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


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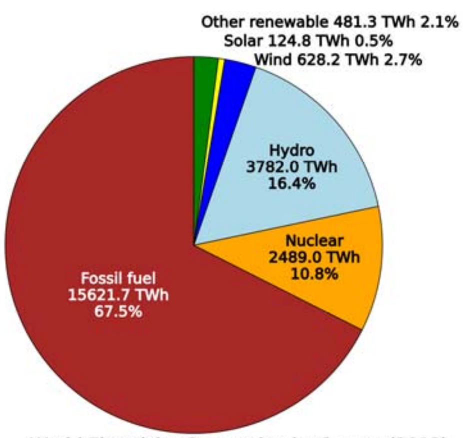
# Agenda

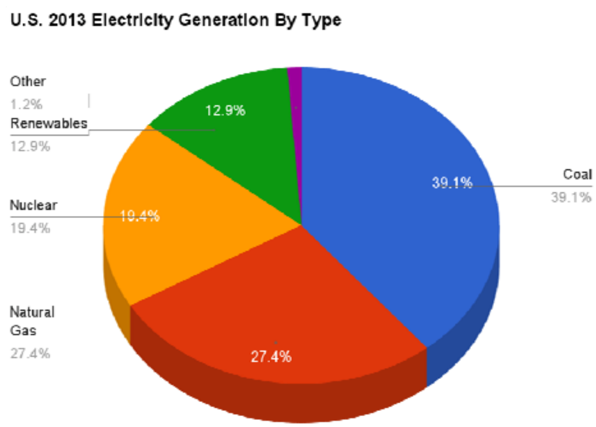
- Introduction and Background
- Objectives
- Technical Approach
- Results
- Summary
- Future Work

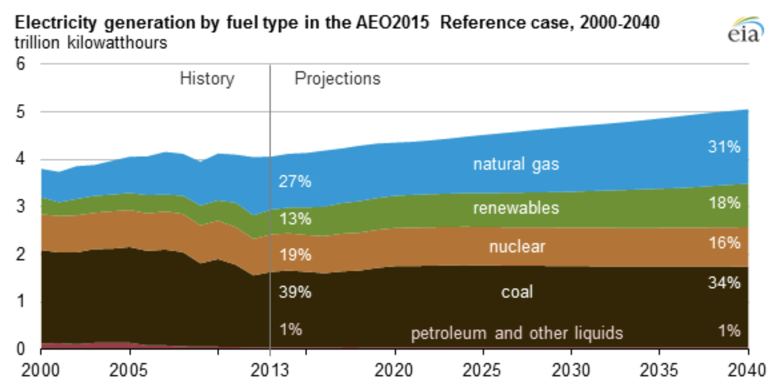
# Motivation

- 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

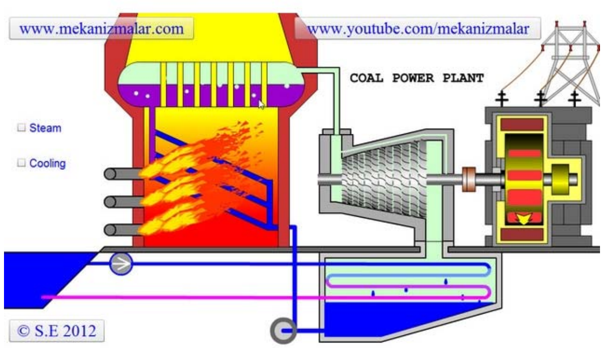
- Harsh high temperature conditions are common to the efficient conversion of fuels and processes for environmental control
- Monitoring/estimating harsh conditions in real time is needed for high system performance and assessing reliability

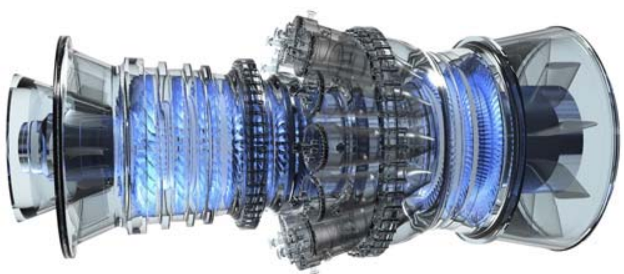
**Gasifiers**

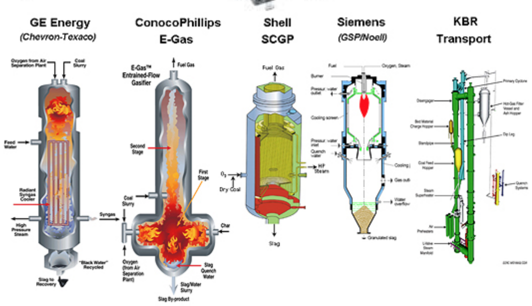
- Up to 1600°C
- Up to 1000 PSI
- Erosive, corrosive, highly reducing

**Combustion Turbines**

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



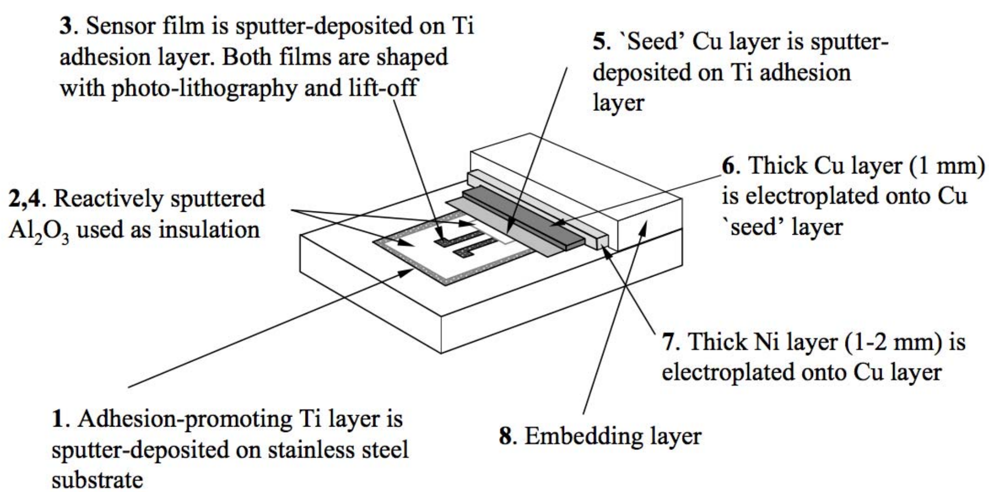





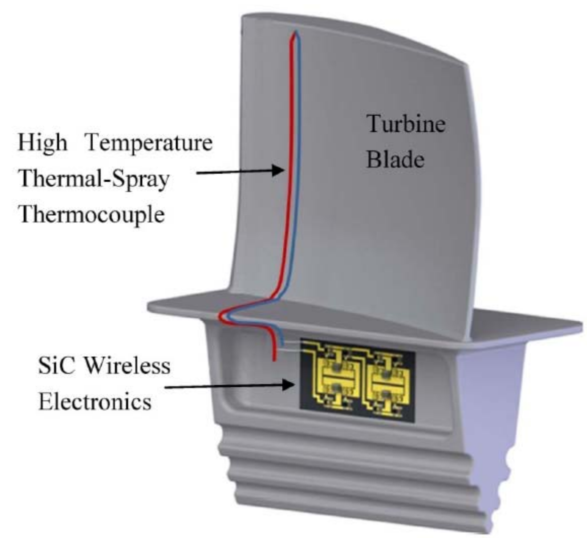

Robert Romanosky, 2013, DOE NETL Crosscutting Project Review Meeting

# 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

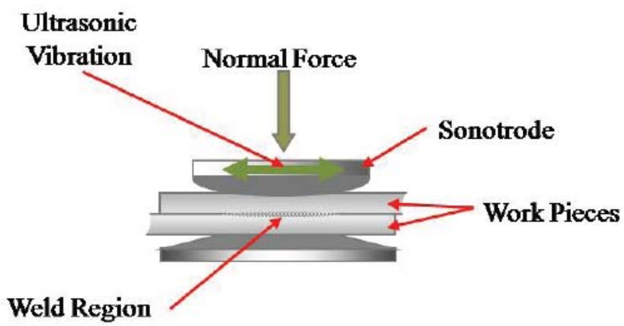



(X. Li, 2001)

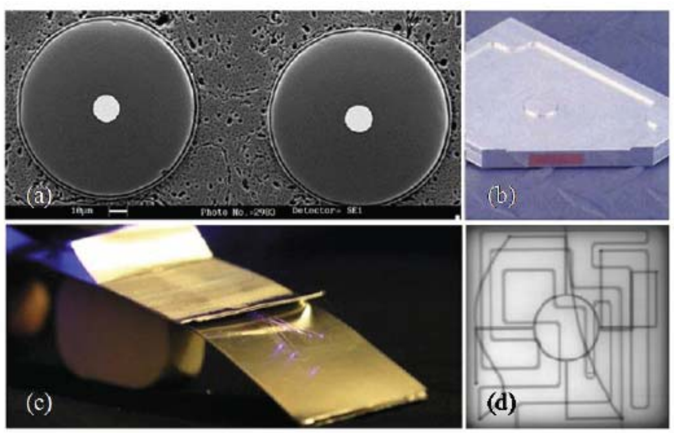


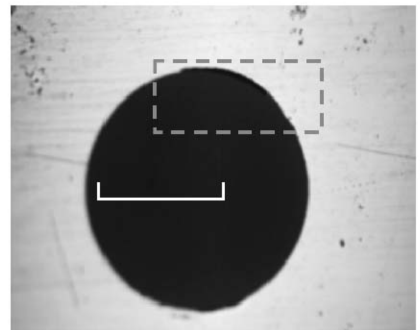

(J. Yang, 2012)

# State-of-the-Art

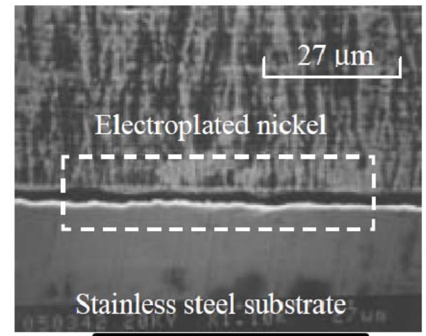



Ultrasonic Operation

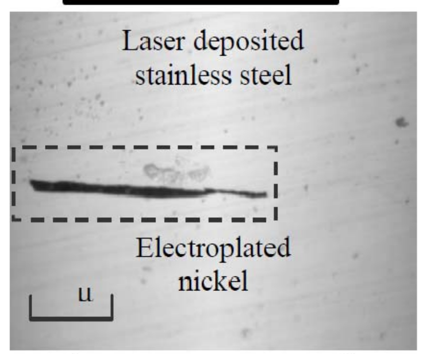


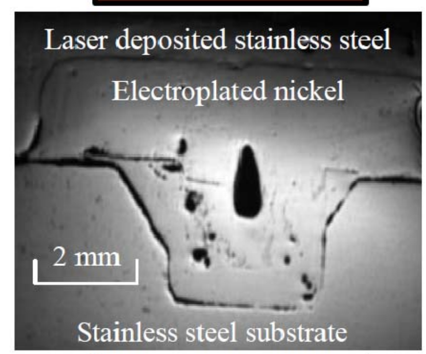
Cracking




Delamination




Cracking

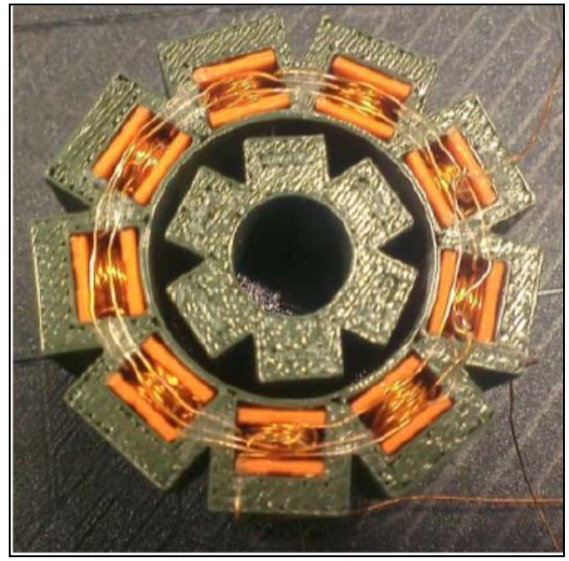



Delamination

Hahnlen, R. M. (2009). Development and characterization of NiTi joining methods and metal matrix composite transducers with embedded NiTi by ultrasonic consolidation (Doctoral dissertation, The Ohio State University).

# Overview and Rationale

Multi-material fabrication using EBM [1]

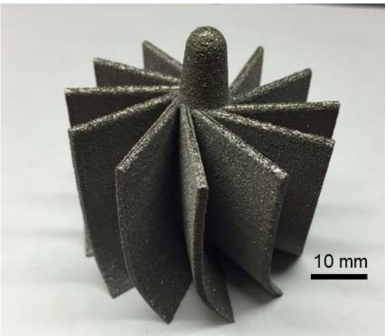


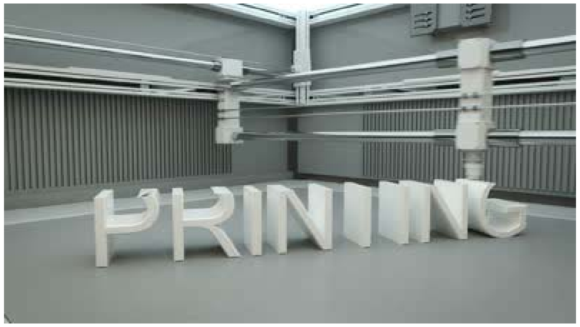
Fabrication of electro-mechanical system [2]

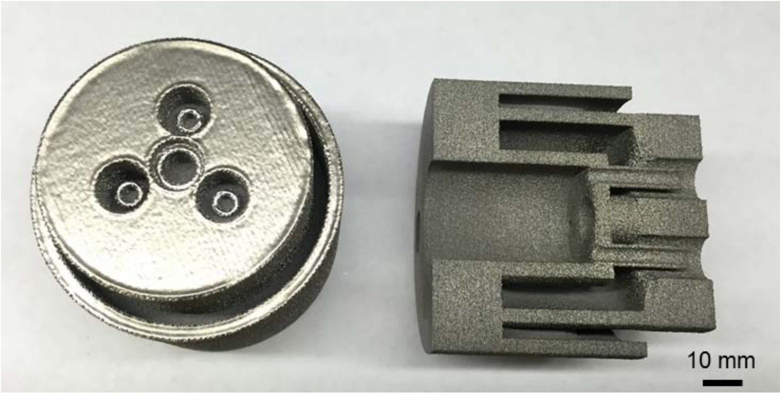
1. C. A. Terrazas,S. M. Gaytan, E. Rodriguez, D. Espalin, L.E. Murr,F. Medina, and R. B. Wicker, " Multi-material metallic structure fabrication using electron beam melting", Int J Adv Manuf Technol, Vol 71, Issue 1-4, pp 33-45, 2014
2. E. Aguilera, J. Ramos, D. Espalin, F. Cedillos, D. Muse, R. Wicker, and E. MacDonald, " 3D Printing of Electro Mechanical Systems",In: Proceedings of the 2013 Annual International Solid Freeform Fabrication Symposium, Austin, TX, USA

