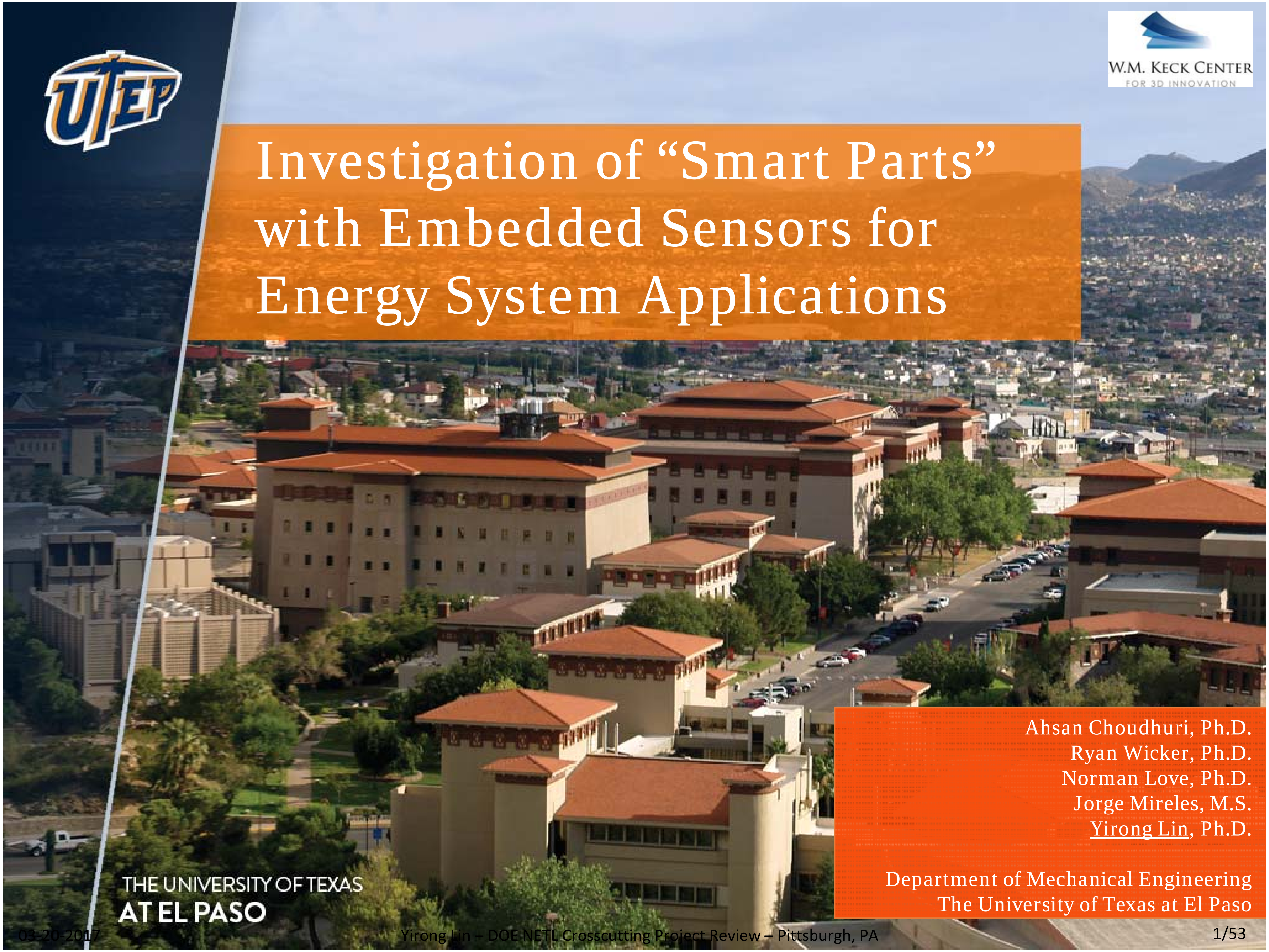


W.M. KECK CENTER
FOR 3D INNOVATION

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

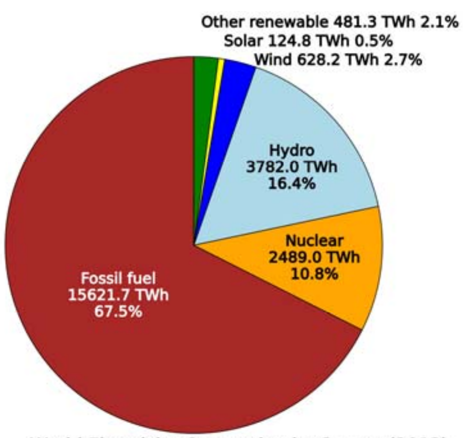
THE UNIVERSITY OF TEXAS AT EL PASO

Agenda

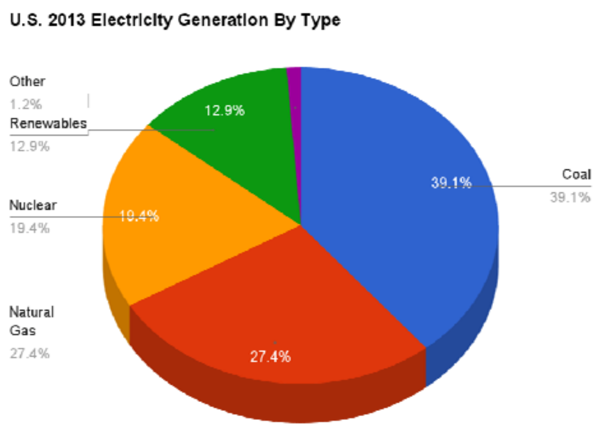
- Introduction and Background
- Objectives
- Technical Approach
- Results
- Summary

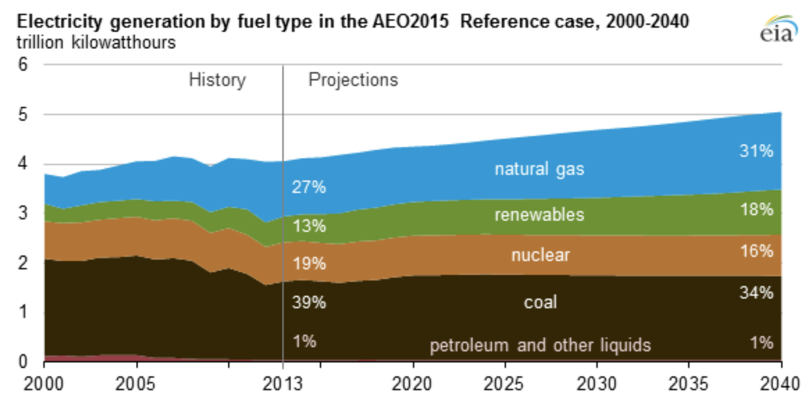
Motivation

- 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



World Electricity Generation by Source (2013)





Advanced Sensing

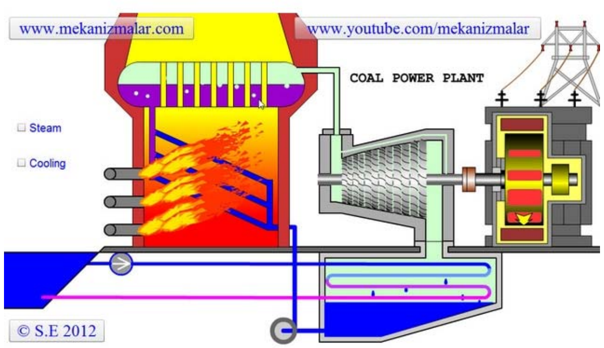
- Harsh high temperature conditions are common to the efficient conversion of fuels and processes for environmental control
- Monitoring/estimating harsh conditions in real time is needed for high system performance and assessing reliability

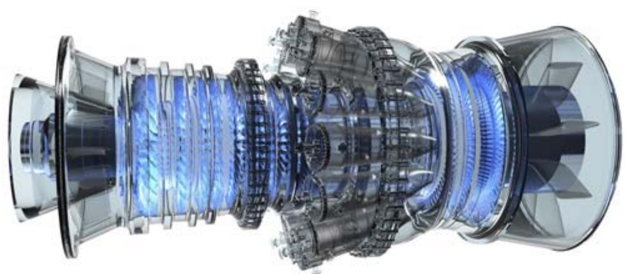
Gasifiers

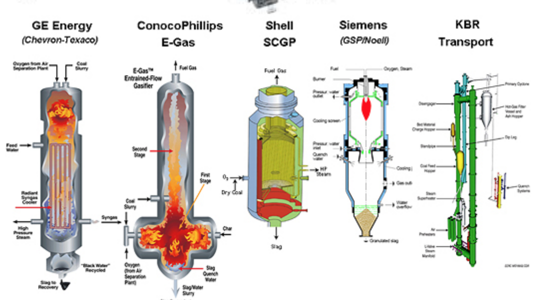
- Up to 1600°C
- Up to 1000 PSI
- Erosive, corrosive, highly reducing

