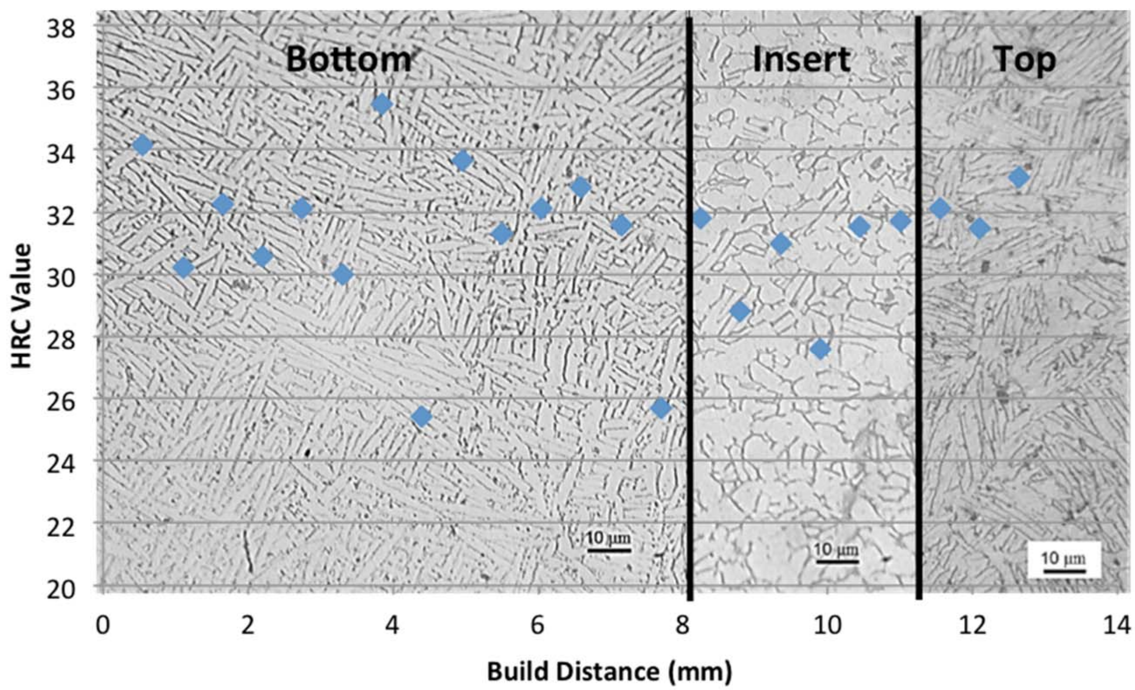




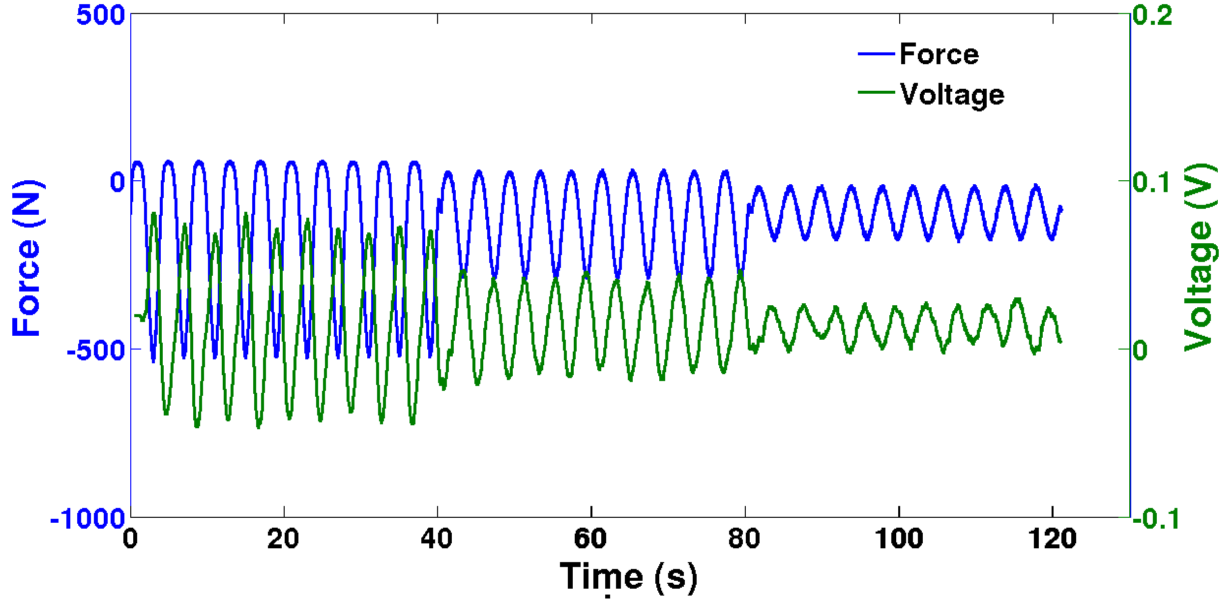


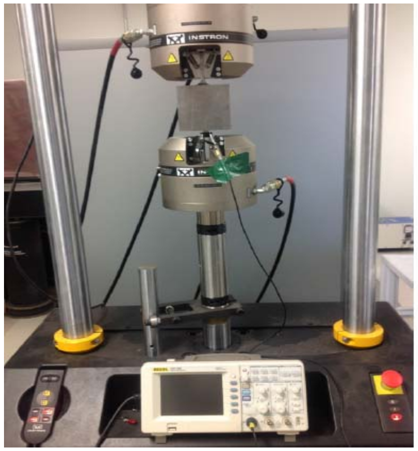
Hardness Testing Results

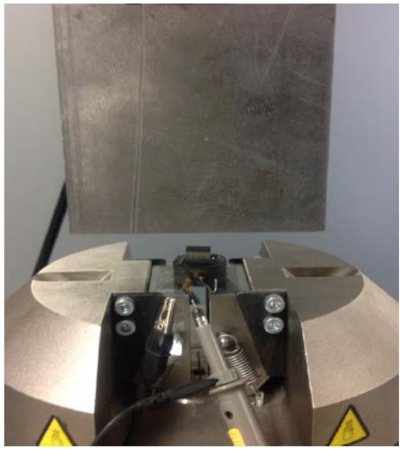
- Vickers Hardness Test was performed on the completed smart part
- No large change in Hardness value throughout the smart part
- EBM Ti-6Al-4V = 40 HRC [5]
- Annealed Ti-6Al-4V = 36 HRC [6]