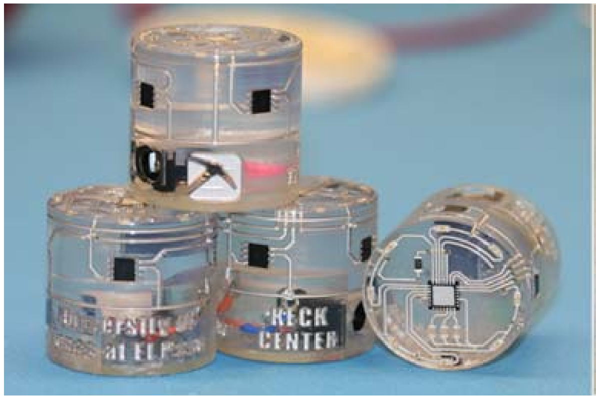
# Overview and Rationale

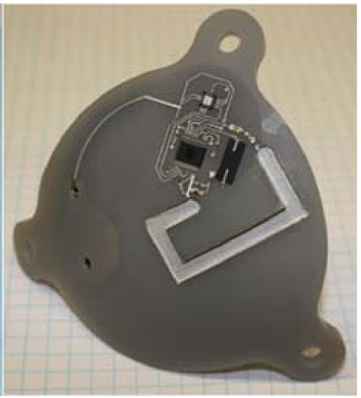
- "Smart parts" with embedded sensor
  - Built-in monitoring capability
  - Accurate sensing at desired location
  - No change required post fabrication
  - Realized by 3D printing technology



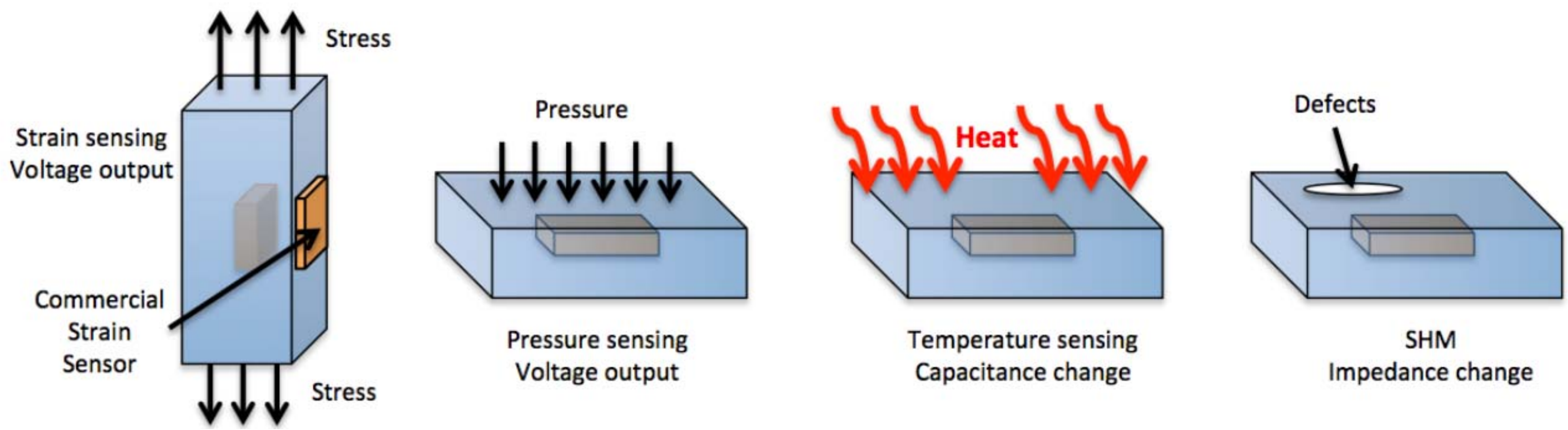


# Scope of Work

- 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".

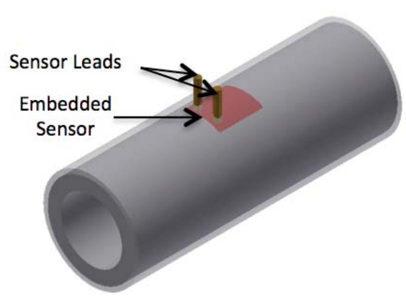


# Objectives

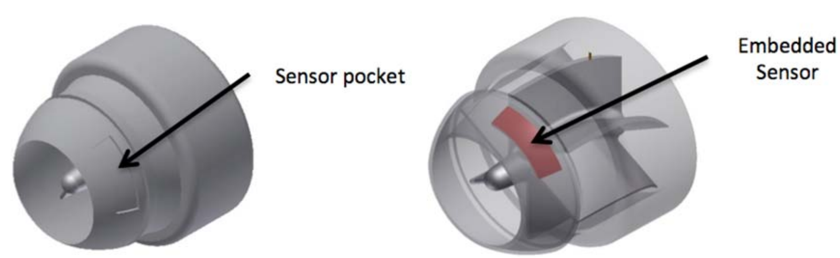
- **Objective 1: Fabricate energy system related components with embedded sensors**
  - Fabrication & evaluation of components without sensor by EBM
  - Manufacturing “Smart Parts” with embedded sensor by EBM

- **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

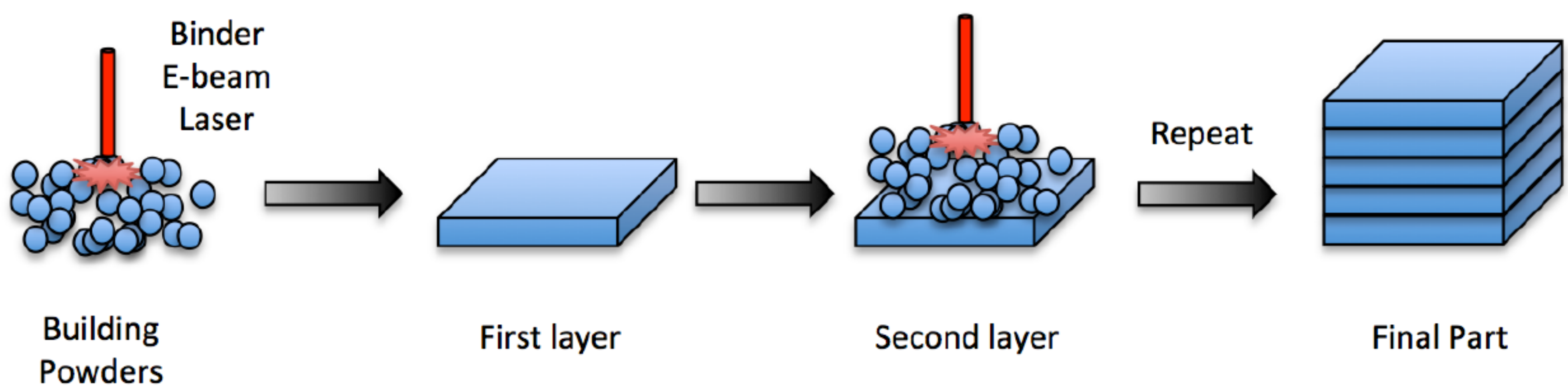



Smart tube with embedded sensor



# Electron Beam Melting

- 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

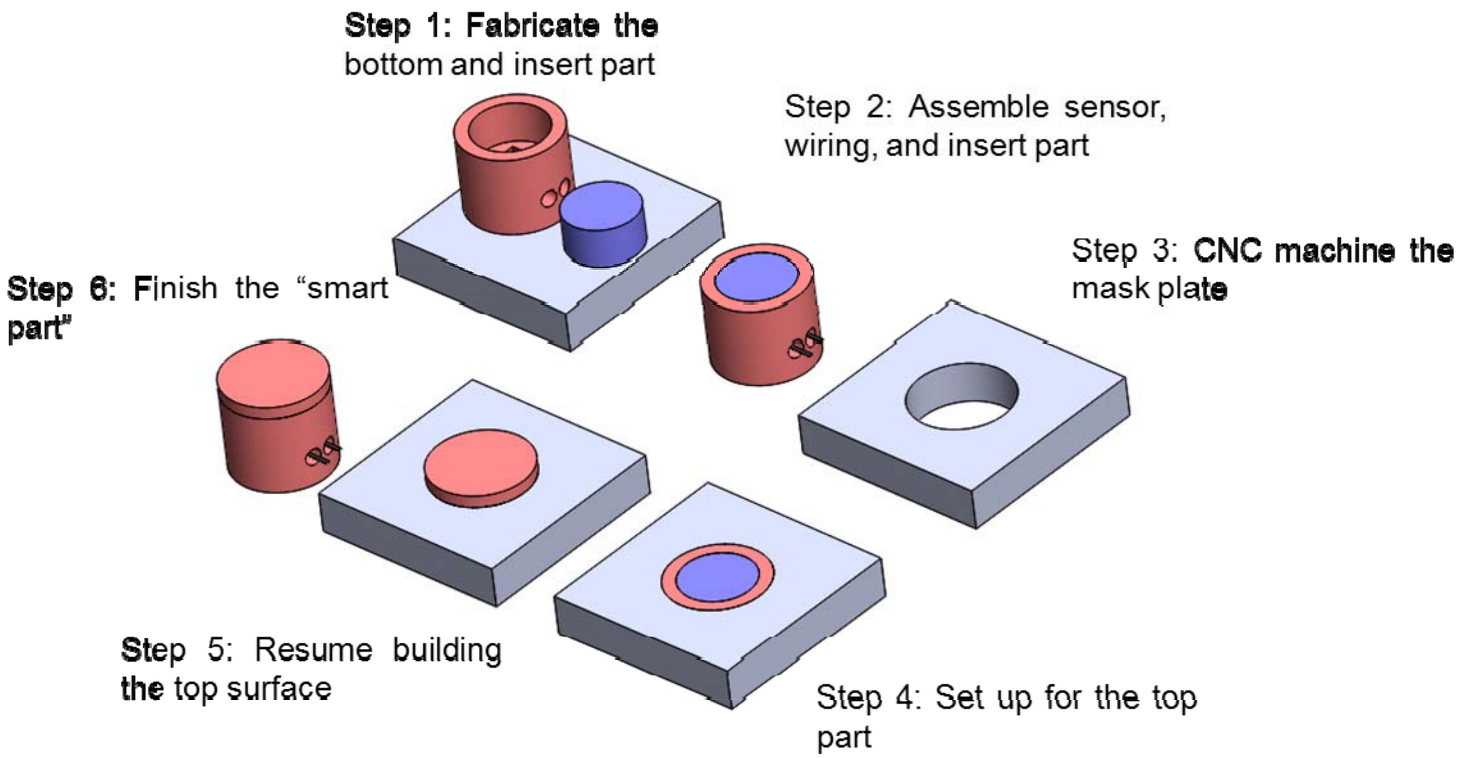


# EBM Animation

by Oakridge National Laboratory

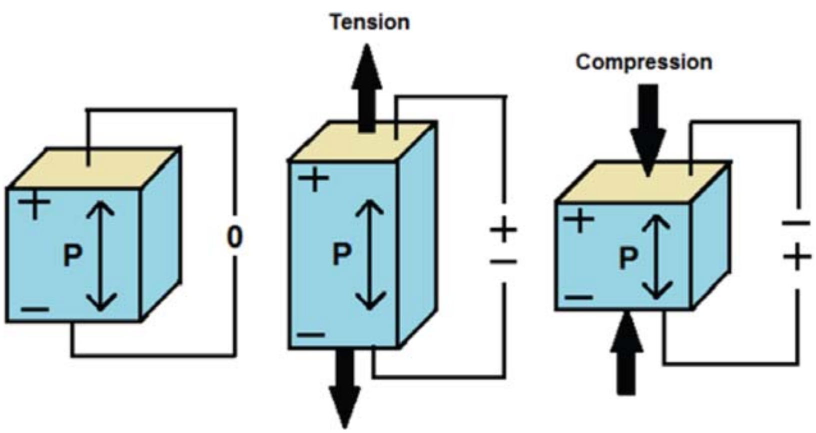
# Design of the Fabrication Process

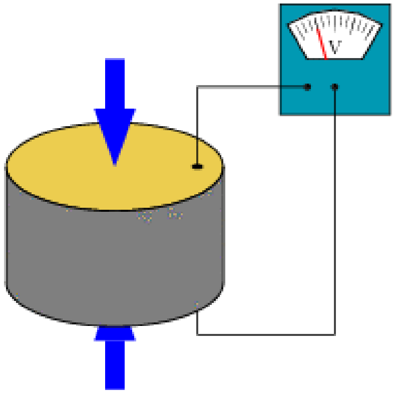
- "Stop and Go" process
- EBM fabricated manually interrupted
- Sensor embedded during fabrication at desired location



# Sensing Materials

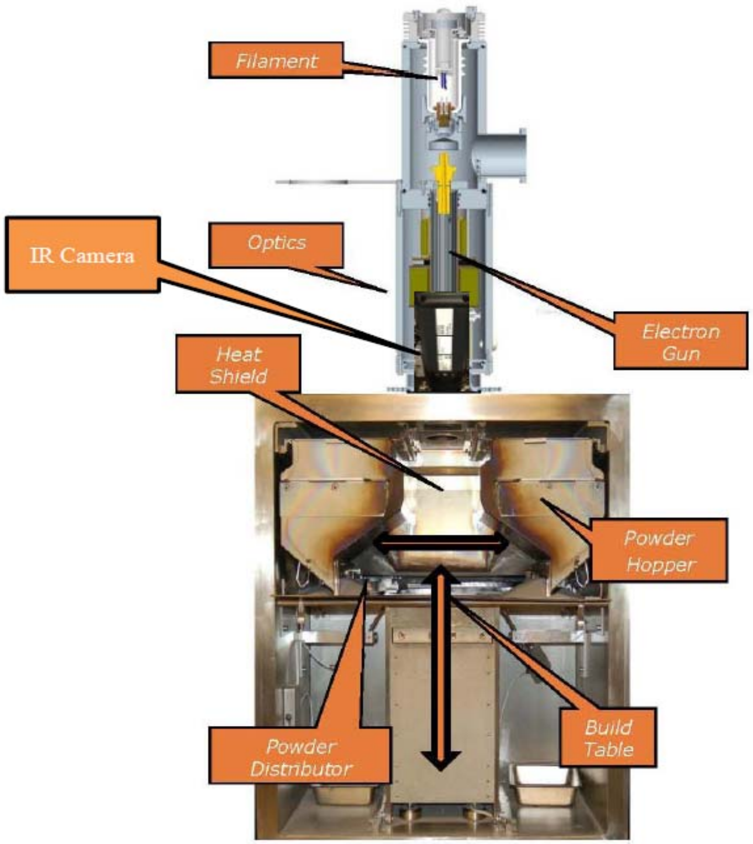
- Piezoceramic for sensing
  - Piezoelectric elements are used in smart systems due their capability of coupling energy in mechanical, thermal, and electrical domain
  - Most of applications rely on relative magnitudes of voltage, or frequency spectrum of signal modified by sensor
  - $Pb(Zr_xTi_{1-x})O_3$, $T_c$ = 350 °C; $LiNbO_3$, $T_c$ = 1200 °C