Combustion Turbines

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

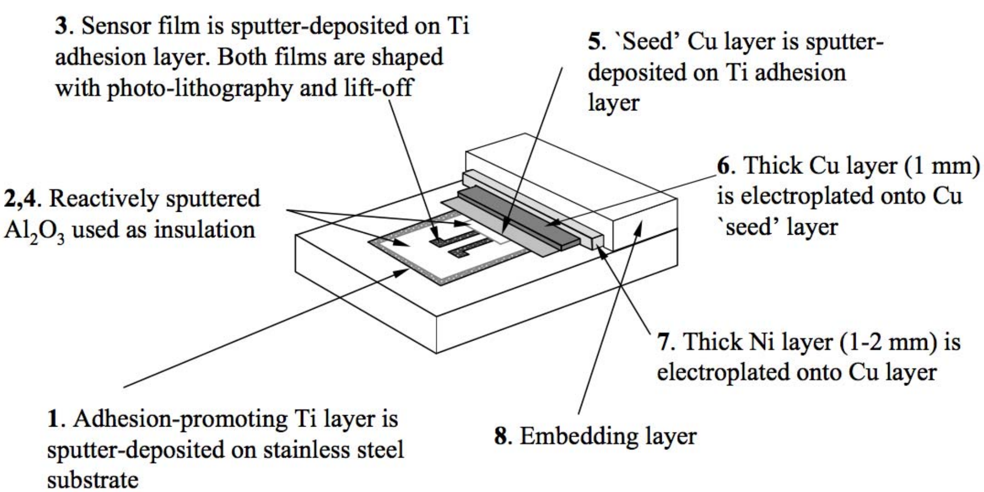




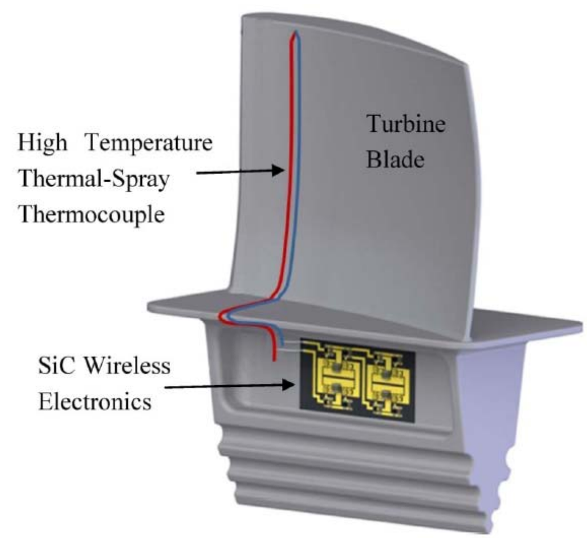


State-of-the-Art

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

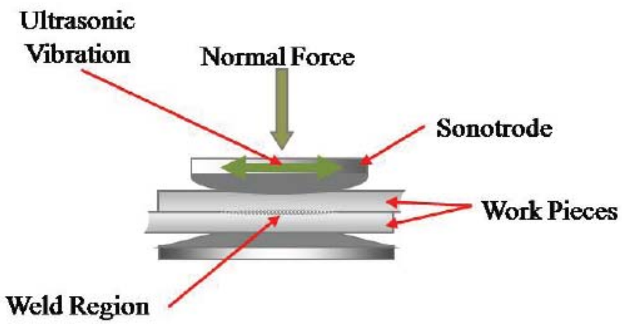


(X. Li, 2001)

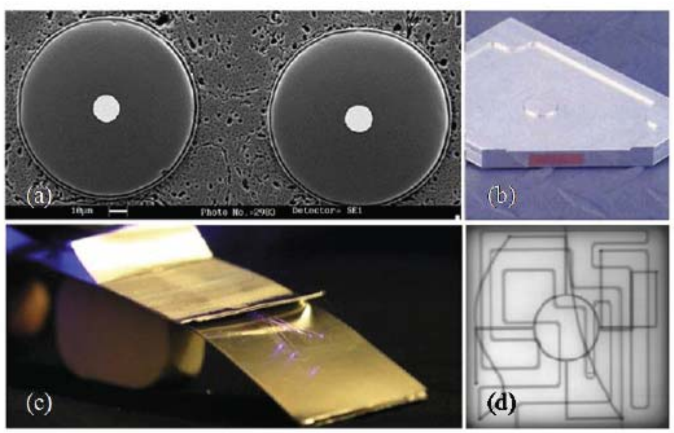


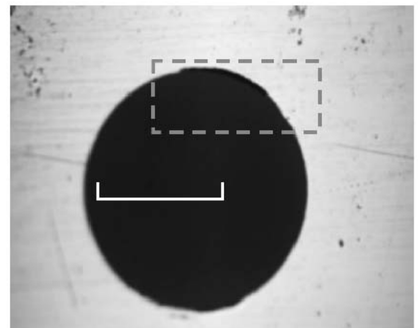
(J. Yang, 2012)

Ultrasonic Sensor Embedding

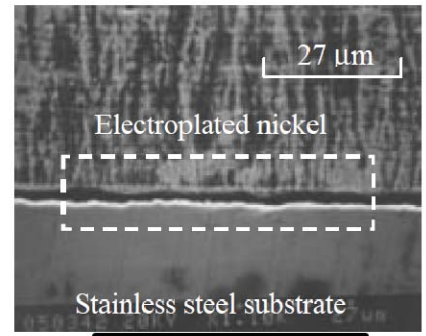


Ultrasonic Operation

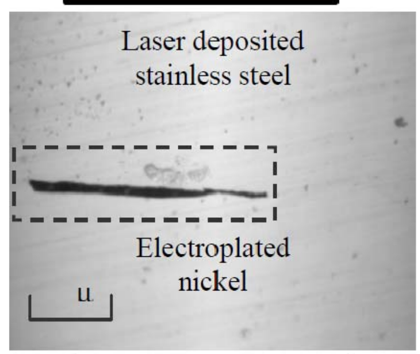




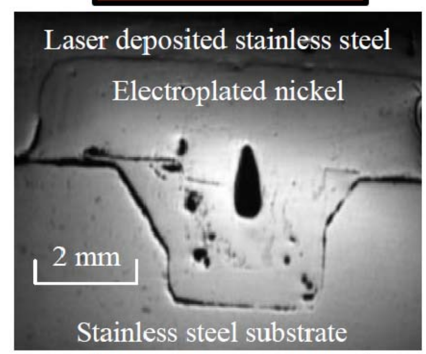
Cracking



Delamination



Cracking



Delamination

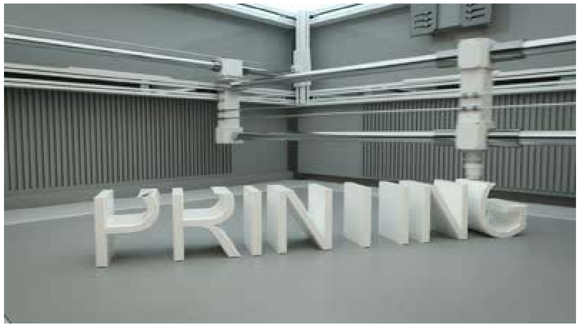
Multi-step Fabrication

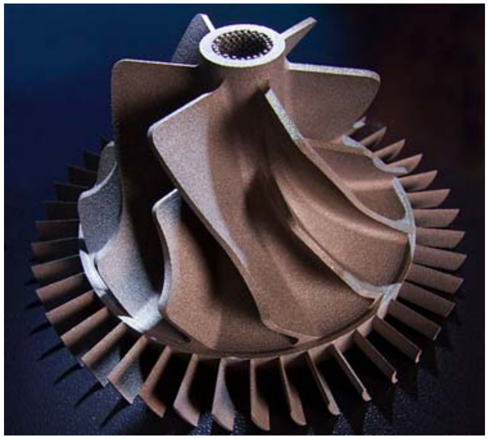
Multi-material fabrication using EBM

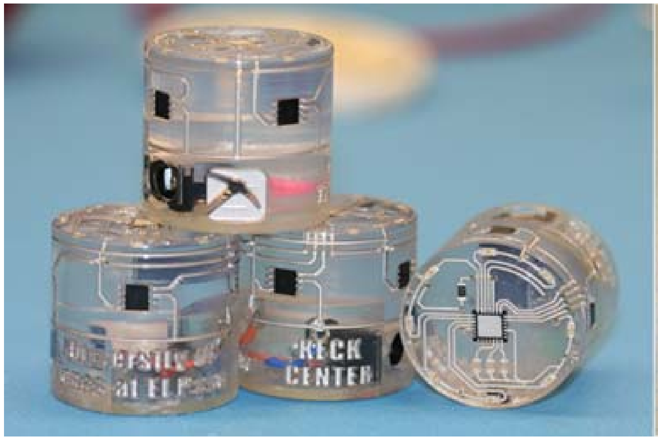
Fabrication of electro-mechanical system