Force Sensing

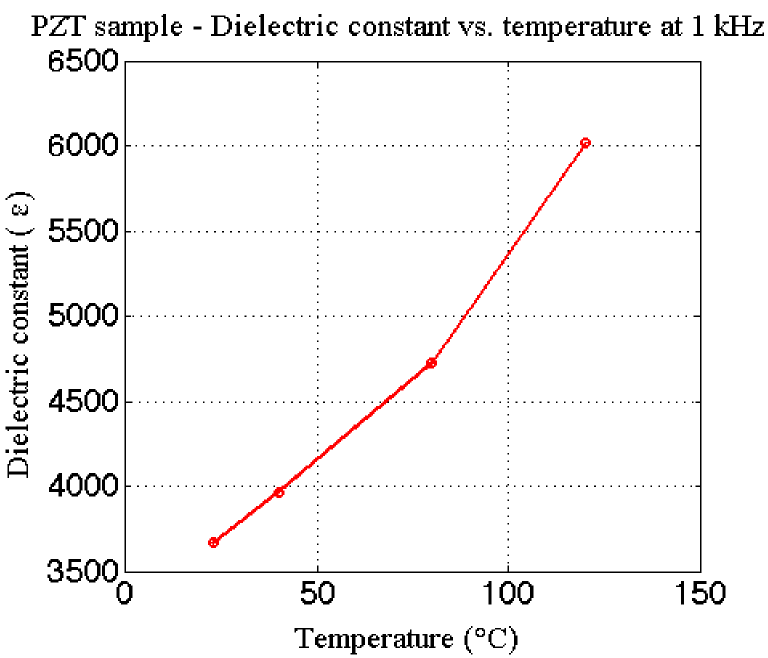


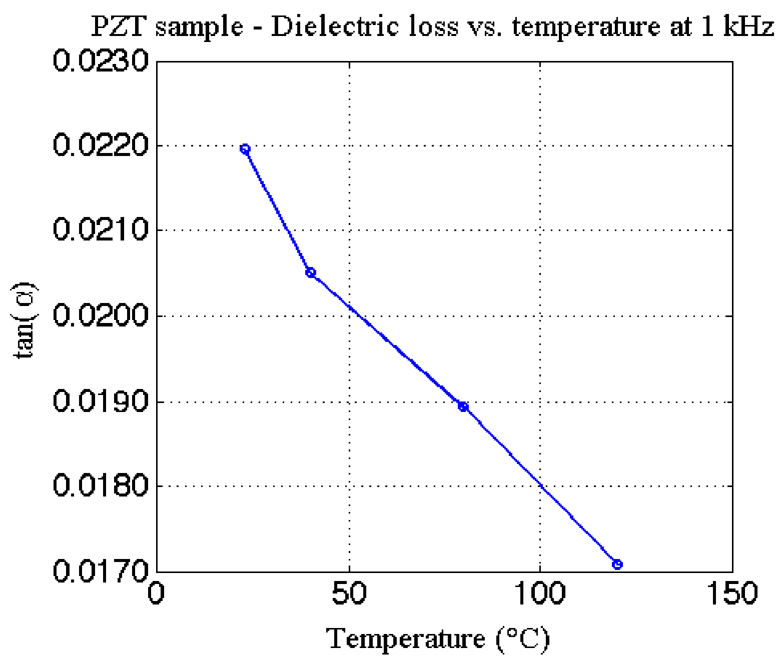




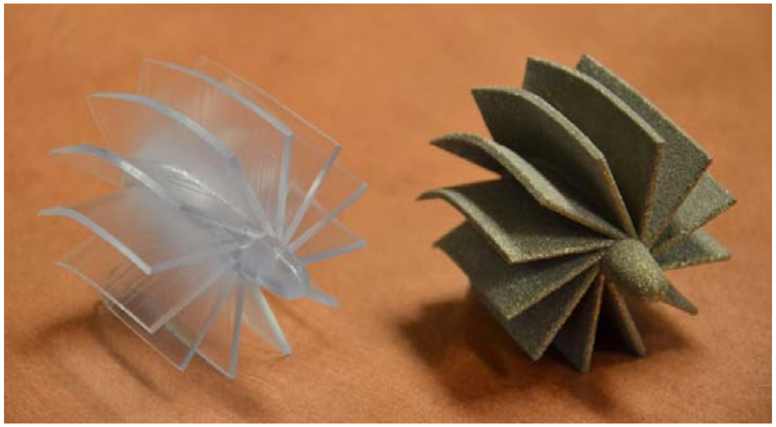
Force-Voltage Correlation

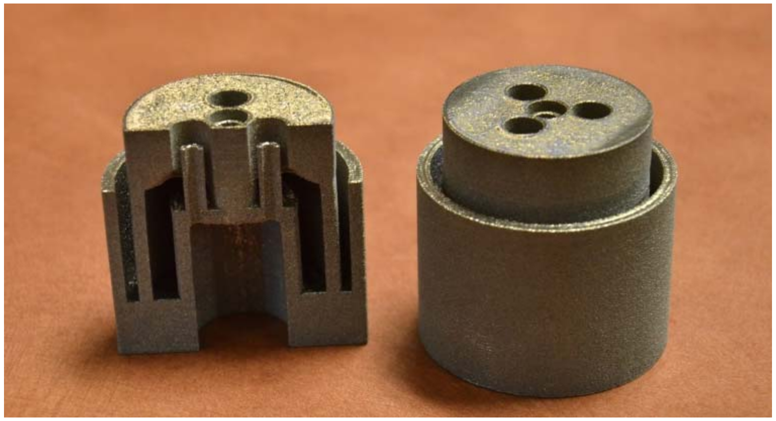
Temperature Sensing