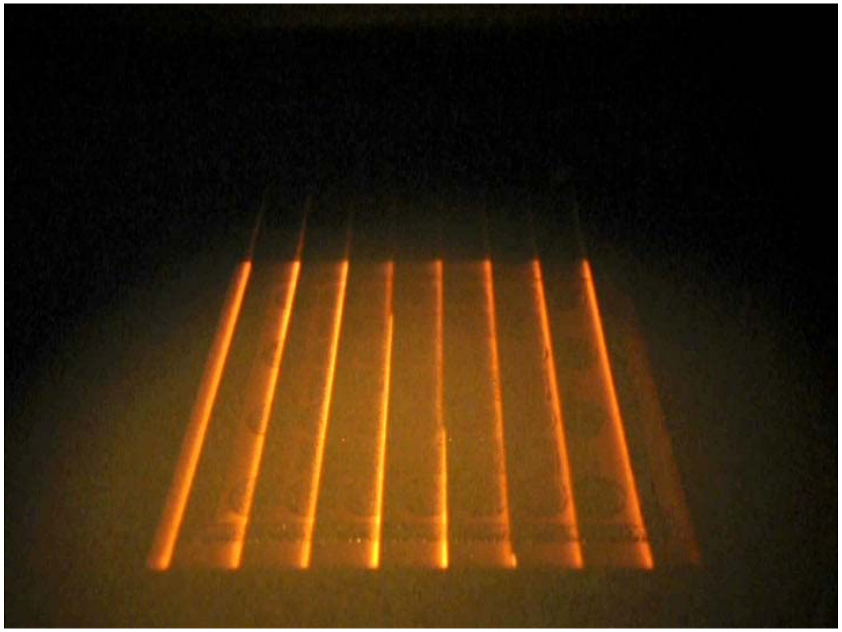


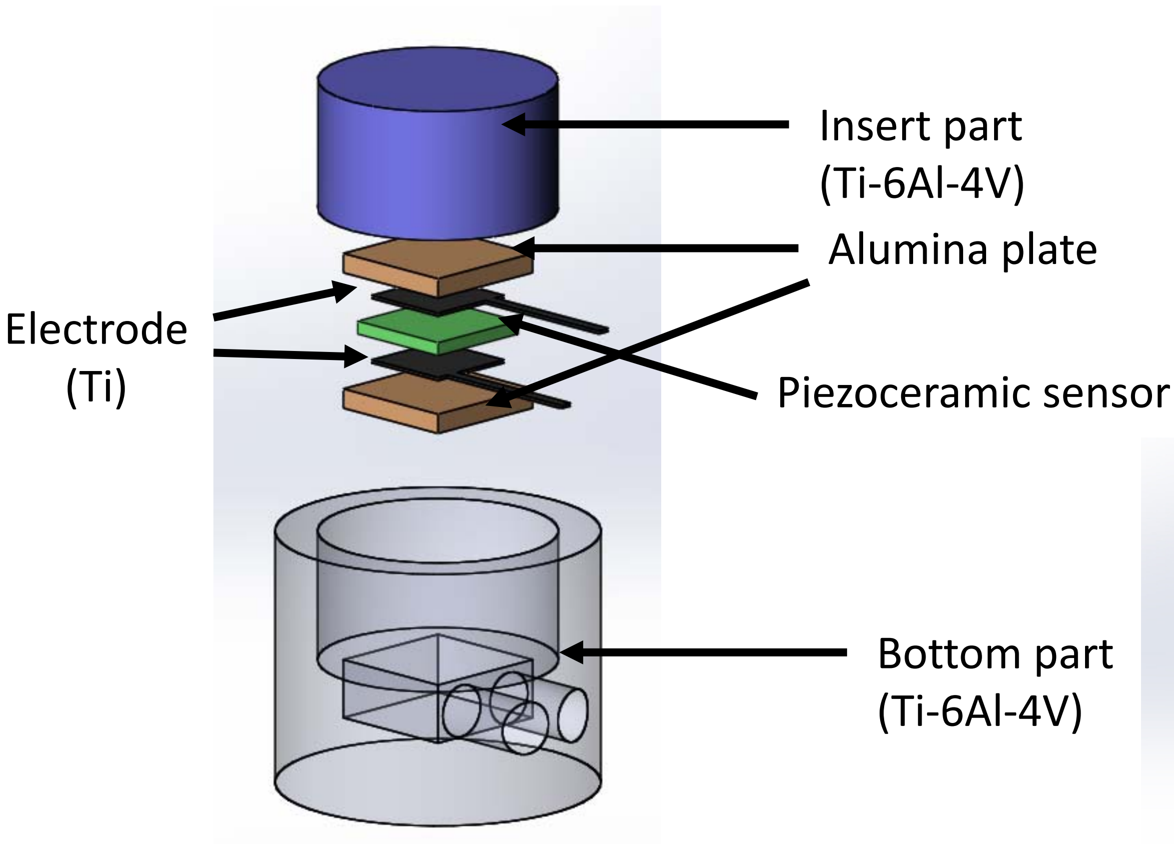
# Fabrication

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

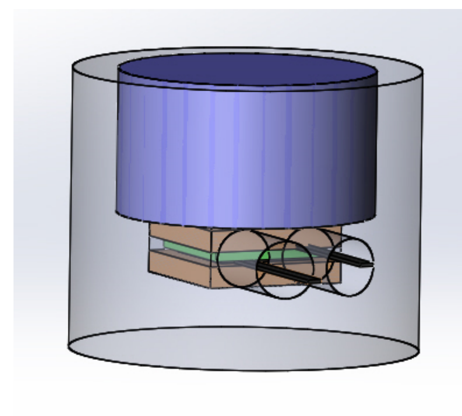


# Design of "Smart parts"



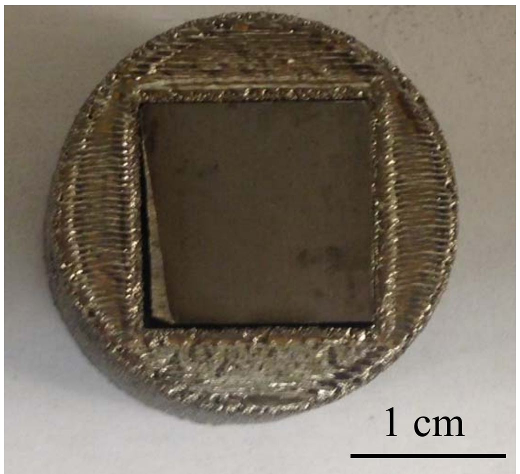

Exploded View



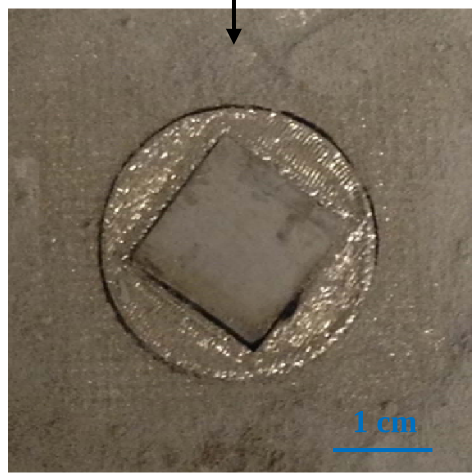
# Fabrication Results

Masking Plate

Misalignment of 435 µm



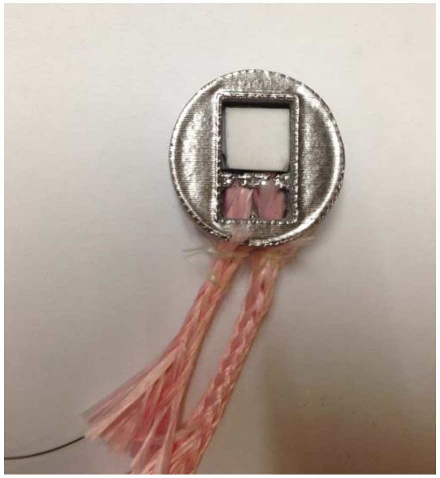

Bottom part




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

Final “smart parts”

# Fabrication of Design A

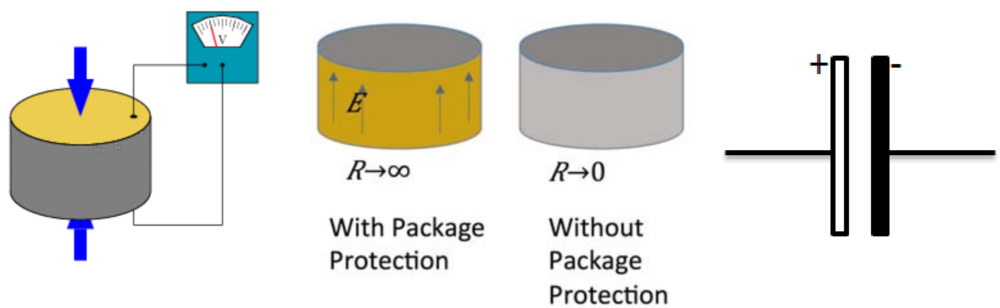


Assemble of parts

After 2nd Fabrication of parts (top view)

After 2nd fabrication of parts (side view)

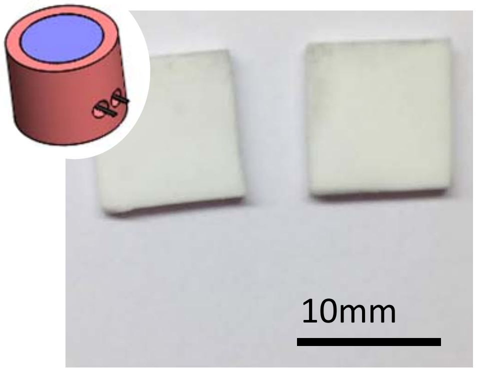
Dissemble of the top parts



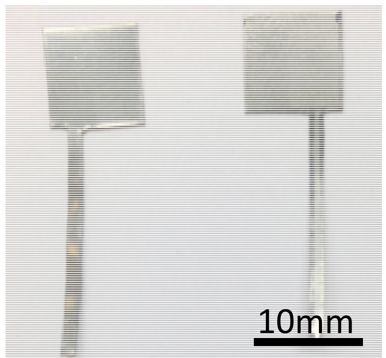
# Characterization

**Before EBM Capping**

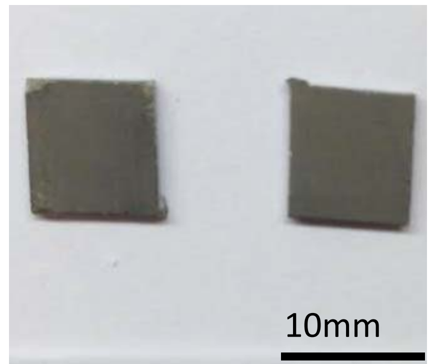
*Alumina Plate*




*Ti Electrodes*

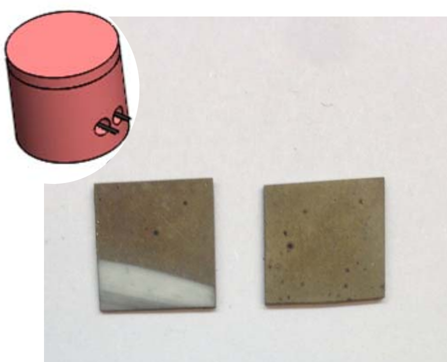


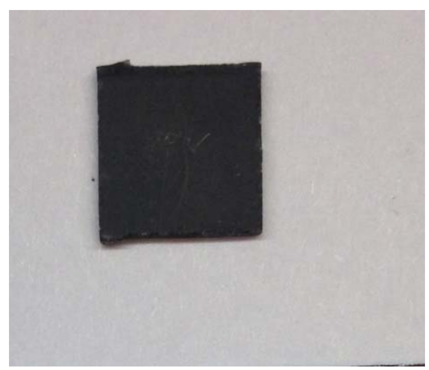

*Ceramic Sensor*



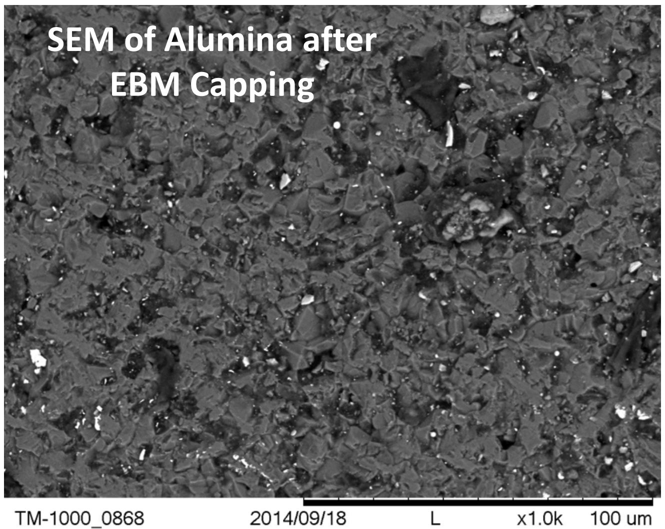

*Alumina Sleeve*

**After EBM Capping**

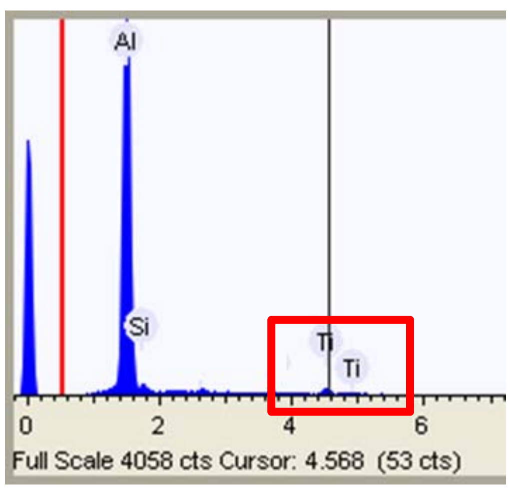




# Metallization



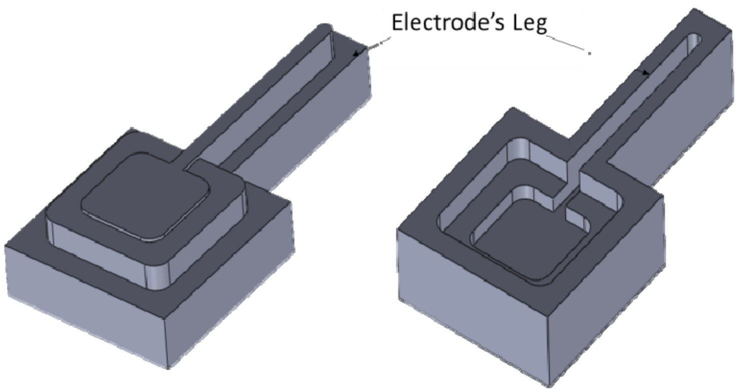

| Element | Weight % |
|---|---|
| Aluminum | 89.3 |
| Oxygen | 6.5 |
| Titanium | 4.2 |