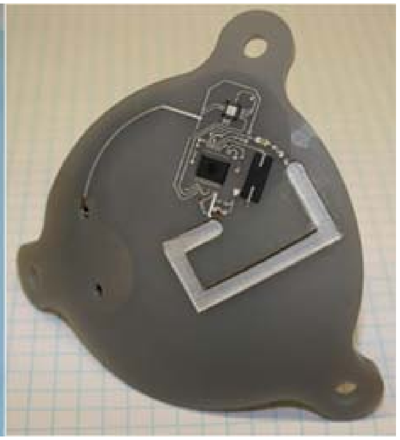
Overview and Rationale

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

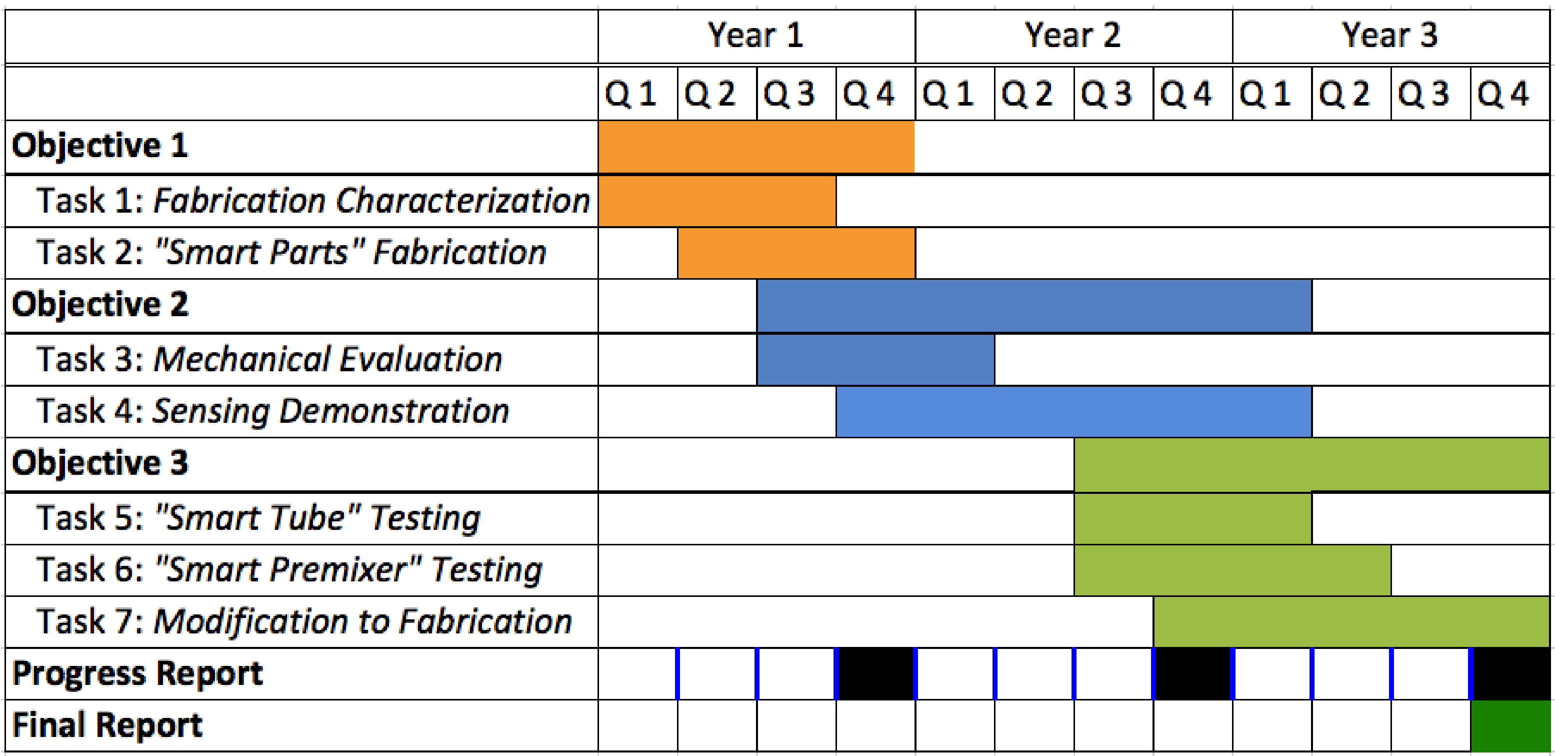








Timeline


Year 1
Year 2
Year 3
Q 1
Q 2
Q 3
Q 4
Q 1
Q 2
Q 3
Q 4
Q 1
Q 2
Q 3
Q 4
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

Team Description and Assignment

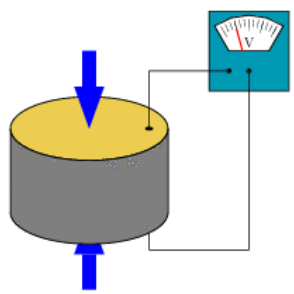

- Ahsan Choudhuri/Norman Love
  - Smart Parts testing
  - Smart Parts case study
  - High temperature assessment

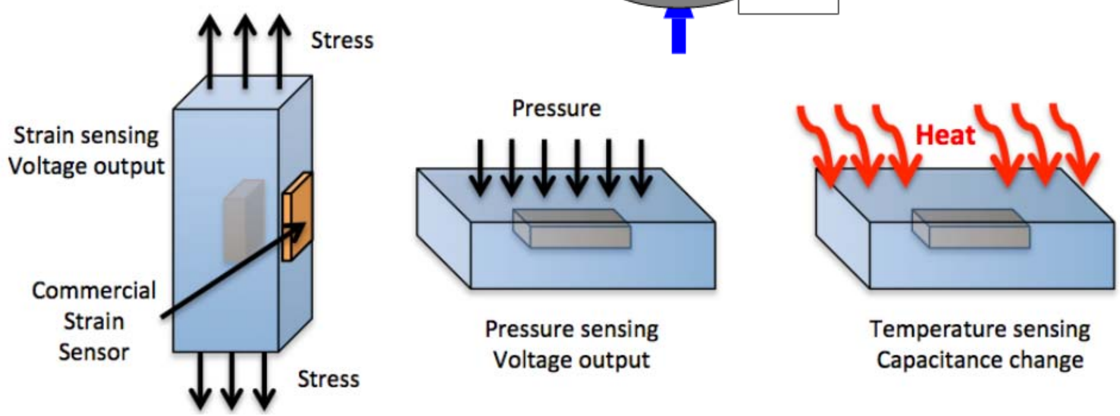

- Ryan Wicker/Jorge Mireles
  - Smart Parts 3D printing
  - Sensor embedding processing

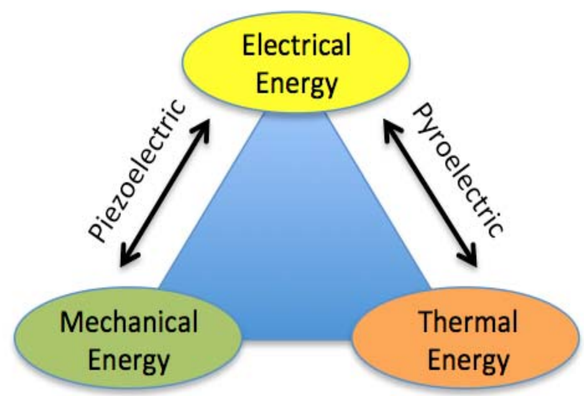
- Yirong Lin
  - Materials characterization
  - Sensing demonstration
  - Smart Parts testing

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.



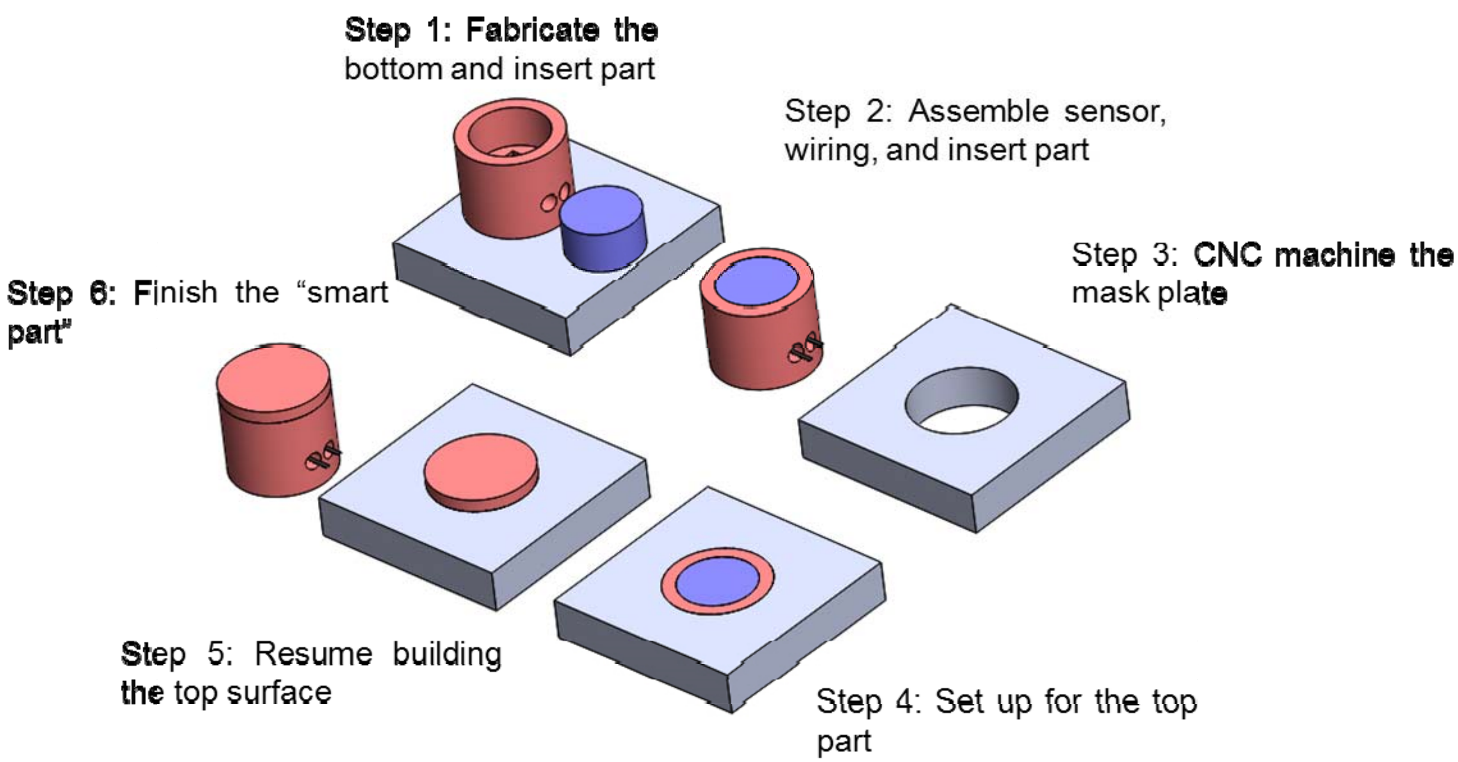




$$i_p = \frac{dQ}{dt} = Ap\frac{dT}{dt}$$

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

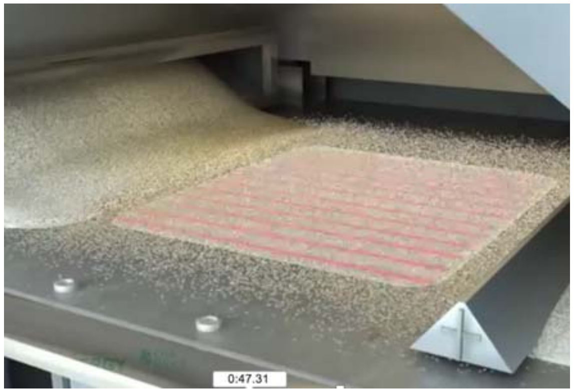
- **Objective 1: Fabricate energy system related components with embedded sensors**
  - Fabrication & evaluation of components without sensor by EBM
  - Manufacturing "Smart Parts" with embedded sensor by EBM