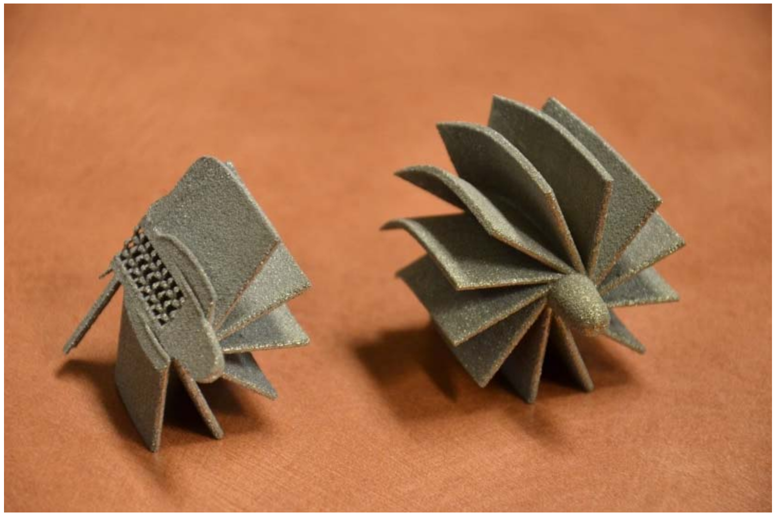


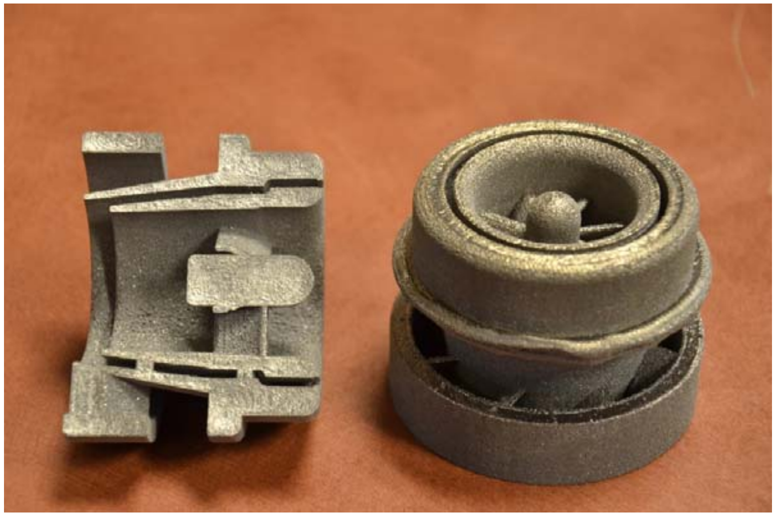


Fabrication of Energy System Components

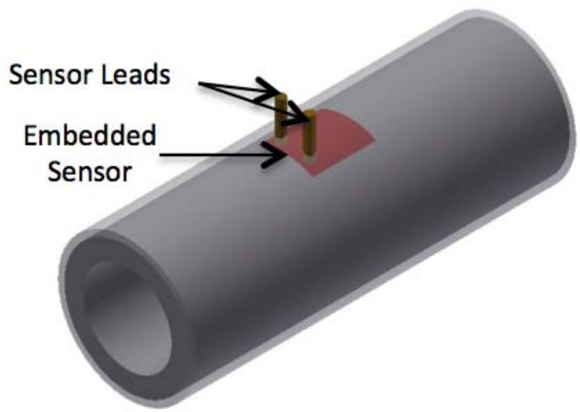




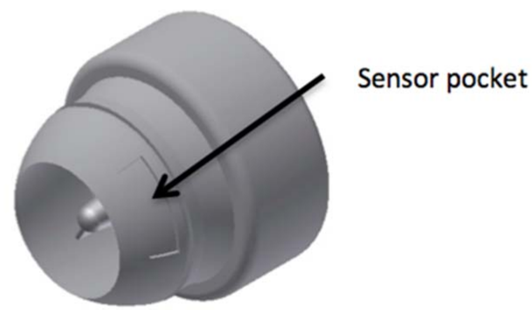