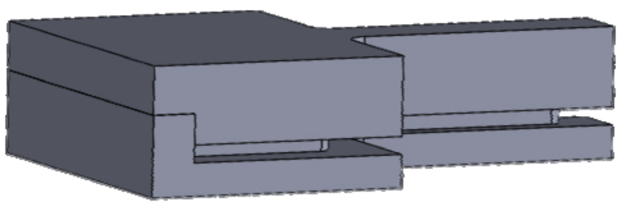


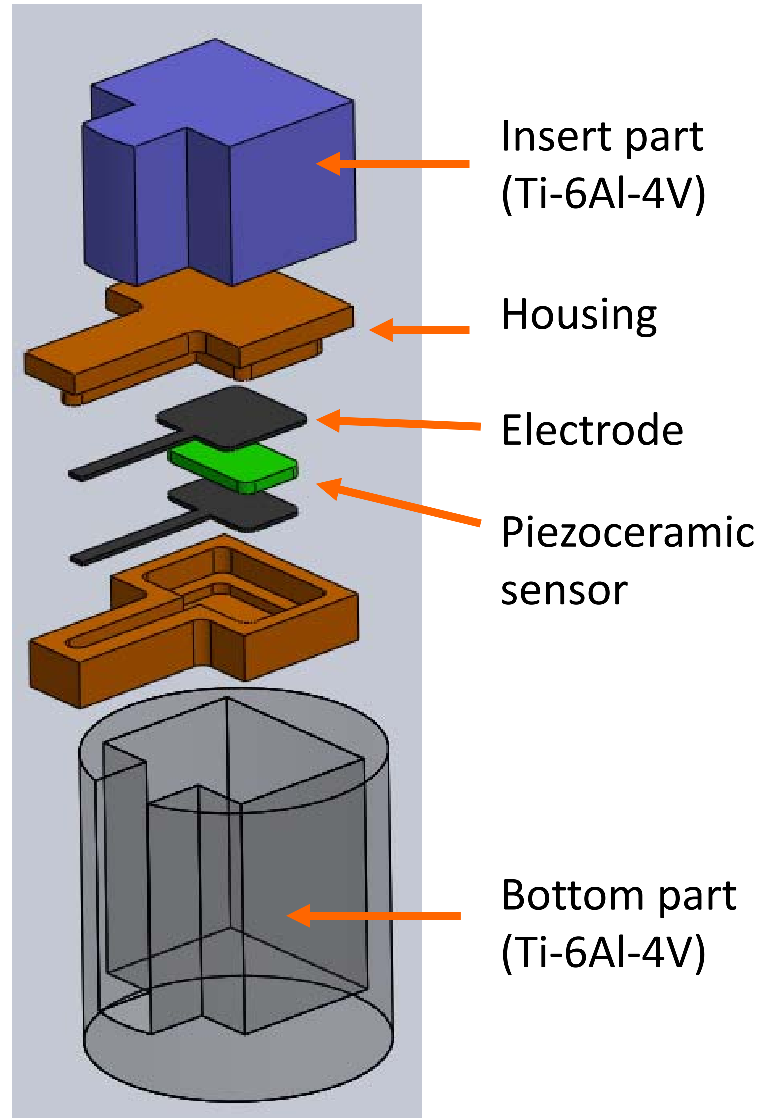

Titanium detected on alumina plate

| 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 |
| | | | | | |

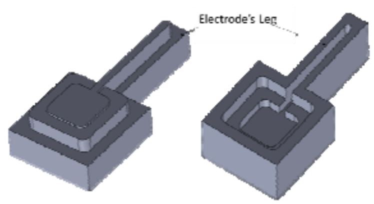
# Sensor Packaging Design



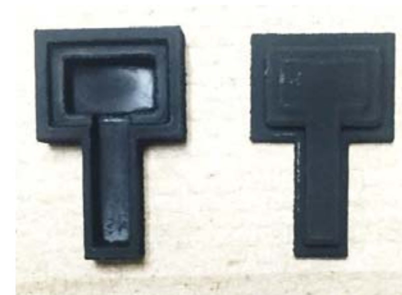



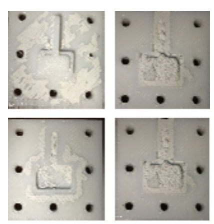


# Sensor Packaging Fabrication









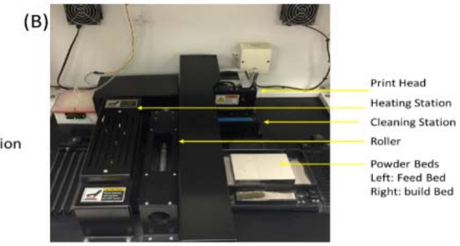
Machinable Alumina

Injection Modeling

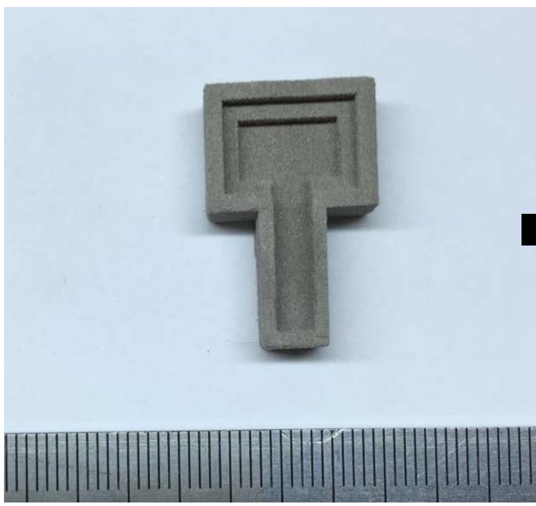
3D printing

3D printing
+
Ceramic spray

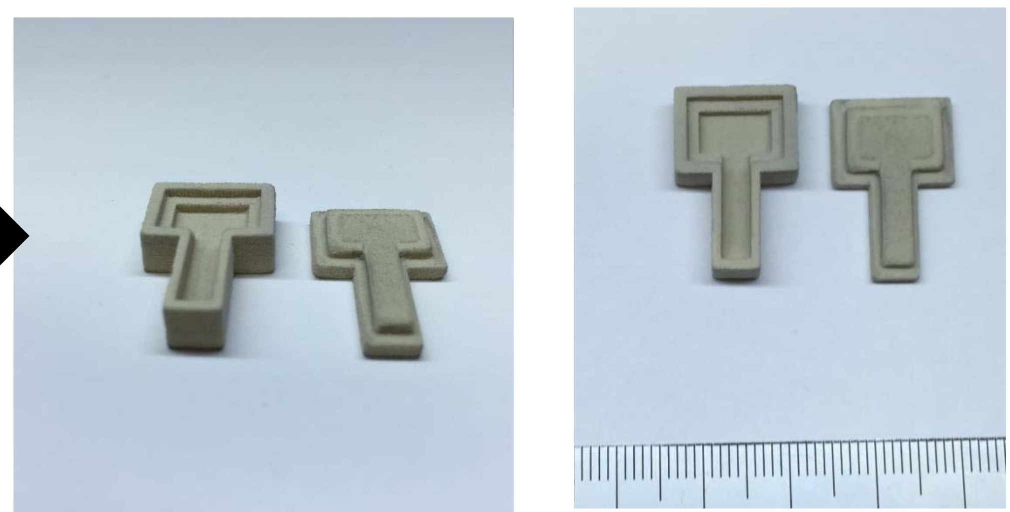
# Alumina Housing by ExOne


Green Body



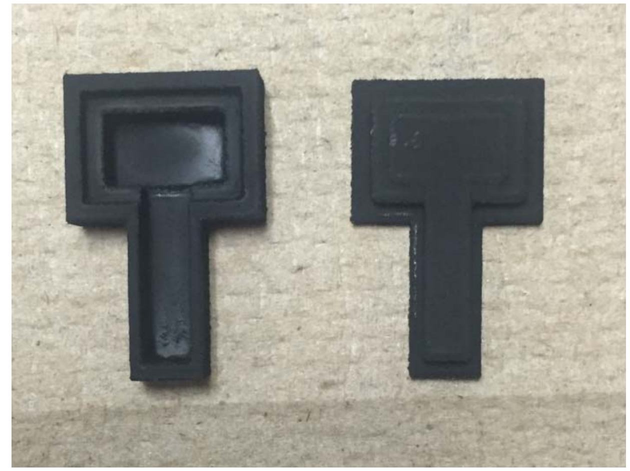
Sintered at 1600˚C for 16hrs



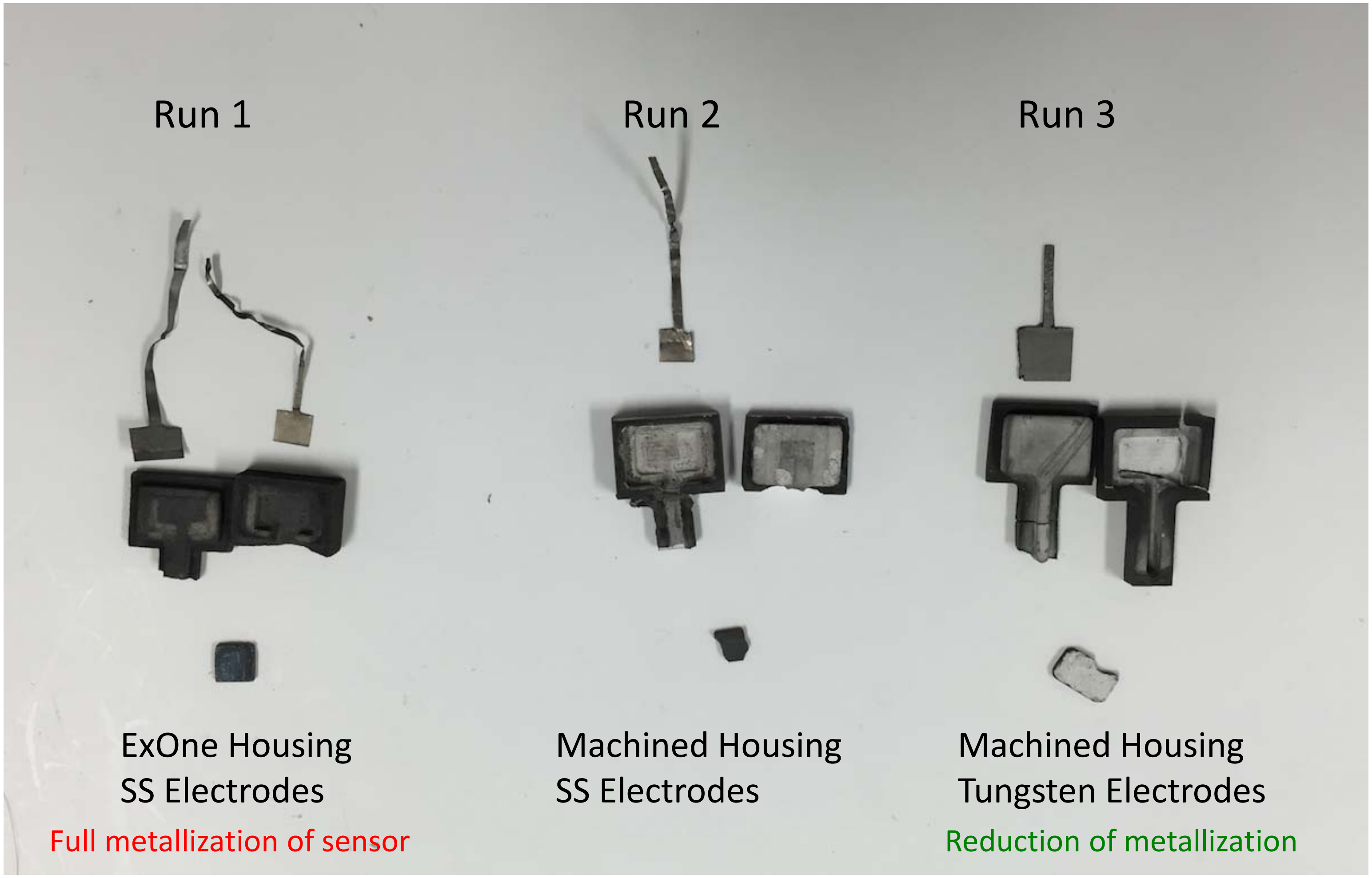
| Particle Size | Layer Thickness | Apparent ρ | % Relative ρ | X% Shinkage | Y% Shrinkage | Z% Shrinkage |
|---|---|---|---|---|---|---|
| Mixed | 45µm | 3.81g/cm3 | 96.51 | 8.75 | 10.92 | 8.63 |

# Ti-6Al-4V Sensor Housing

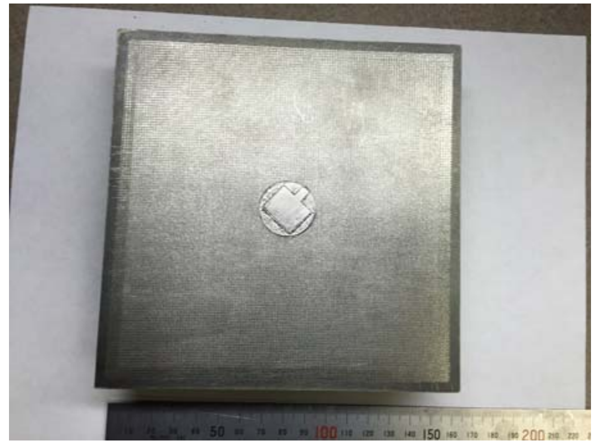
- Ti-6Al-4V sensor housing fabricated by EBM
- $SiO_2$ ceramic coating
- Each applied layered is air dried
- A rougher surface finish was created for better application
- Coating is furnace cured at 650˚C for 30min.
- Coating Still cracked
- Primer needed before