- **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

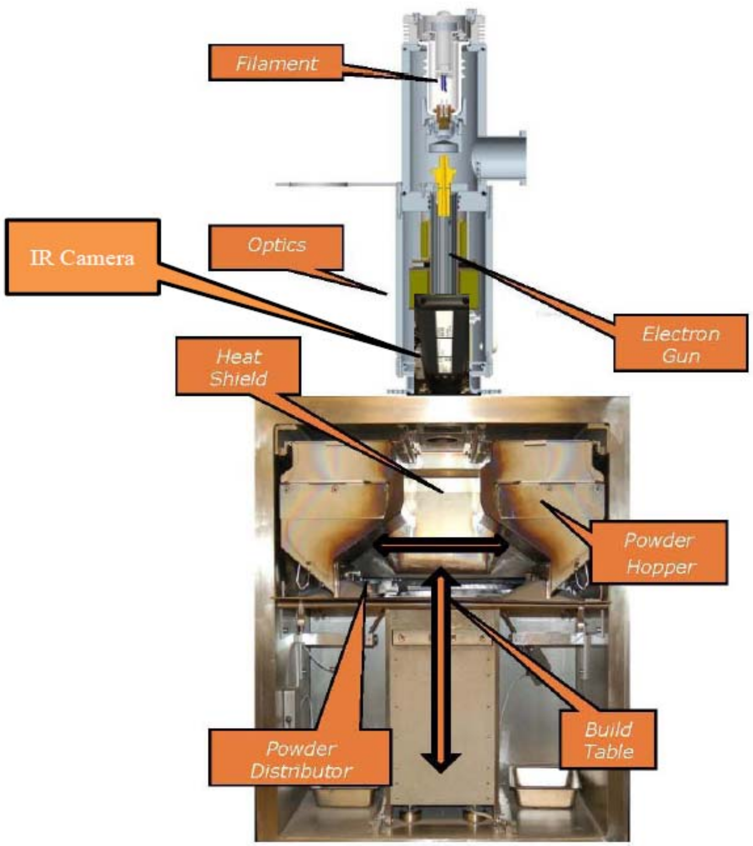
by Oakridge National Lab

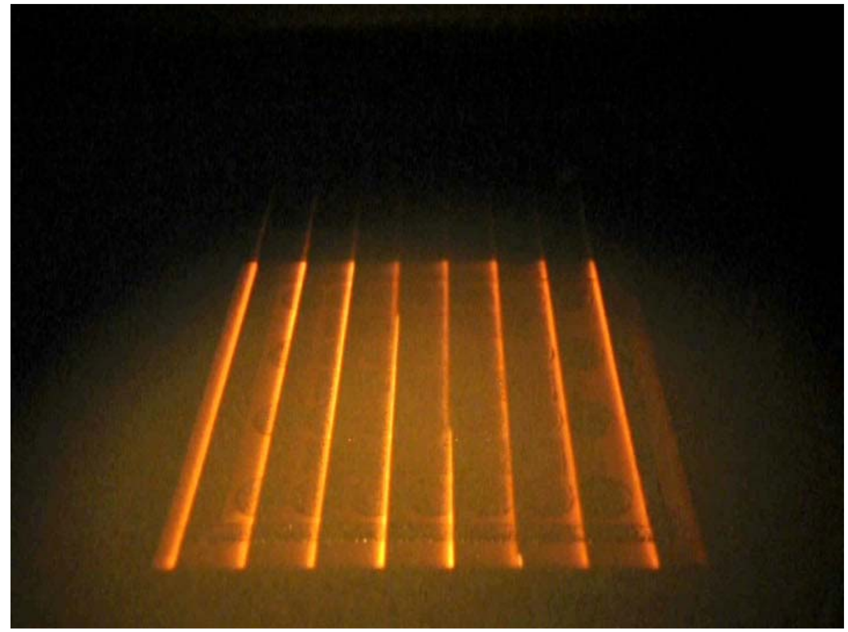





Fabrication

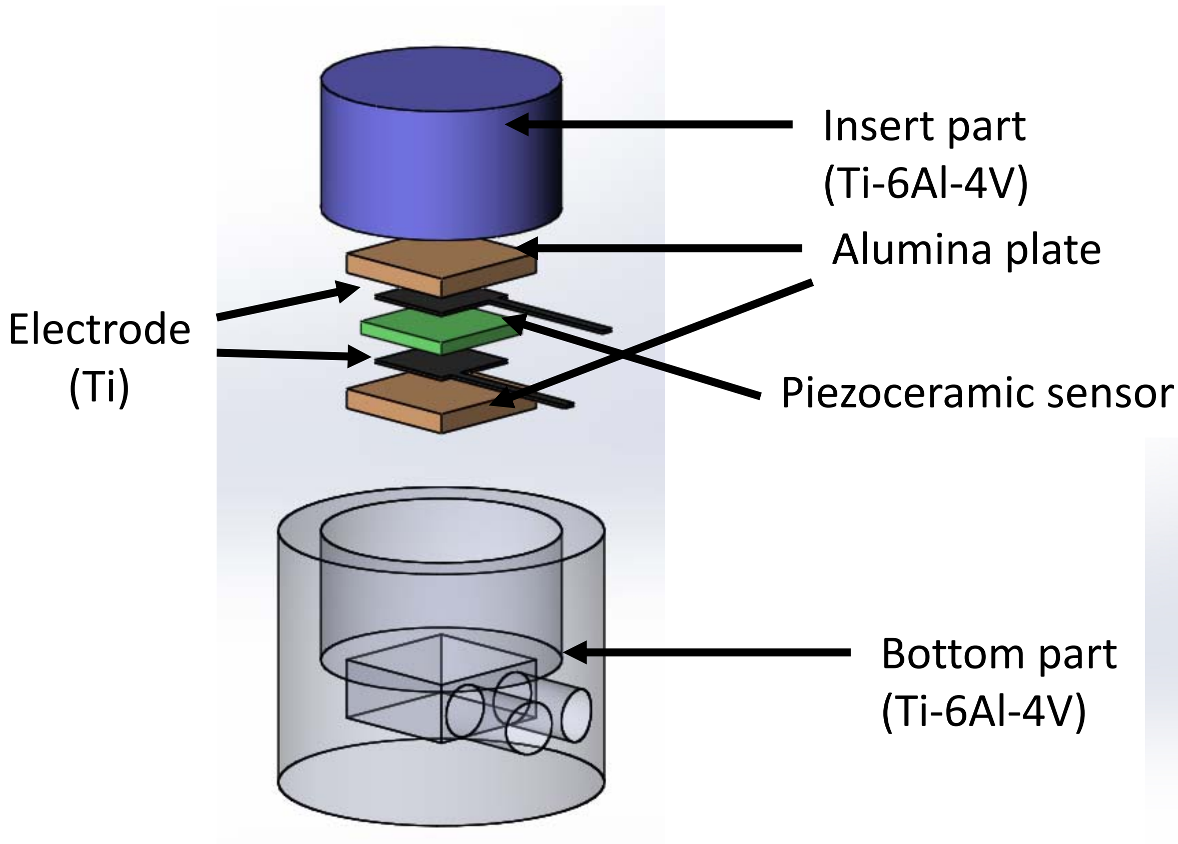
- Powder Material: Ti-6Al-4V
- Mask Plate and Start Plate: Stainless steel
- Layer Thickness: 50 µm

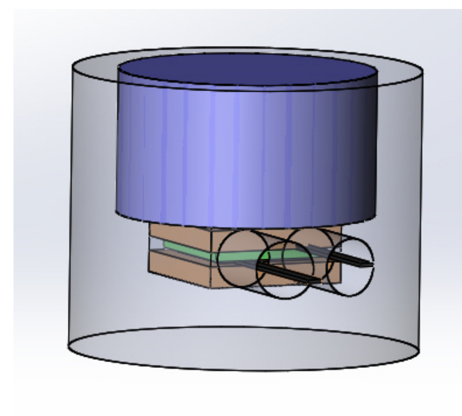




Powder Material:
Ti-6Al-4V
Mask Plate and Start Plate:
Stainless steel
Layer Thickness:
50µm

Sensor assembly in "Smart parts"



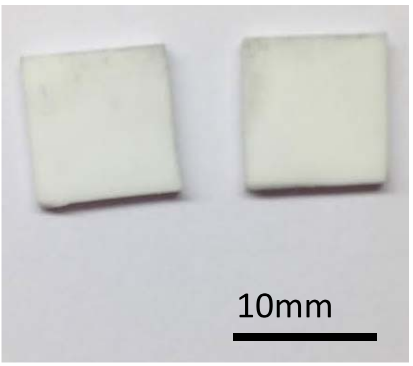


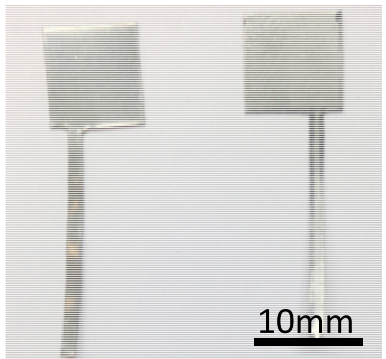
Exploded View

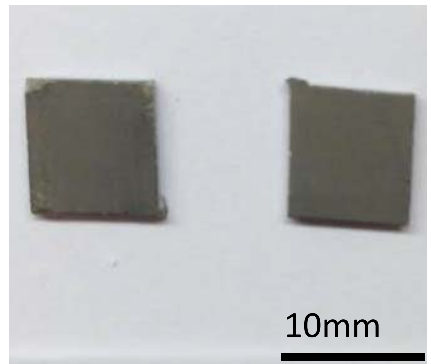
Characterization

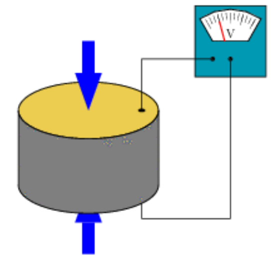
Before EBM

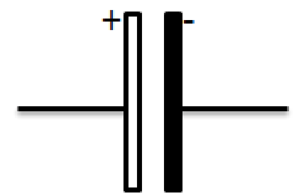
Alumina Plate | *Ti Electrodes* | *Piezoelectric Sensor*