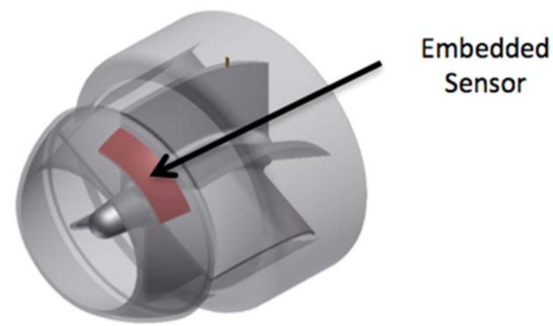


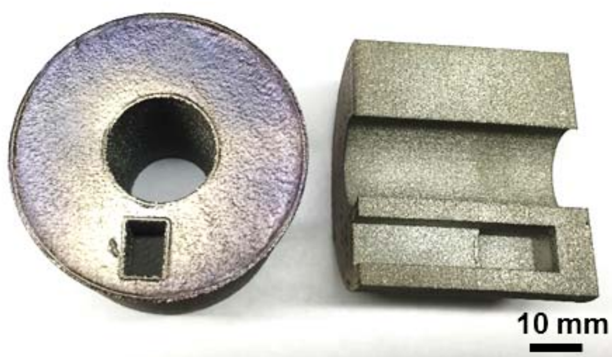
Future Work



Smart tube with embedded sensor







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- Program Manager: Maria Reidpath

     

Thank you

Questions?