# Successfully Fabricated Smart Parts



# Smart parts Fabrication (1$^{st}$ run)

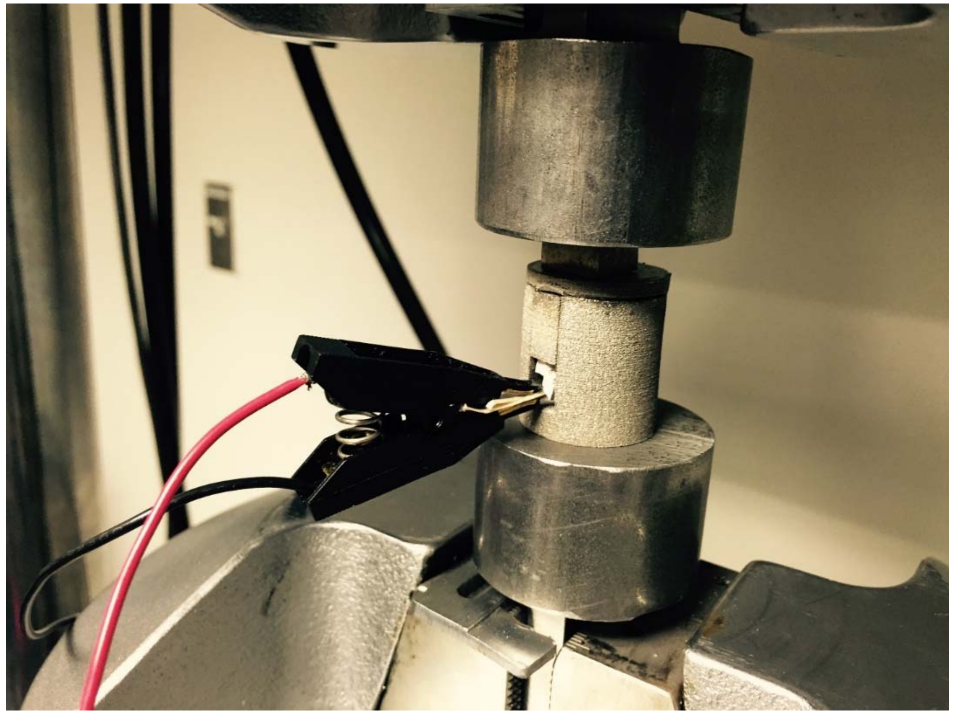



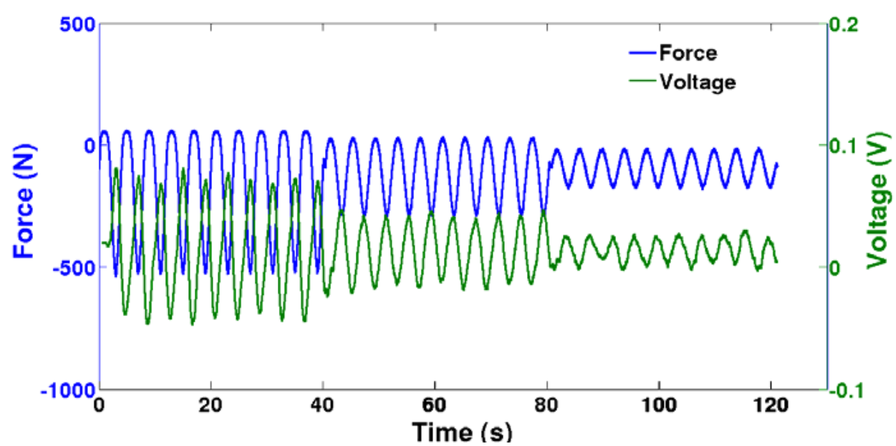
Before Fabrication



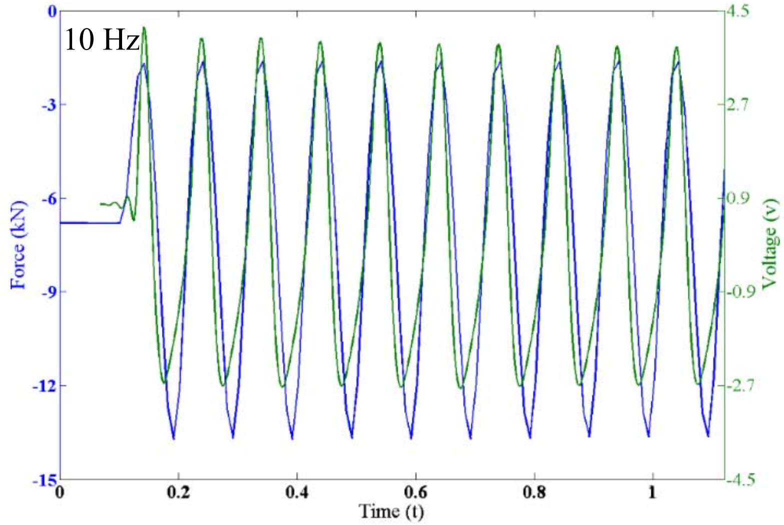

Final Part

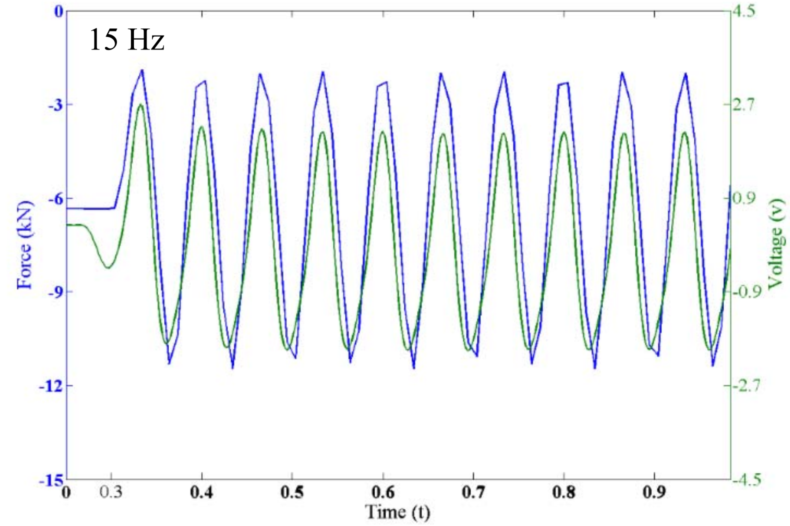
# Force Sensing

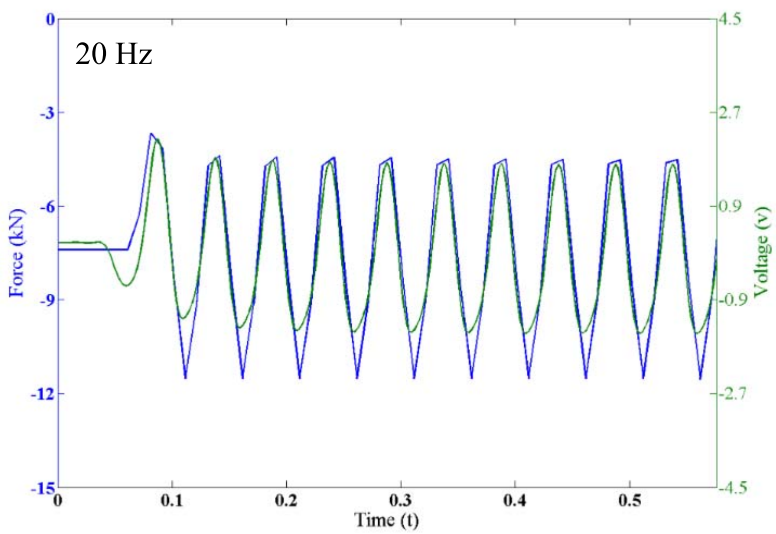


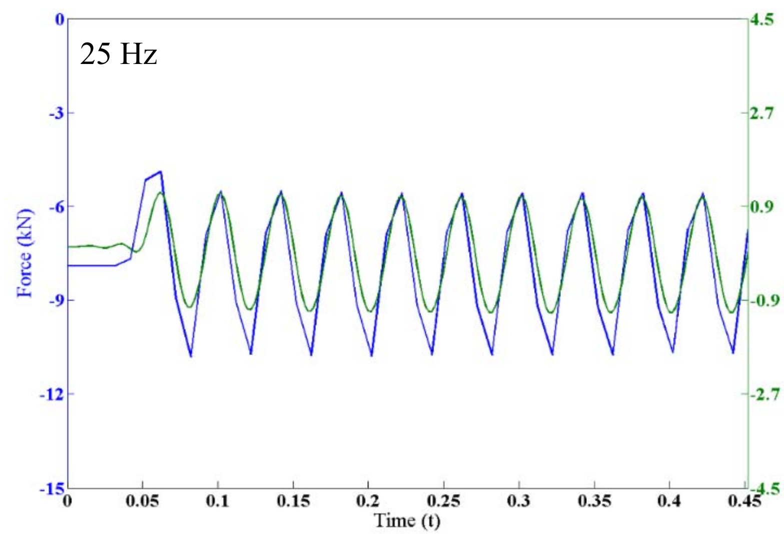


# Compression Force sensing

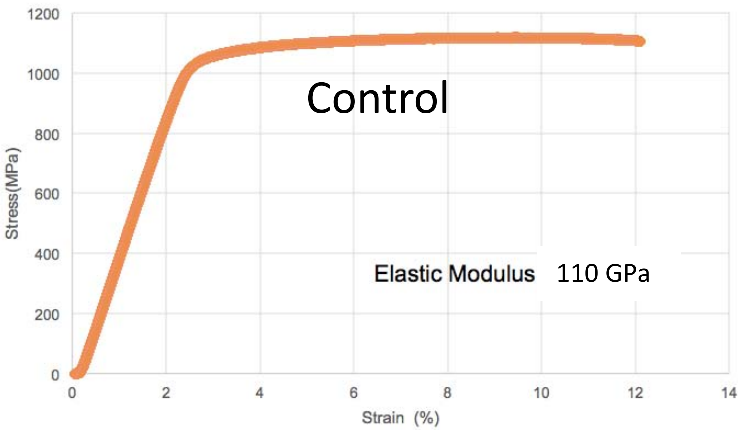


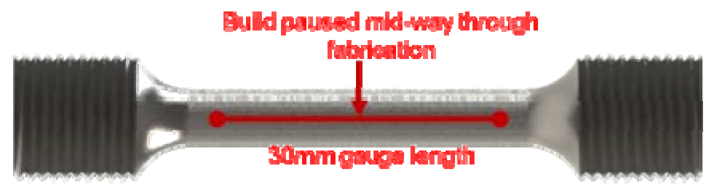



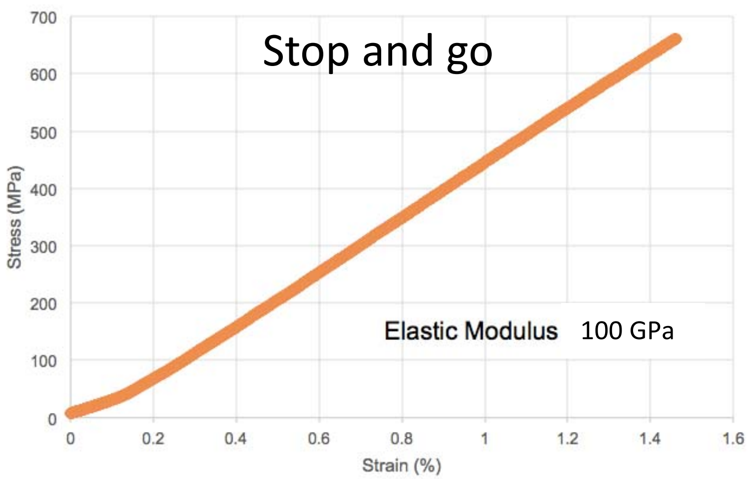



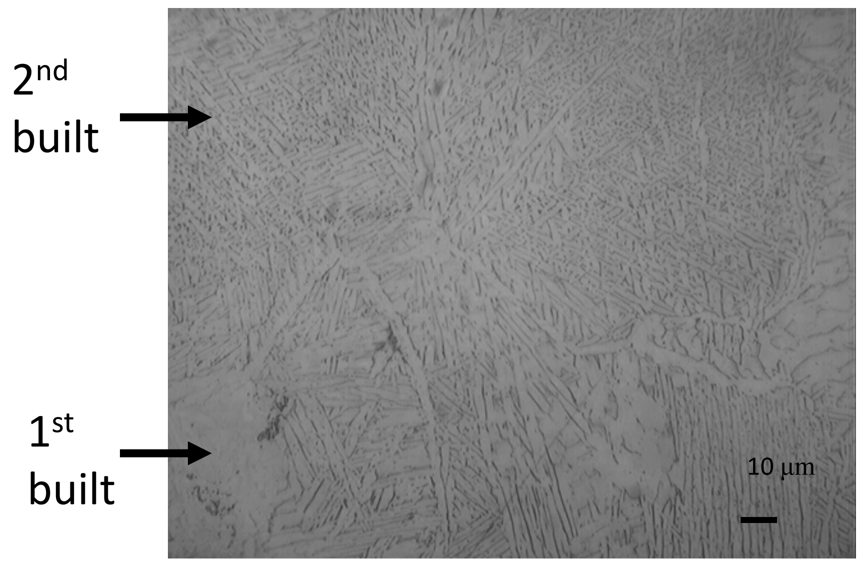



# Mechanical Property Testing

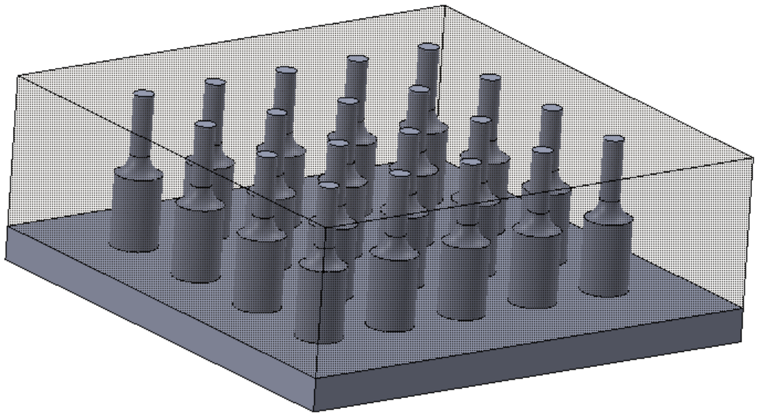


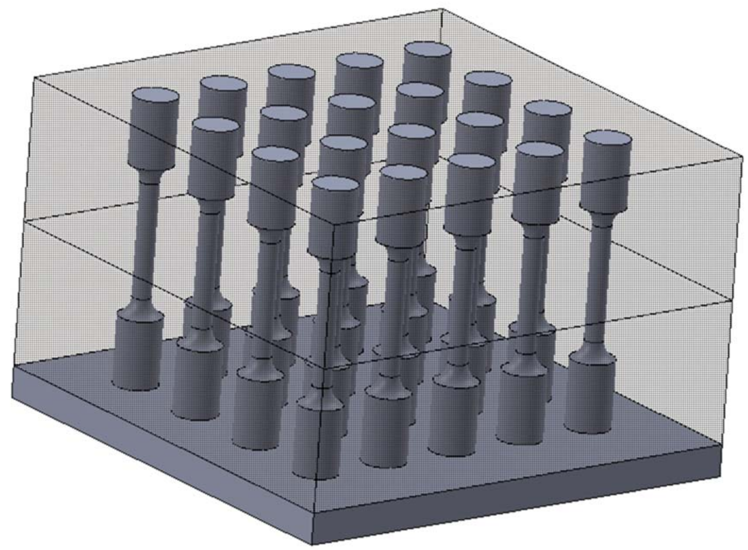



# Interfacial Property Enhancement Experimental Setup



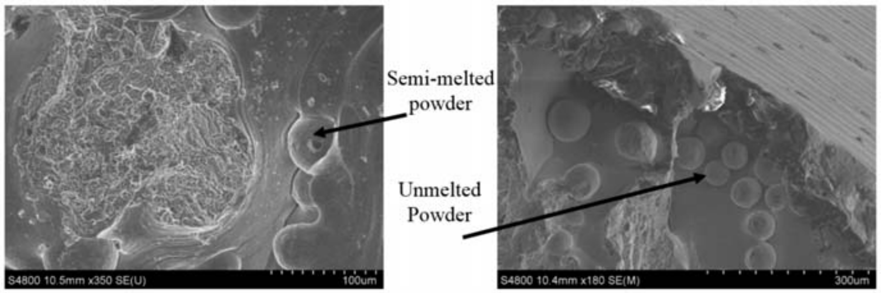
Tensile bars were fabricated to test mechanical properties after interrupting the fabrication process