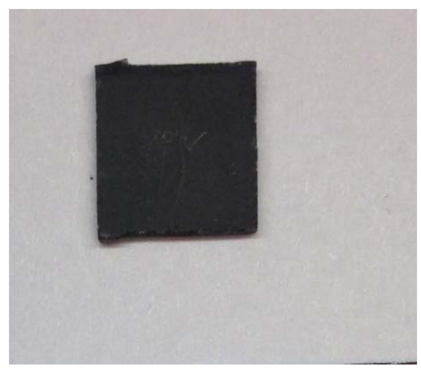


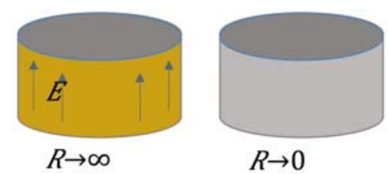






After EBM

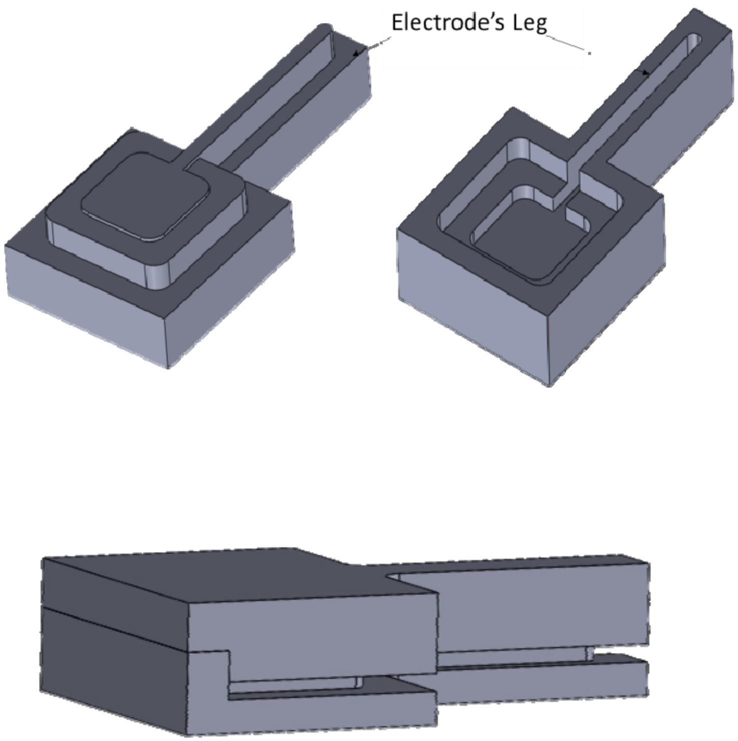


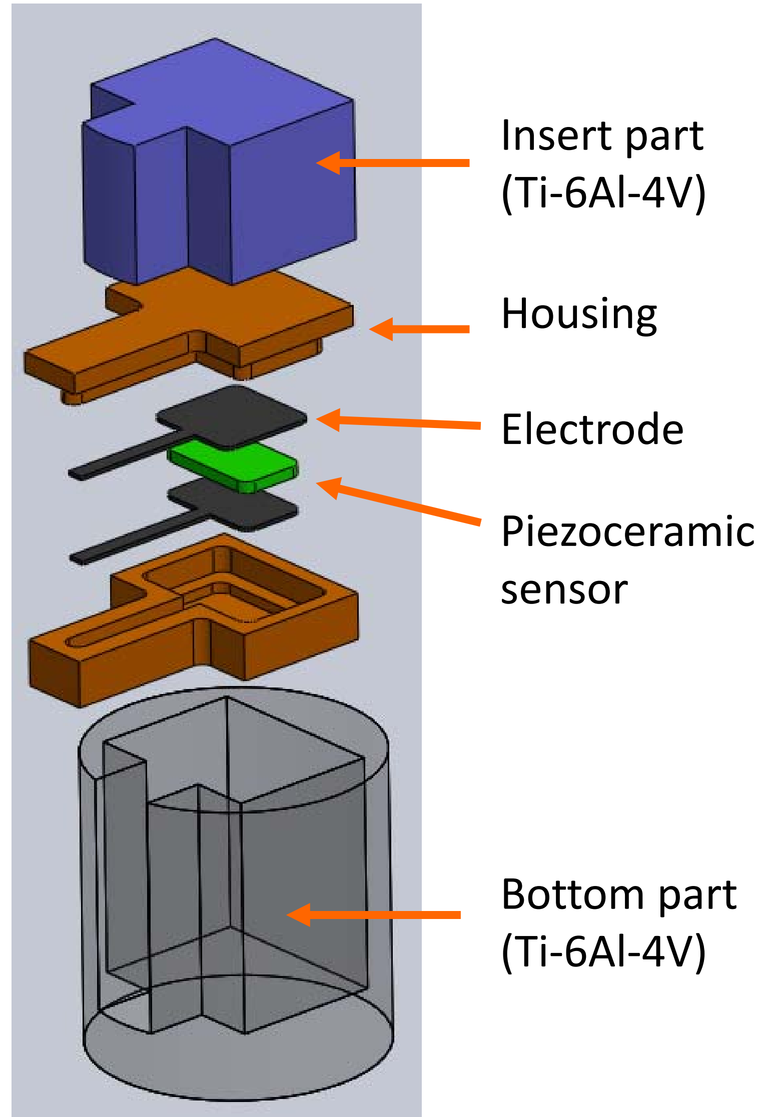


With Package Protection

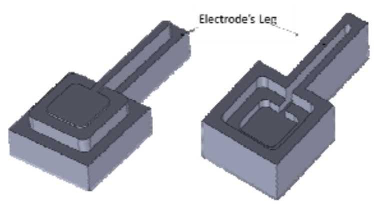
Without Package Protection

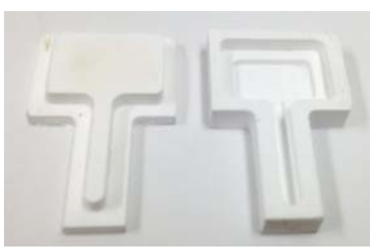
Sensor Packaging Design



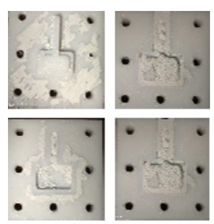


Sensor Packaging Fabrication



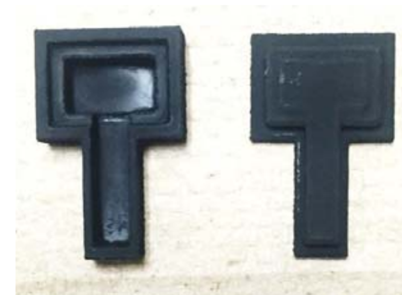


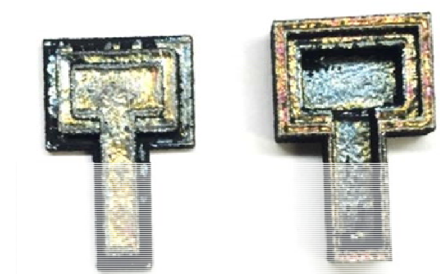
Machinable
Alumina



Injection
Modeling

3D printing

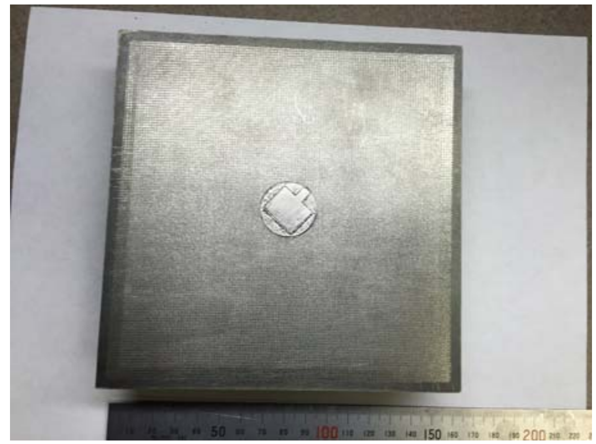




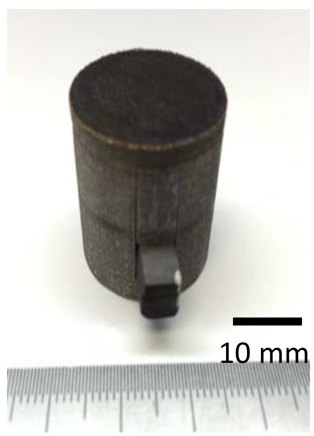
3D printing
+
Ceramic spray

W.M. KECK CENTER
FOR 3D INNOVATION

Smart parts Fabrication (1st run)