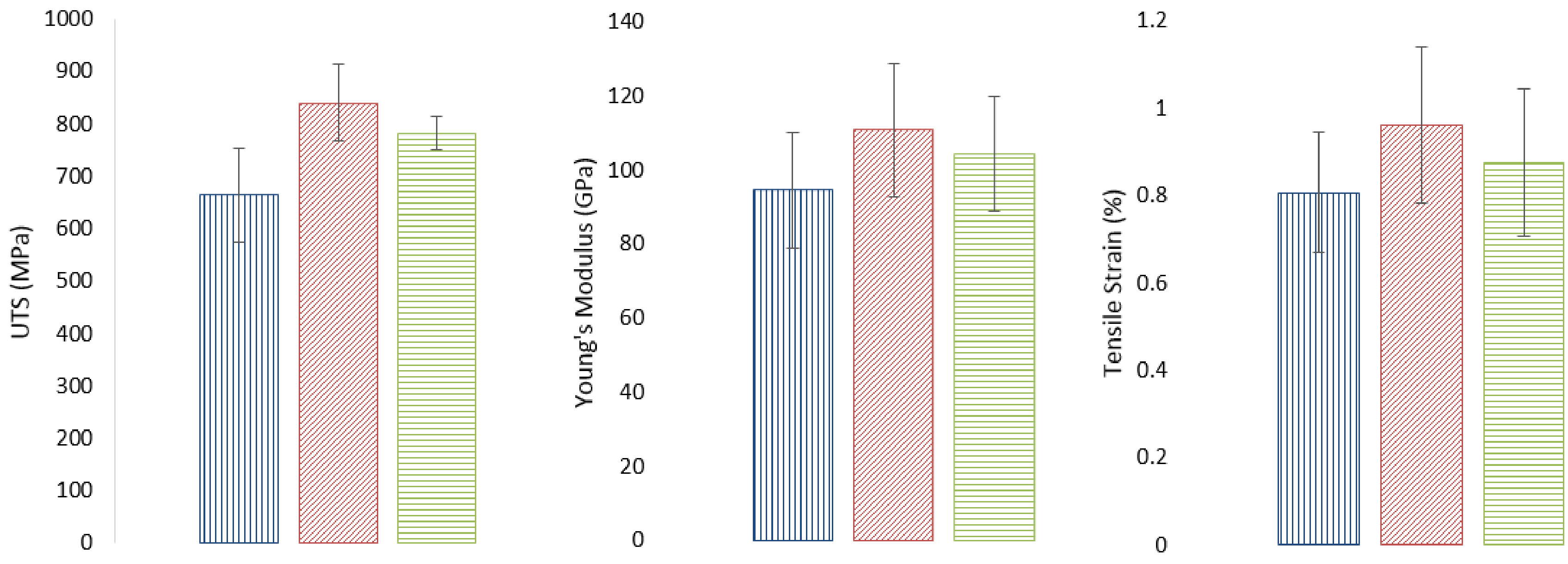


Fabrication was stopped at gauge's midpoint, the machine was allowed to fully cool and the process was restarted to simulation the process of sensor embedding

Fabricated tensile dog-bone samples

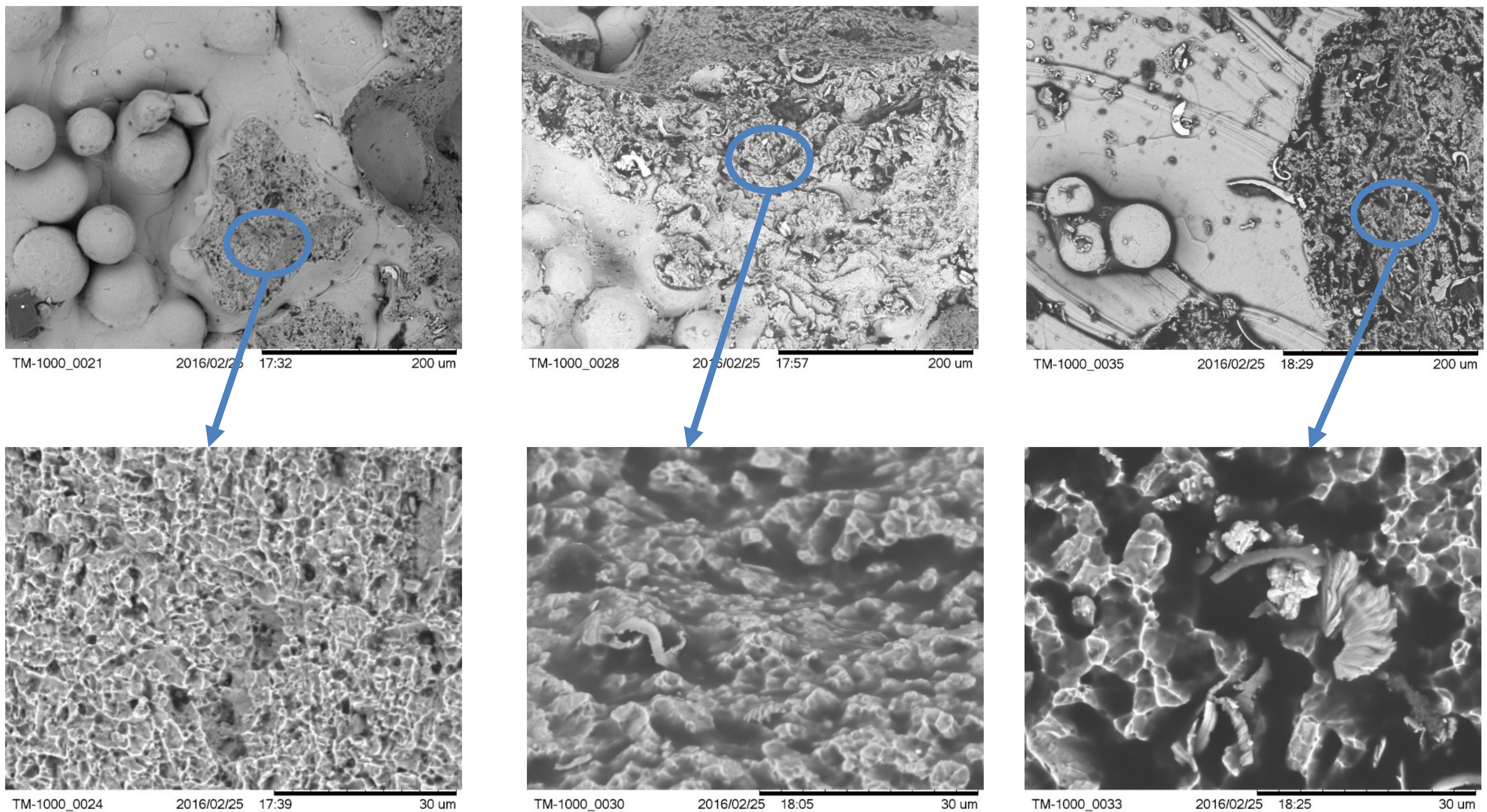
# Interfacial Property Enhancement Testing Results



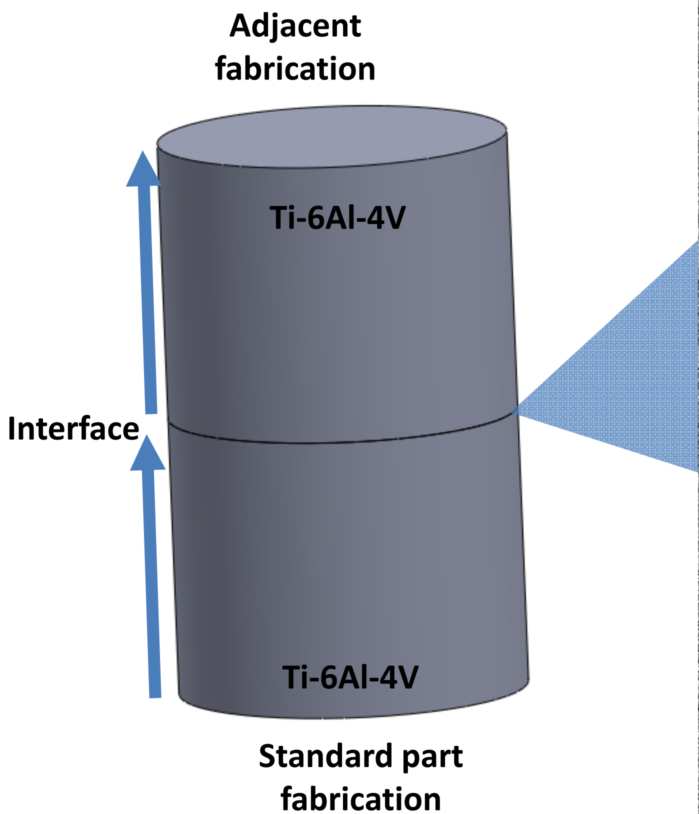



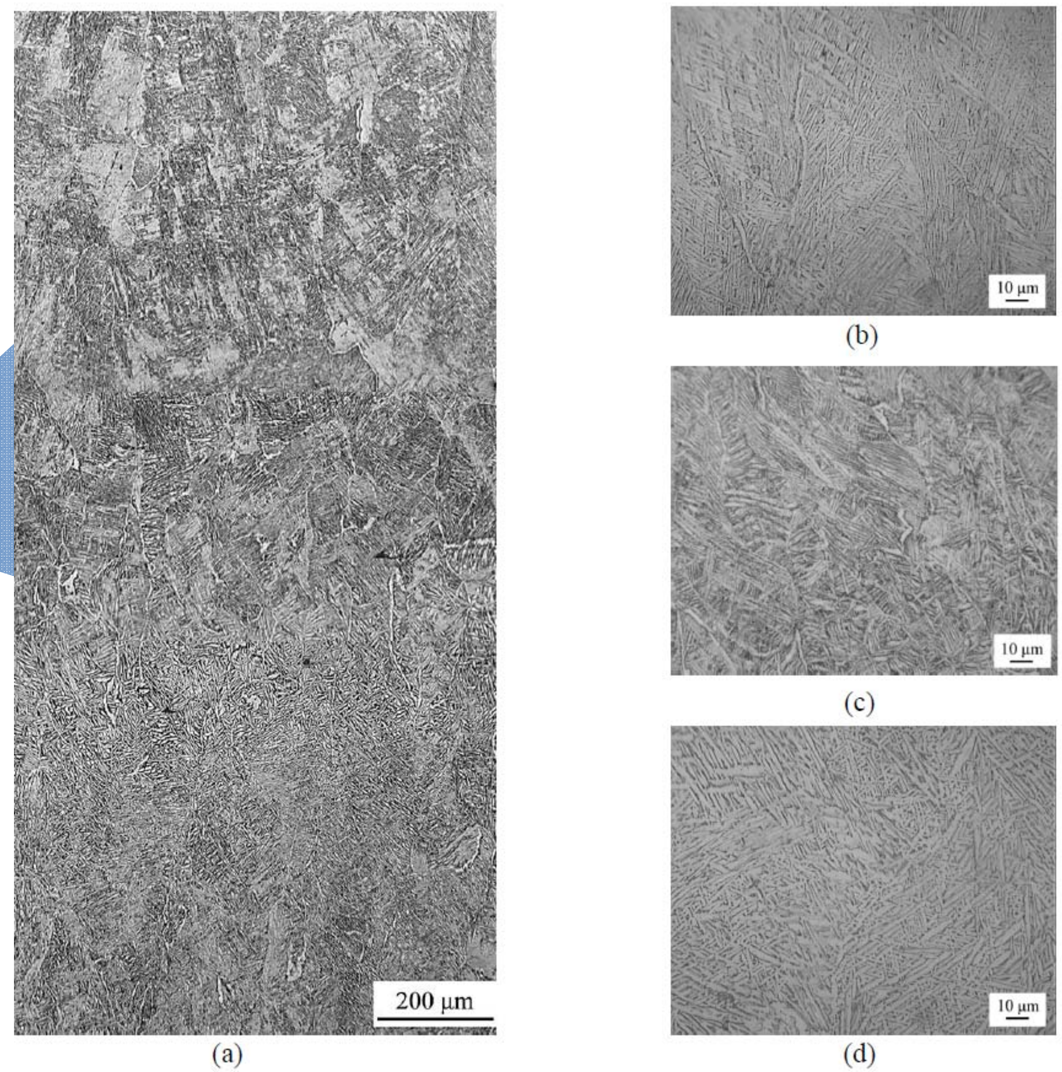
# Fracture Surface

Single Melt | Double Melt | Triple Melt



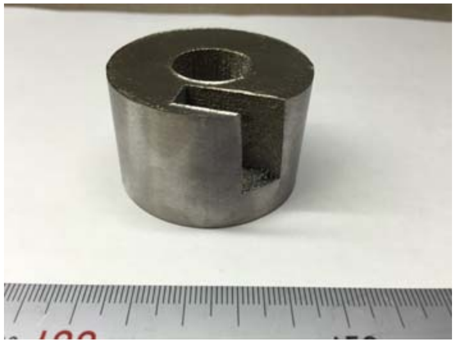
# Joint Microstructure

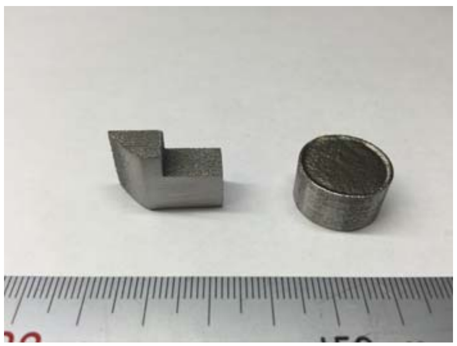


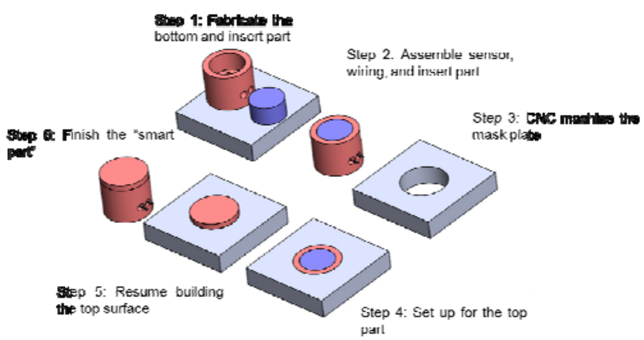




Hossain, M.S., Gonzalez, J.A., Martinez-Hernandez, R., Shuvo, M.A., Mireles, J., Choudhuri, A., Lin, Y., Wicker, R.B., (2016). *Fabrication of smart parts using powder bed fusion additive manufacturing technology*. Journal of Additive Manufacturing,10, pp. 58-66