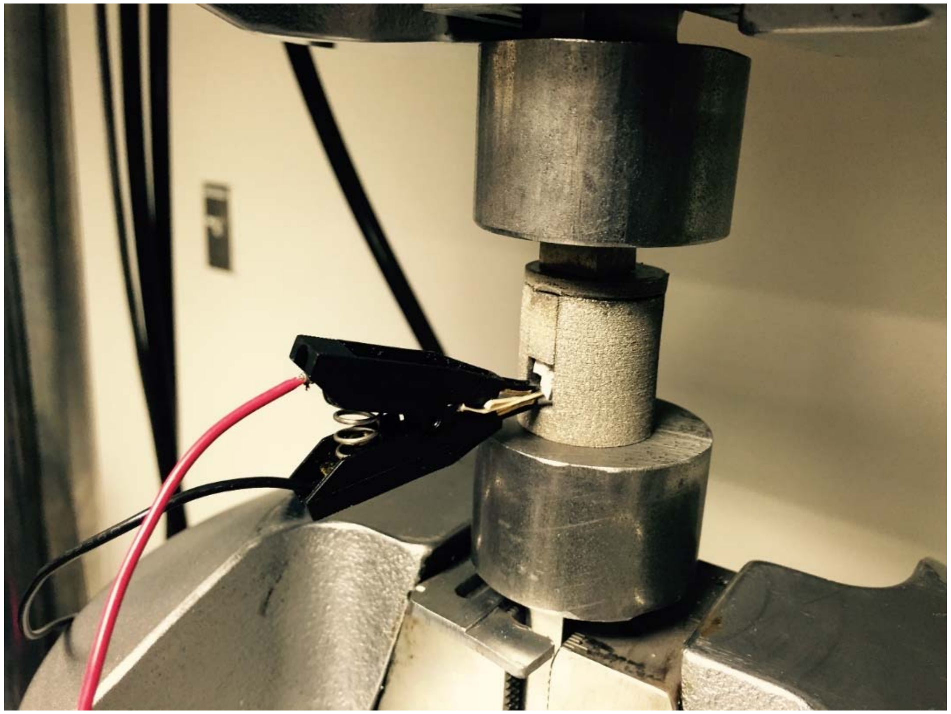


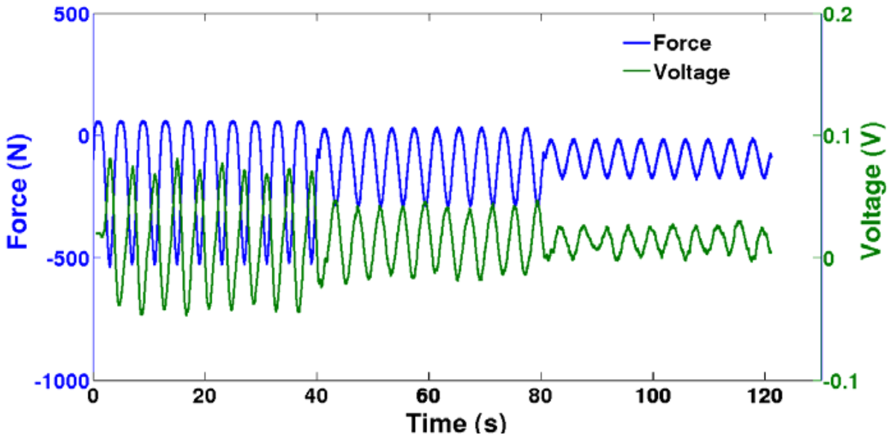
Before Fabrication



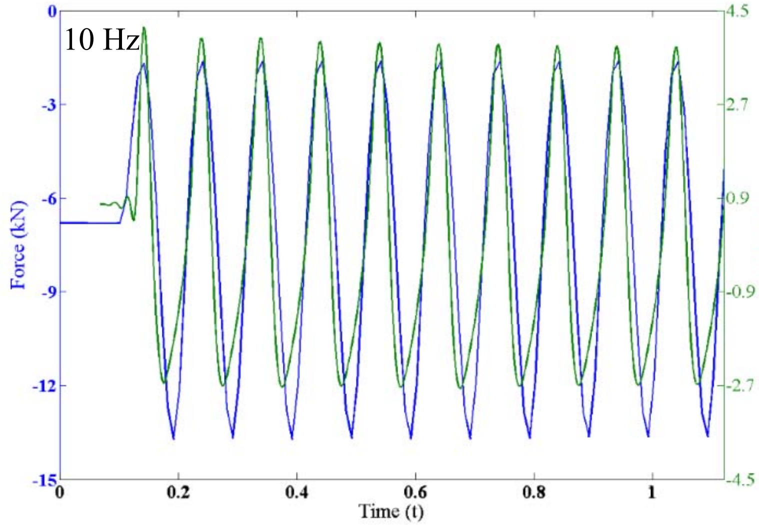
Final Part

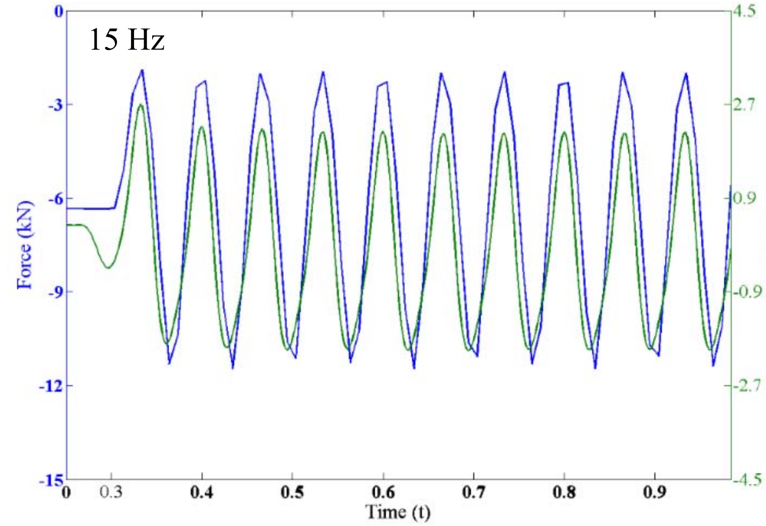
Force Sensing

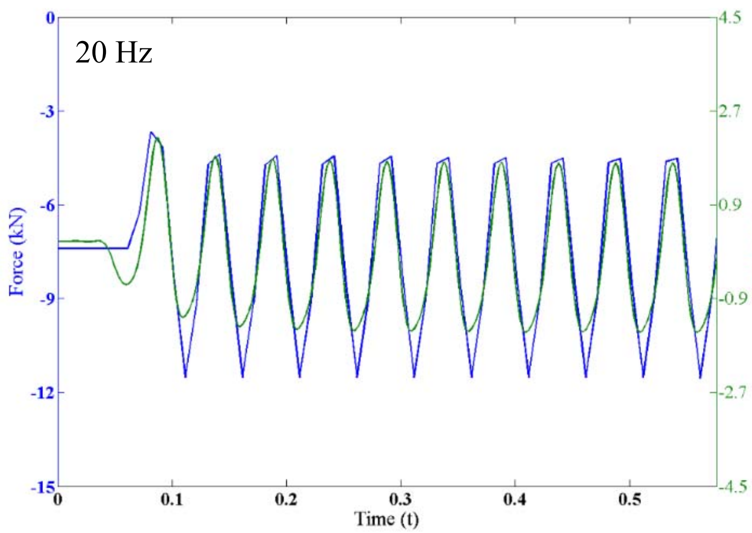


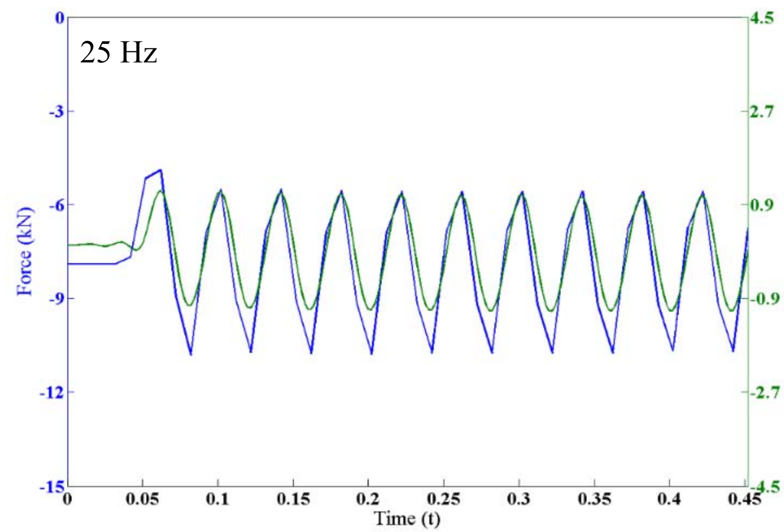


Compression Force sensing

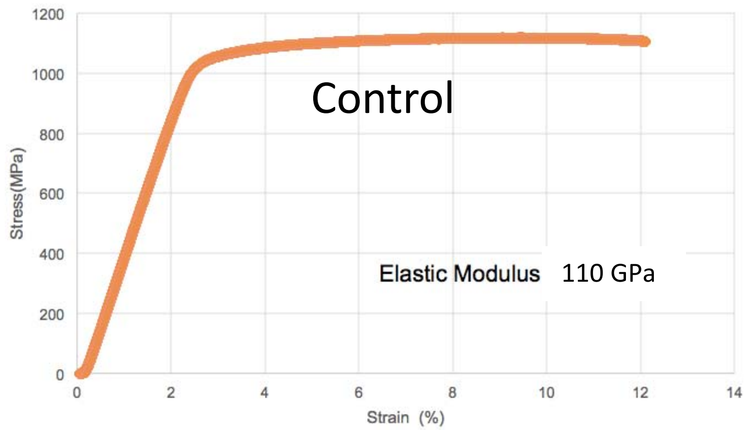


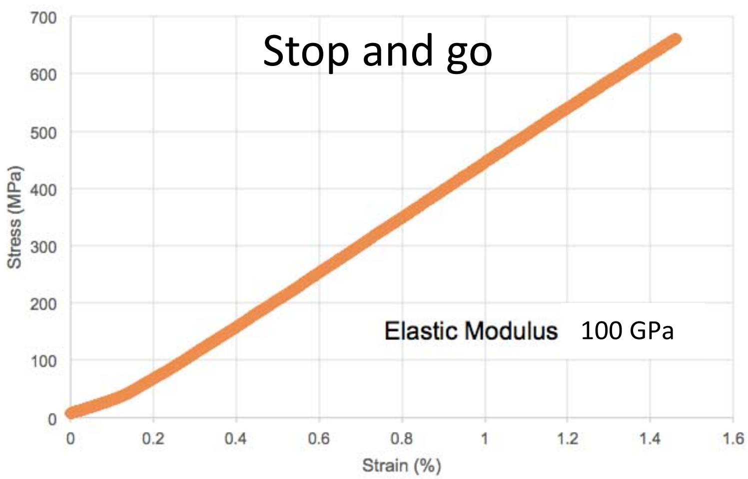


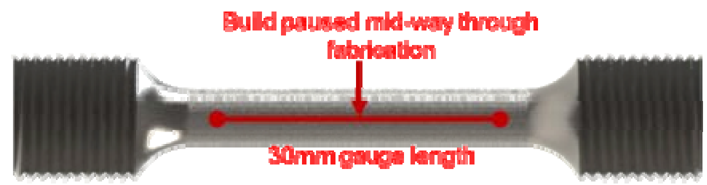




Mechanical Property Testing