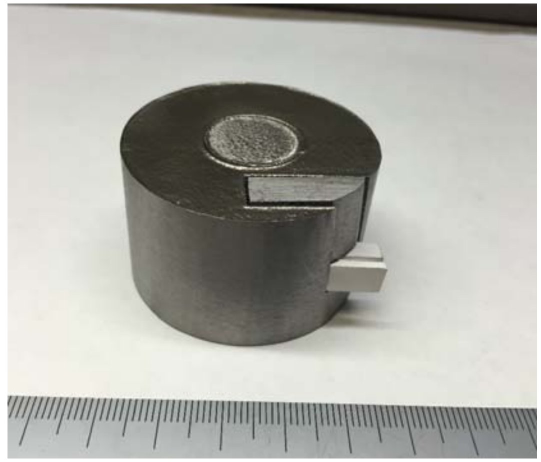
# Smart Tube Fabrication



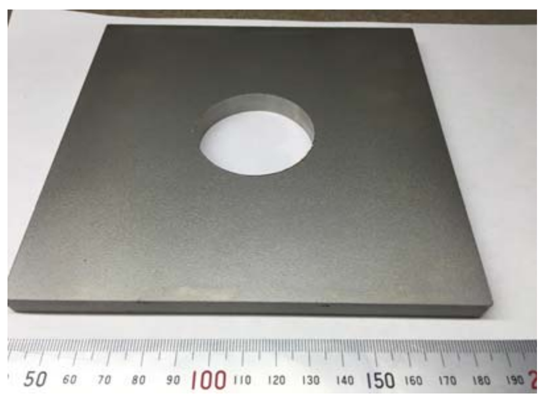








Assembled Bottom Section

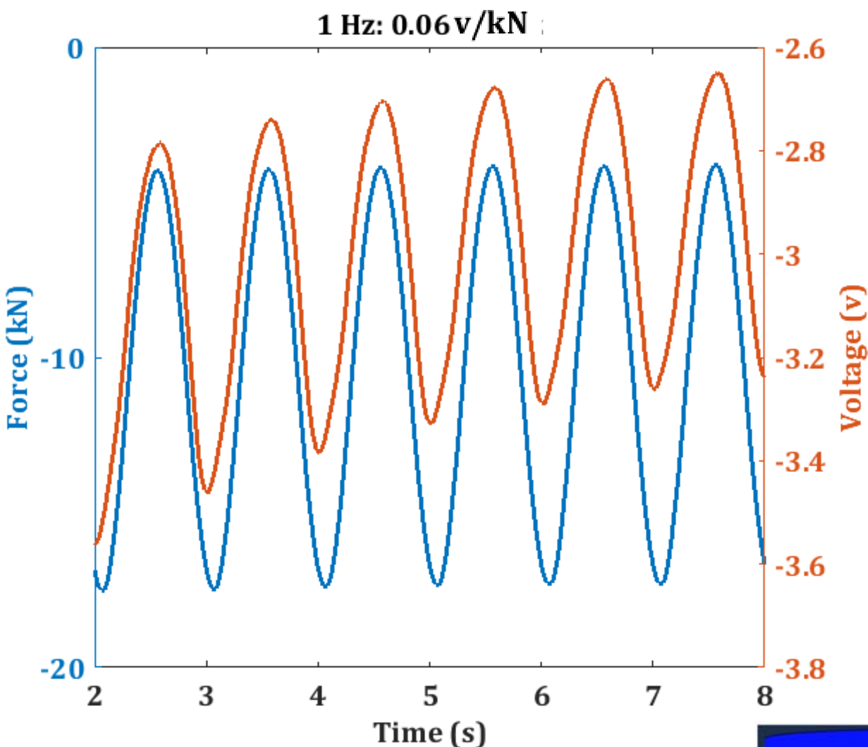


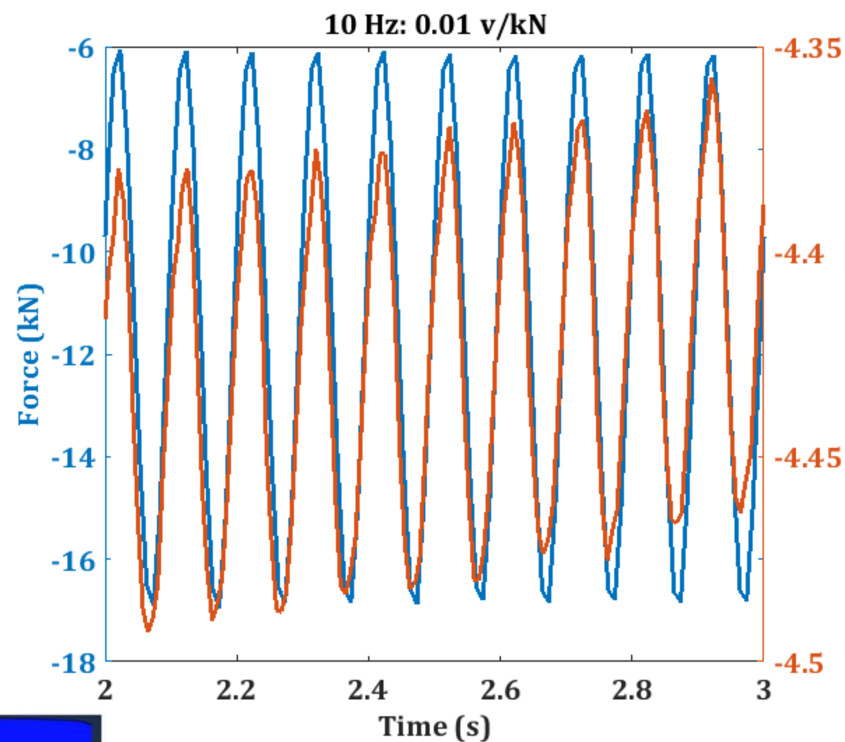
Masking plate

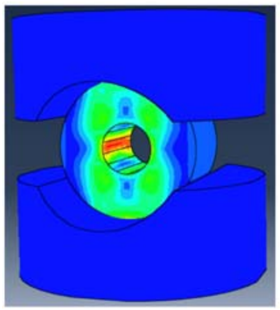
Top View

Side View

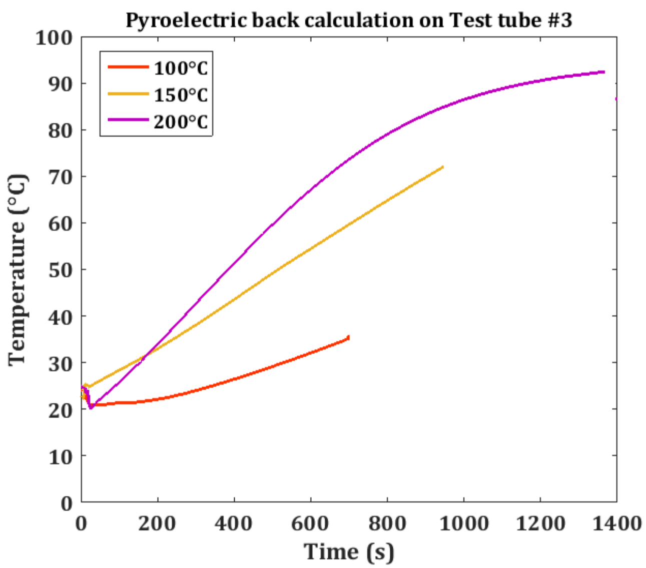
# Smart Tube Force Sensing

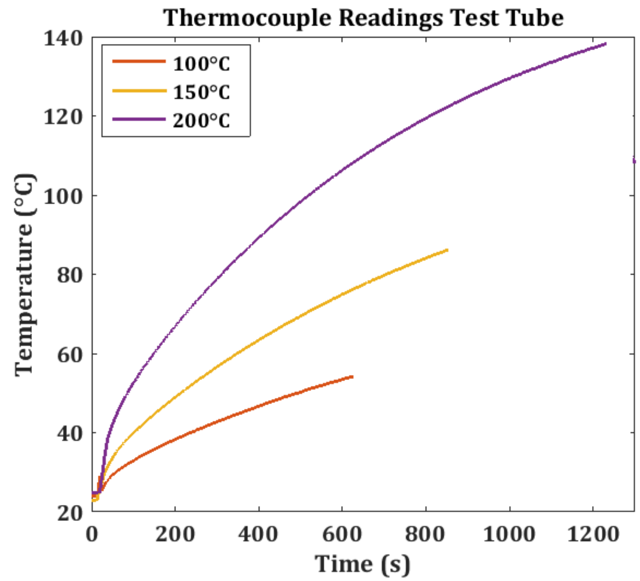


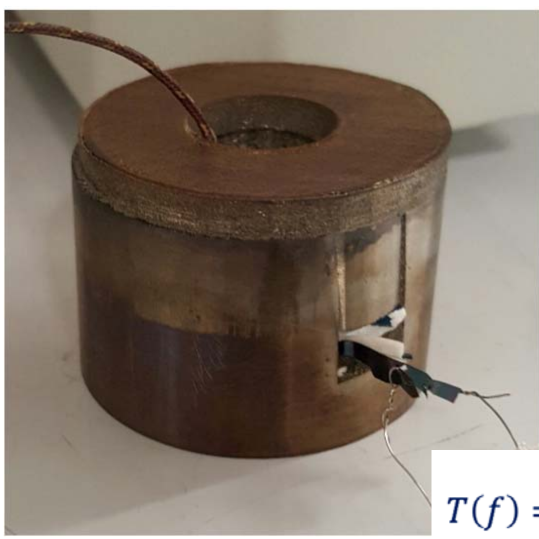



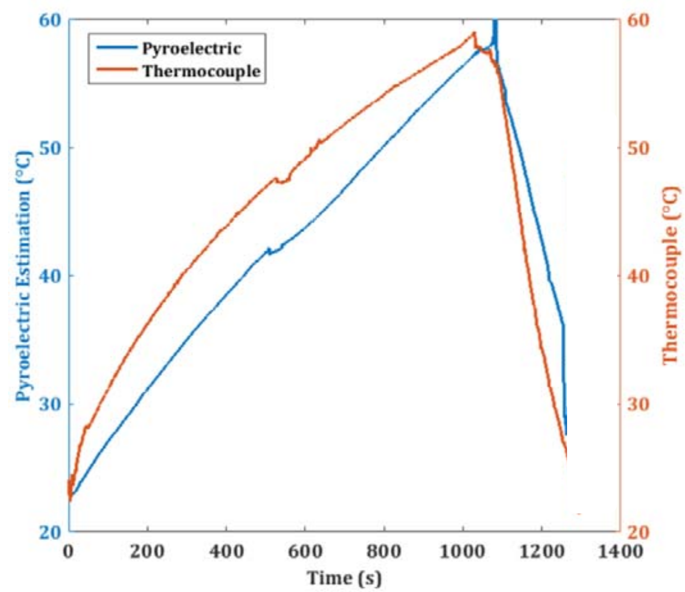
# Temperature Sensing



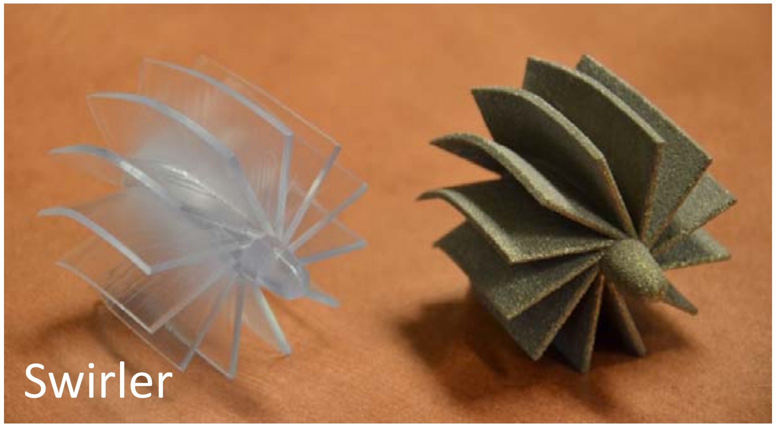



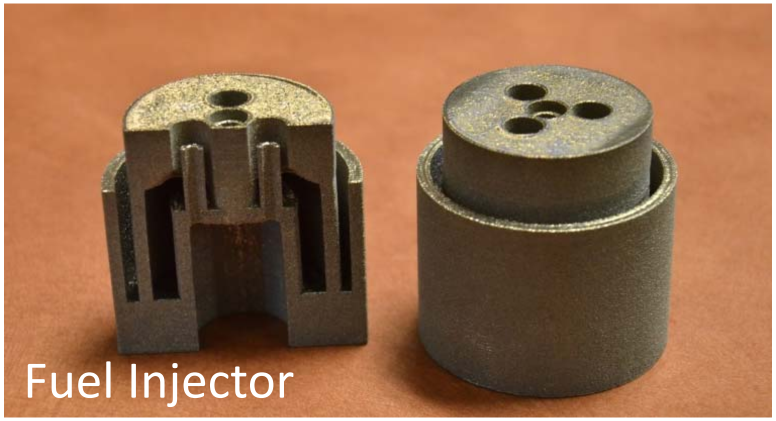



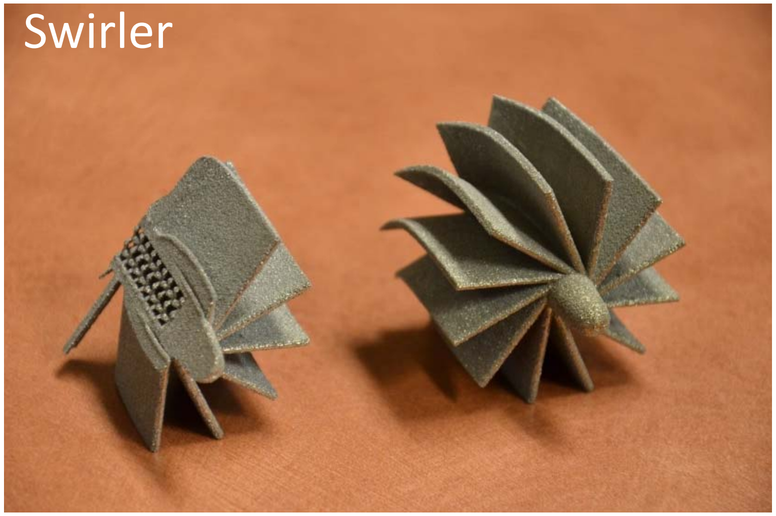
$$T(f) = \frac{1}{pA}\int_{t_o}^{t_f} Idt + T(0)$$