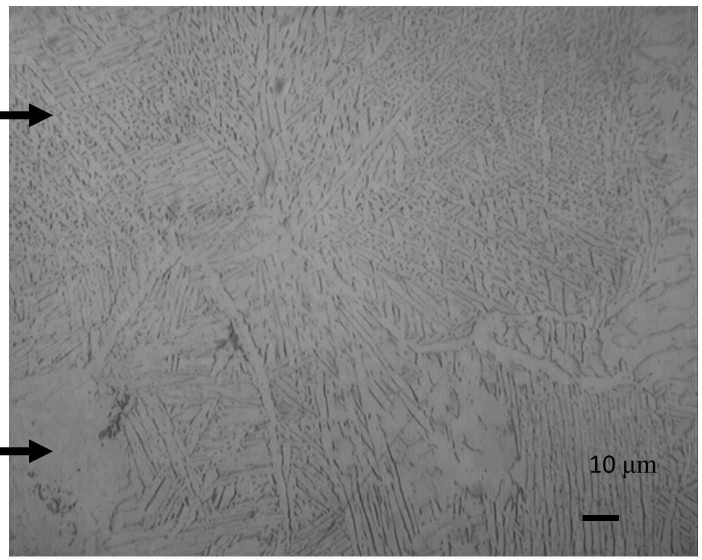




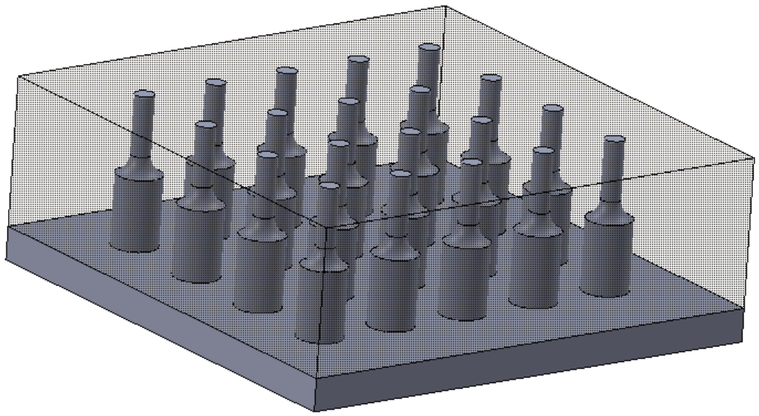


2nd built

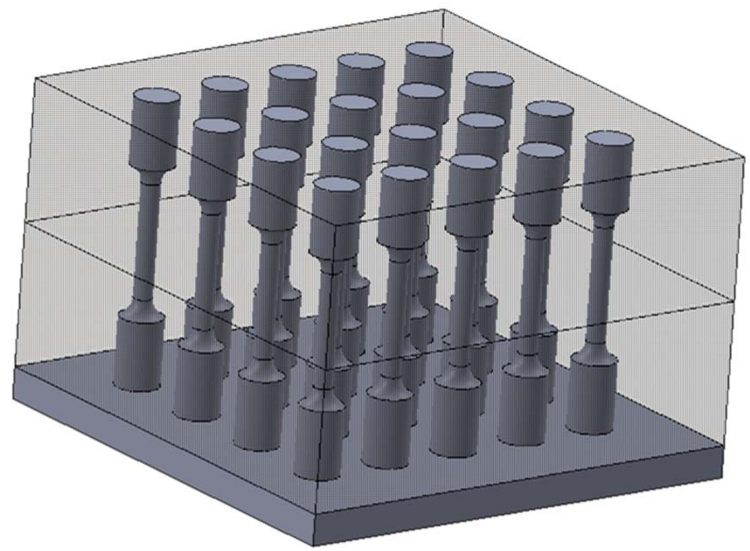
1st built



Interfacial Property Enhancement Experimental Setup



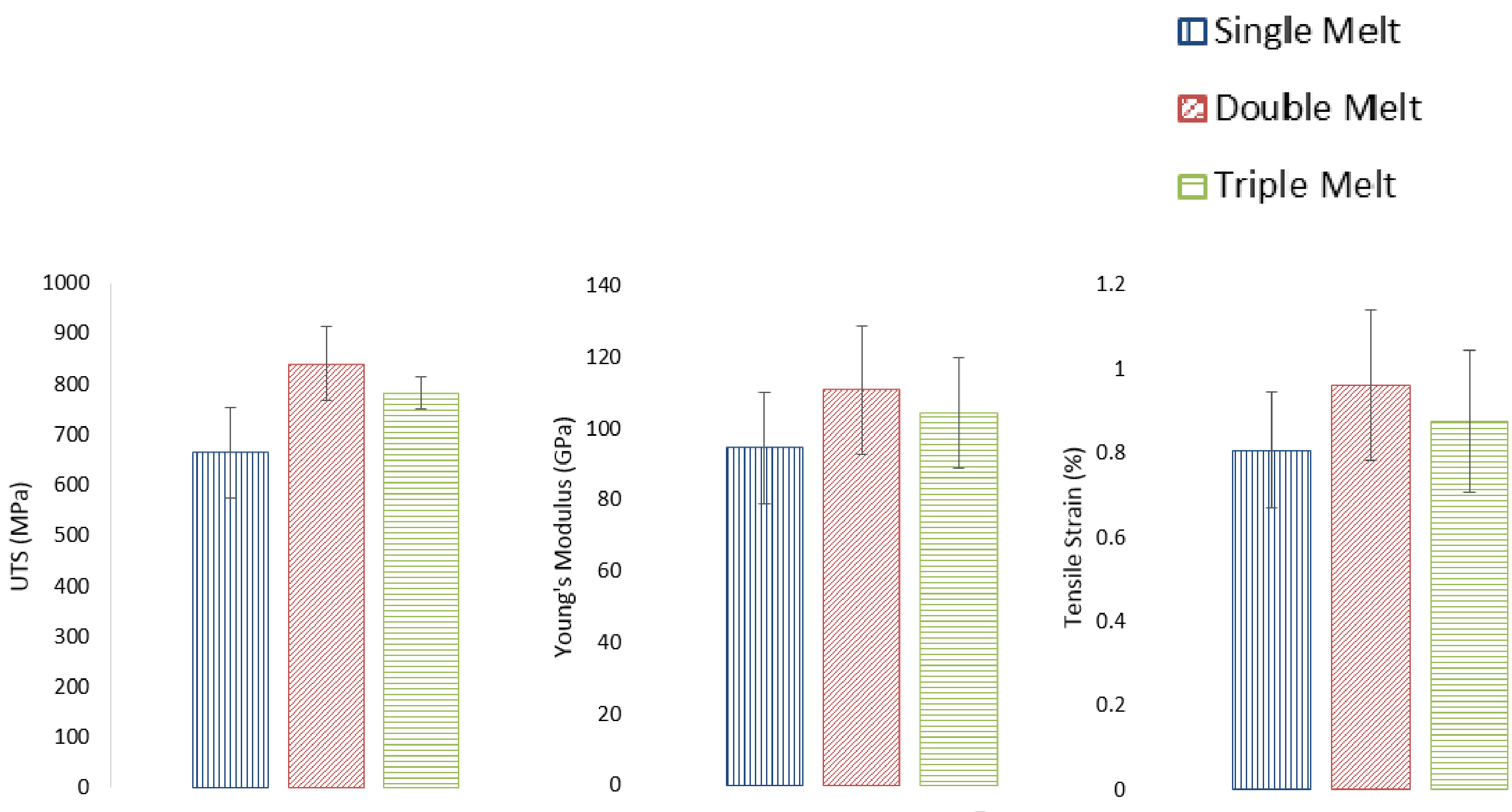
Tensile bars were fabricated to test mechanical properties after interrupting the fabrication process



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

Fabricated tensile bars

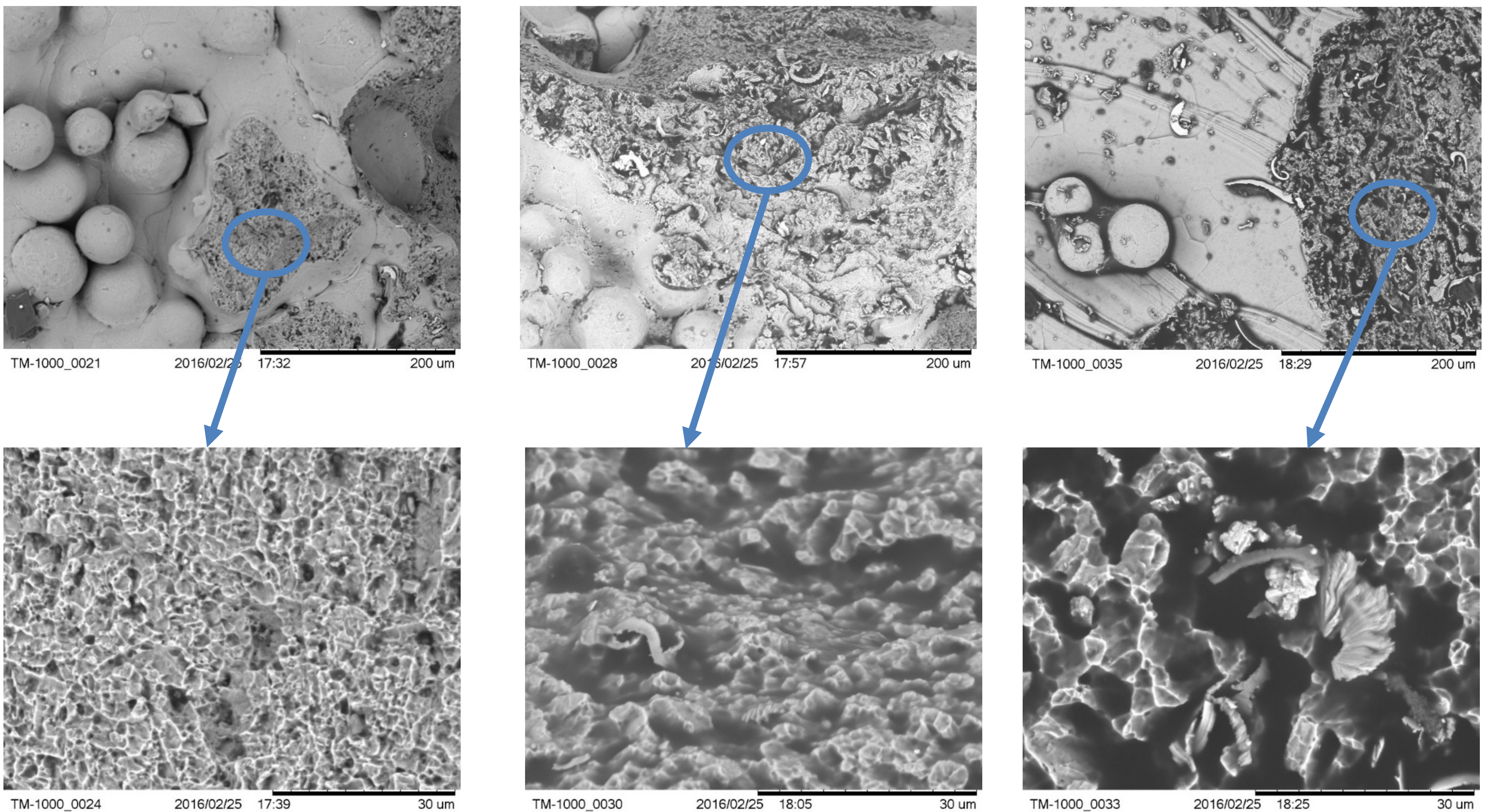
Interfacial Property Enhancement Experimental Setup