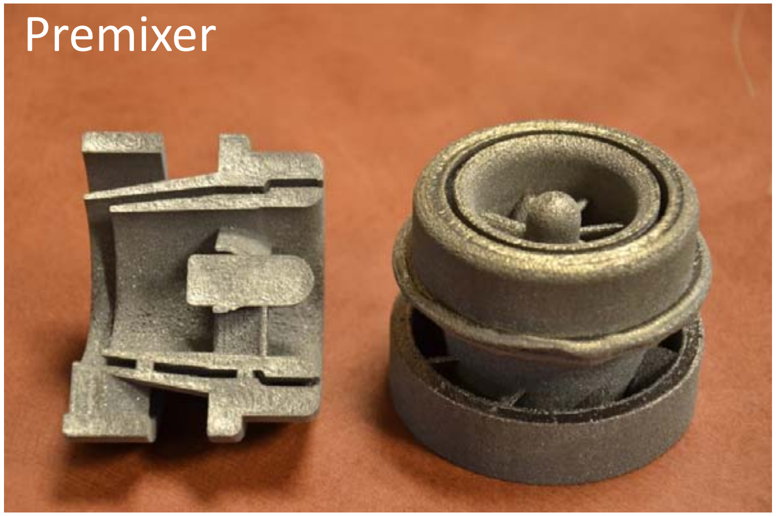


# Ongoing Work



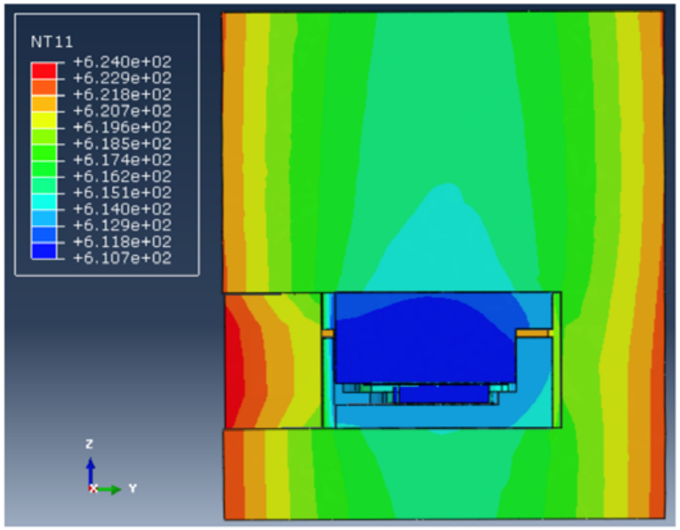



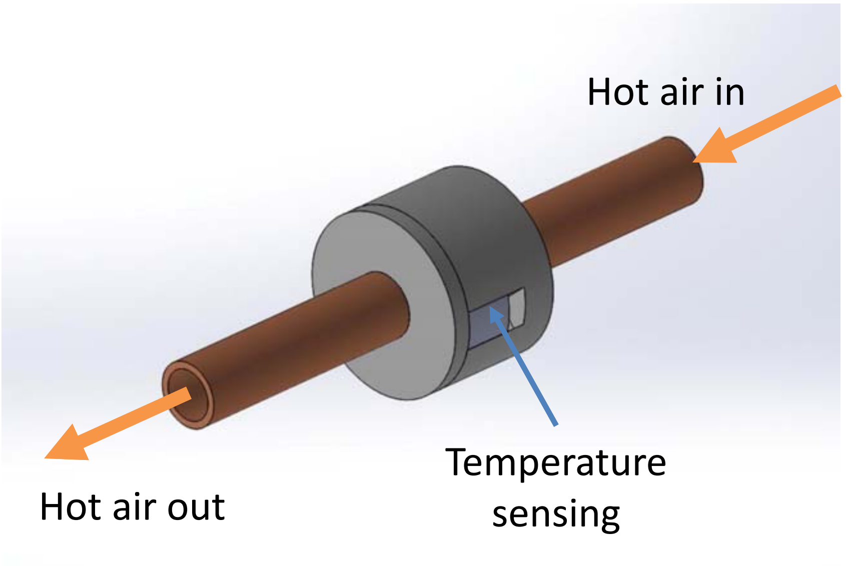



# Ongoing Work

- Simulation

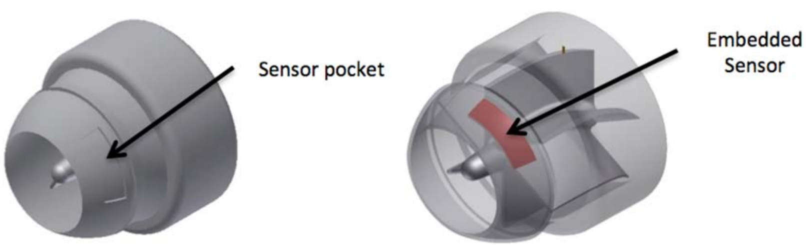


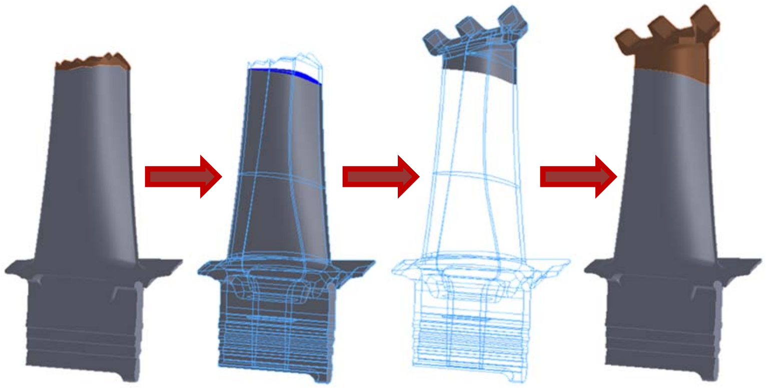

- Hot air temperature sensing



# Conclusion and Future Work

- **Smart part fabrication** was successful
  - "Stop and Go" process was developed for sensor embedding
  - Masking plate was needed for the second fabrication
  - Interface between first and second EBM fabrication is key in material failure
- **Sensor packaging** was critical for sensor protection
  - Low pressure, high temperature harsh environment in EBM
  - Metal vaporization contamination common issue in EBM
  - Further sensor size reduction is needed for better sensor integration
- **Future Work**
  - IR Imaging of the fabrication process for *in situ* monitoring of paused build fabrication will be performed
  - Masking plate less fabrication process for sensor embedding
  - HIPing of the fabricated parts will be performed



# Publication and Patent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- Hossain, M., Gonzalez, J., Martinez, R., Shuvo, M., Mireles, J., Choudhuri., Wicker., and Lin, Y., 2015. “Fabrication and Characterization of Smart Parts using Electron Beam Melting Additive Manufacturing Technology”. *Additive Manufacturing*, in Press.
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- Gonzalez, J. A., Hossain, M. S., Martinez, R., Rodriguez, G., Shuvo, M.A.I., Mireles, J., Wicker, R., Choudhuri, A., Lin, Y. 2015, "Investigation on Smart Parts with Embedded Piezoelectric Sensors via Additive Manufacturing: Characterization of Smart Parts", 5th Southwest Energy Science and Engineering Symposium (SESES), April 4th, El Paso, TX.
- Hossain, M. S., Gonzalez, J. A., Mireles, J., Lin, Y., Choudhuri, A., and Wicker, R., 2015, “Smart Part Fabrication using Electron Beam Melting Additive Manufacturing Technology”, 5th Southwest Energy Science and Engineering Symposium, El Paso, TX.
- Gonzalez, Jose A., Mireles J., Lin Y., Wicker R.B., 2015, "Fabrication of Ceramic Components Using Binder Jetting Additive Manufacturing Technology." 5th Southwest Energy Science and Engineering Symposium (SESES), April 4th, El Paso, TX.
- Hossain, M. S., Gonzalez, J. A., Mireles, J., Lin, Y., Choudhuri, A., and Wicker, R., 2015, “Smart Part Fabrication using Electron Beam Melting Additive Manufacturing Technology”, 2016 Southwest Emerging Technology Symposium, El Paso, TX.
- Hossain, M. S., Gonzalez, J. A., Gaytan, S. M., Lin, Y., Choudhuri, A., and Wicker, R., “Stop and Go Process to Fabricate Smart Parts using Electron Beam Melting”, Power Industry Division Symposium, 2014.

# Acknowledgment


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- Maria Reidpath
  - Federal Project Manager, CCRA

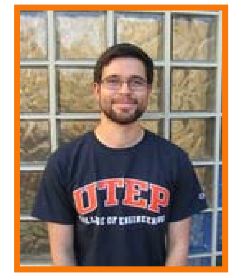
- Robert Romanosky
  - Acting Portfolio Manager, CCRA


NavAir

Exxon

Intel, inc

Intel, inc




Intel, inc

Thank you

Questions?

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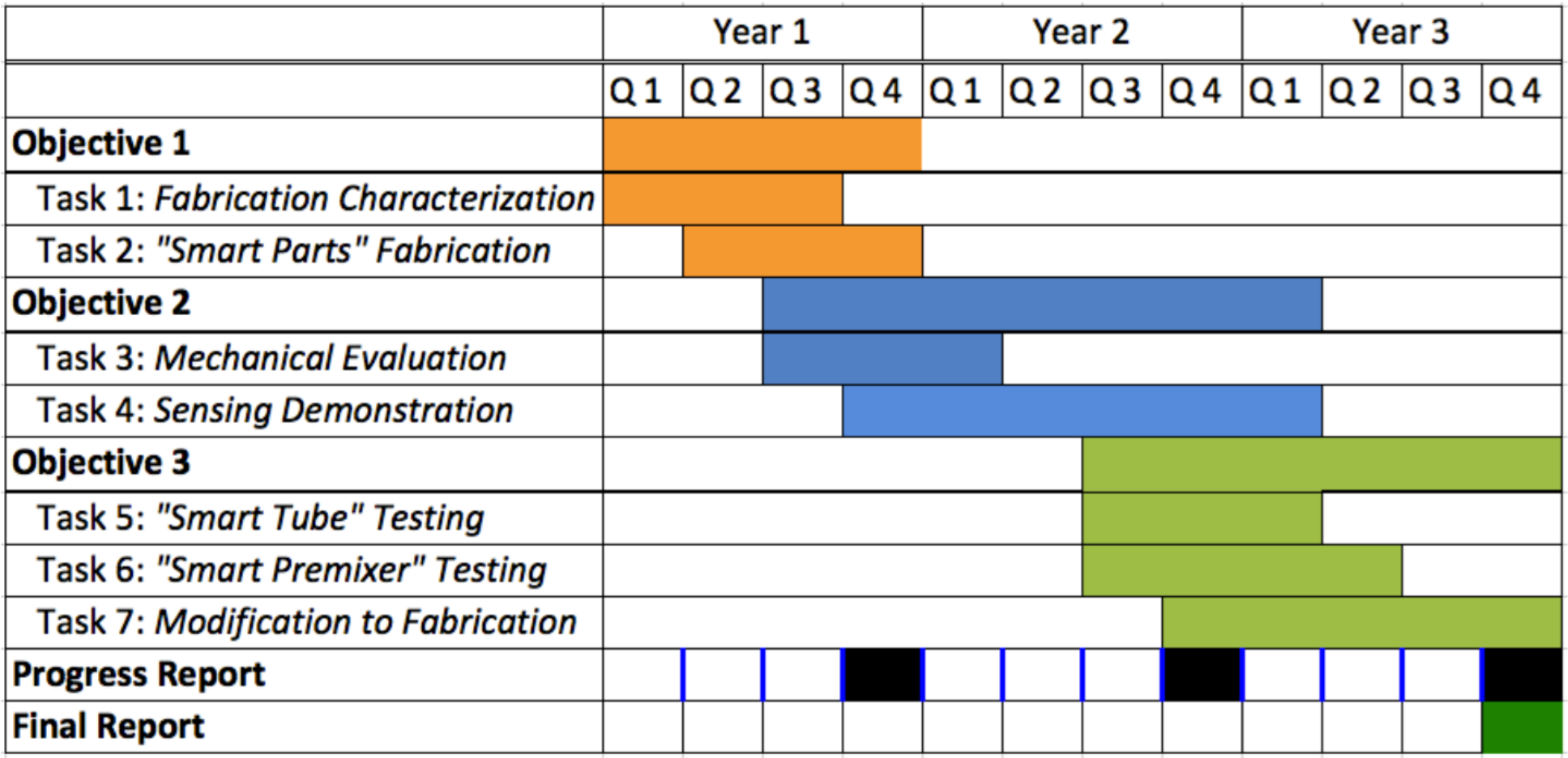
1. Hahnlen, R. M. (2009). Development and characterization of NiTi joining methods and metal matrix composite transducers with embedded niti by ultrasonic consolidation (Doctoral dissertation, The Ohio State University).
2. C. A. Terrazas,S. M. Gaytan, E. Rodriguez, D. Espalin, L.E. Murr,F. Medina, and R. B. Wicker, " Multi-material metallic structure fabrication using electron beam melting", Int J Adv Manuf Technol, Vol 71, Issue 1-4, pp 33-45, 2014
3. E. Aguilera, J. Ramos, D. Espalin, F. Cedillos, D. Muse, R. Wicker, and E. MacDonald, " 3D Printing of Electro Mechanical Systems",In: Proceedings of the 2013 Annual International Solid Freeform Fabrication Symposium, Austin, TX, USA
4. Rodriguez, Emmanuel, et al. "Integration of a Thermal Imaging Feedback Control System in Electron Beam Melting." *WM Keck Center for 3D Innovation, University of Texas at El Paso* (2012).

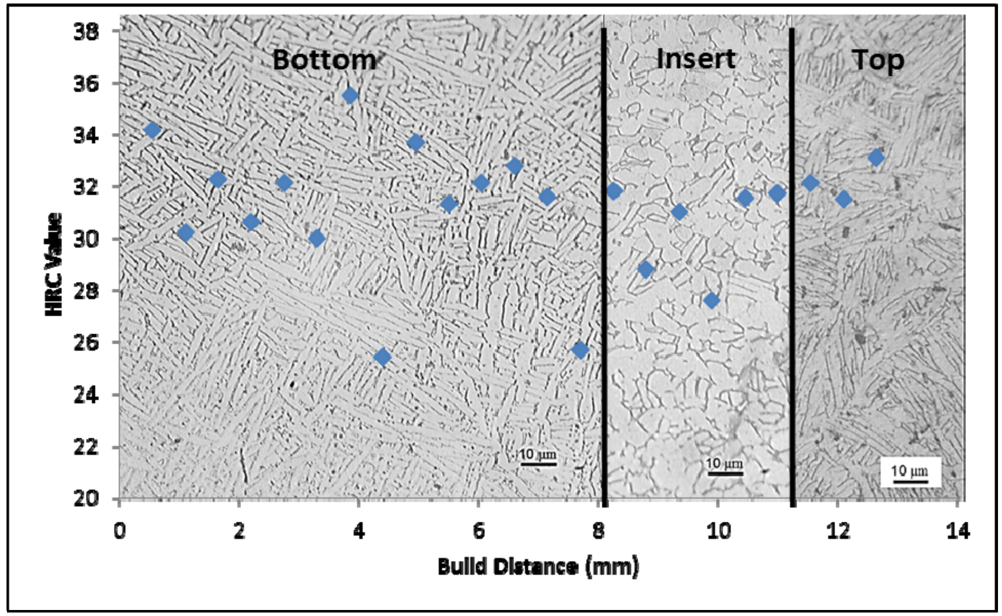
# Schedule



Year 1
Year 2
Year 3
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
Objective 1
Task 1: Fabrication Characterization
Task 2: "Smart Parts" Fabrication
Objective 2
Task 3: Mechanical Evaluation
Task 4: Sensing Demonstration
Objective 3
Task 5: "Smart Tube" Testing
Task 6: "Smart Premixer" Testing
Task 7: Modification to Fabrication
Progress Report
Final Report

# 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
- Annealed Ti-6Al-4V = **36** HRC



# Backup

- Add Shojib slides
- Simulation results
- Premix Fabrication
- Alternative sensor materials
- Hipping process
- Sensor packaging size reduction

# Milestones

| | Mile-stone | Title | Description | Relation | Validation | Date |
|---|---|---|---|---|---|---|
| **Budget Period 1** | | | | | | |
| | M1 | Updated Project Management Plan | Complete plans for Facility, Resources, Quality, Safety, Documentation Management, etc. | Predecessor of all following tasks | Report Plan delivered to DOE PM | 12/31/13 |
| | M2 | Kickoff Meeting | Review of objectives, technical and managerial approach and other facets of project | Predecessor for tasks | Presentation delivered to DOE PM | 01/31/14 |
| | M3 | Embedded Sensor Parts Fabrication | Selection of High Temperature Piezoelectric Material, determination of fabrication technique for embedded sensors | Data set for 1st Decision Point | Summarized in nearest Quarterly Report | 09/30/14 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Budget Period 2** | | | | | | |
| | M4 | Mechanical strength evaluation and sensing demonstration | Interfacial shear strength and strain, temperature, and pressure sensing demonstration | Predecessor for subsequent tasks | Summarize results in Quarterly Report | 12/31/14 |
| | M5 | Calibration of Sensor performance | Calibration of sensor, determine the sensitivities of strain, temperature, and pressure sensing | Predecessor for subsequent tasks | Summarize results in Quarterly Report | 03/30/15 |
| | M6 | Reliability Testing | Sensor reliability, repeatability, and stability testing | Data set for 2nd Decision Point | Summarize results in Quarterly Report | 09/30/15 |
| | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Budget Period 3** | | | | | | |
| | M7 | Case study 1: “smart tube” | Demonstration of embedded sensing capability for its usage in a combustion system | Predecessor for subsequent tasks | Summarize results in Quarterly Report | 12/31/15 |
| | M8 | Case study 2: “smart premixer” | Demonstration of embedded sensing of a premixer for turbine system | Data set for 3rd Decision Point | Summarized in Quarterly Report | 06/30/16 |
| | M9 | Modification to fabrication process | Fabrication parameter optimization based on Case study testing results | Predecessor for subsequent tasks | Summarize results in Quarterly Report | 09/30/16 |

# Facility

Additive Manufacturing

Energy System Testing