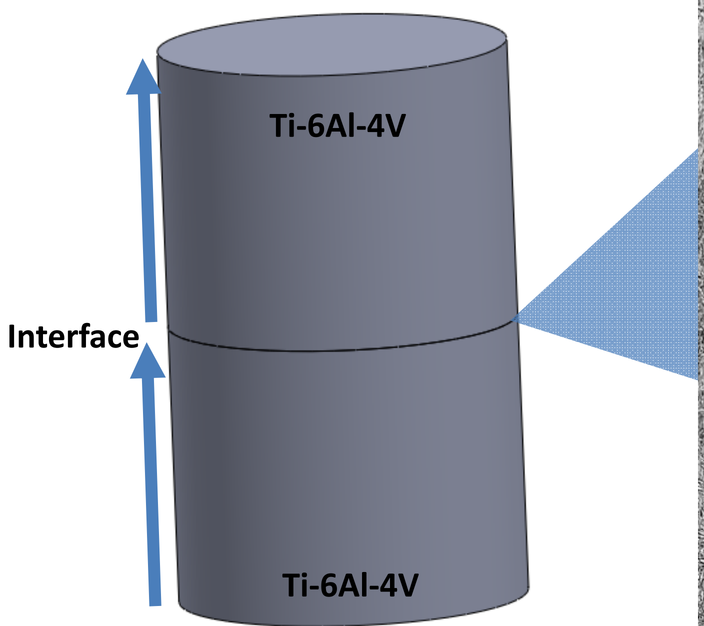
25

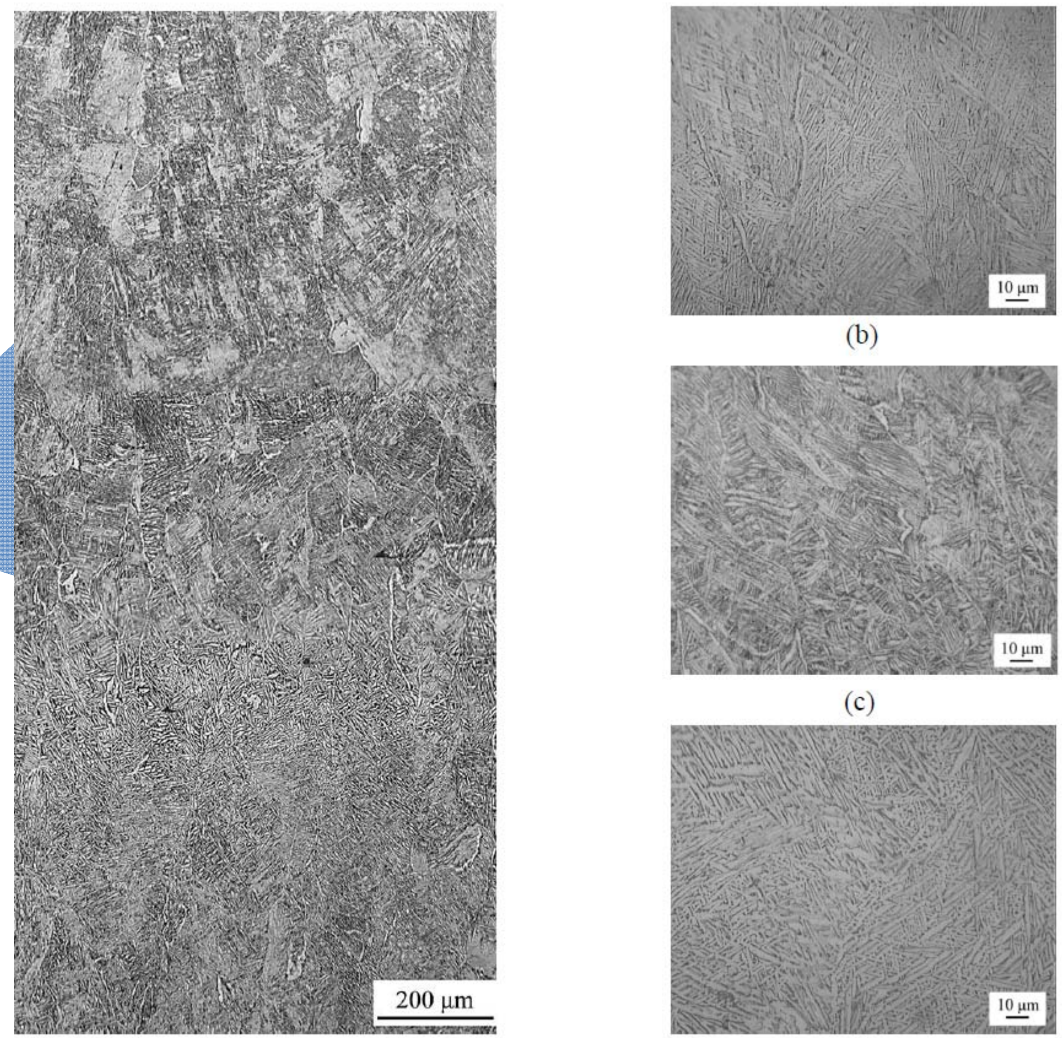
Fracture Surface

Single Melt | Double Melt | Triple Melt



Joint Microstructure

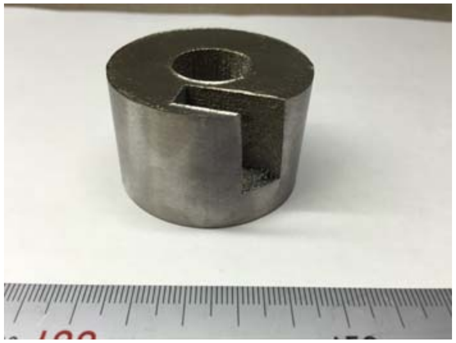


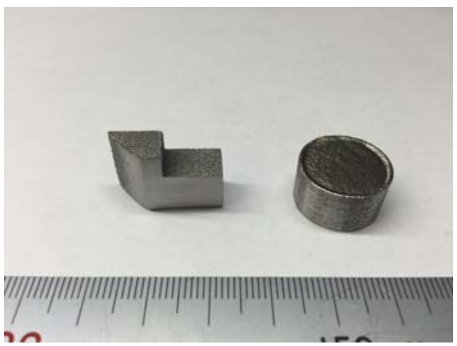


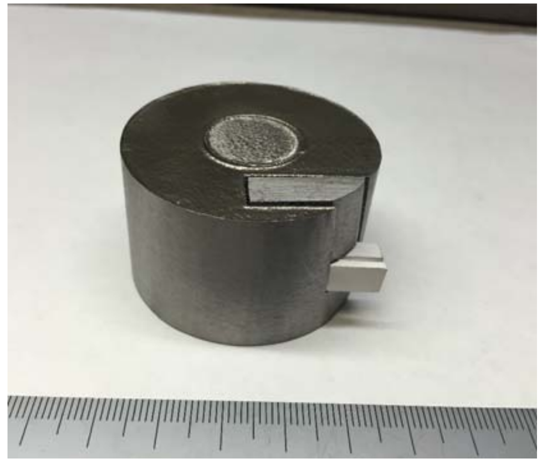
(a) (b) (c) (d)

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

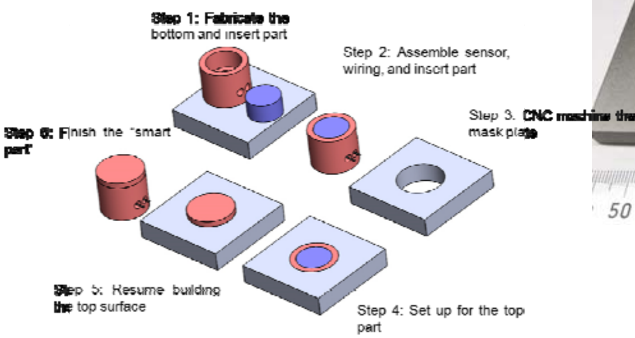
Smart Tube Fabrication

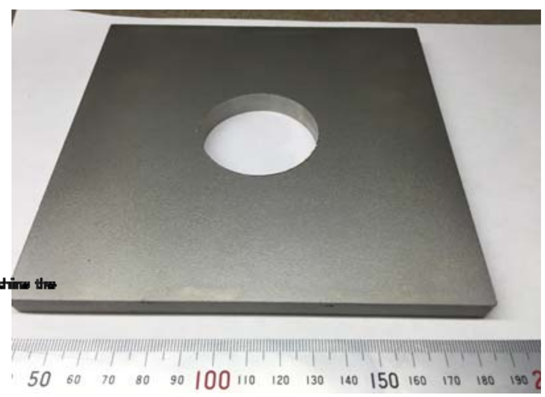




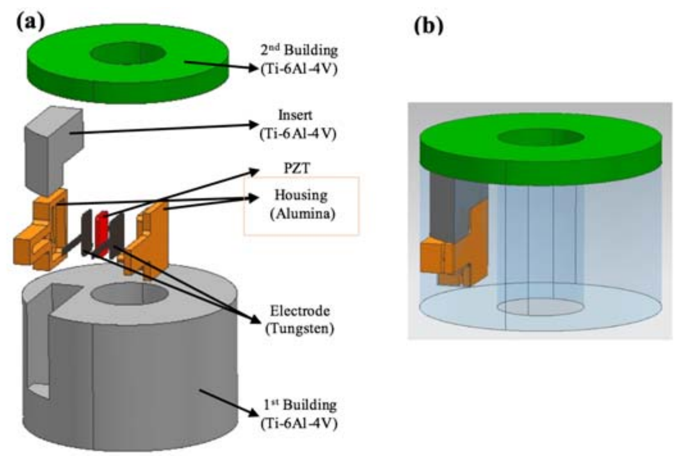


Assembled Bottom Section

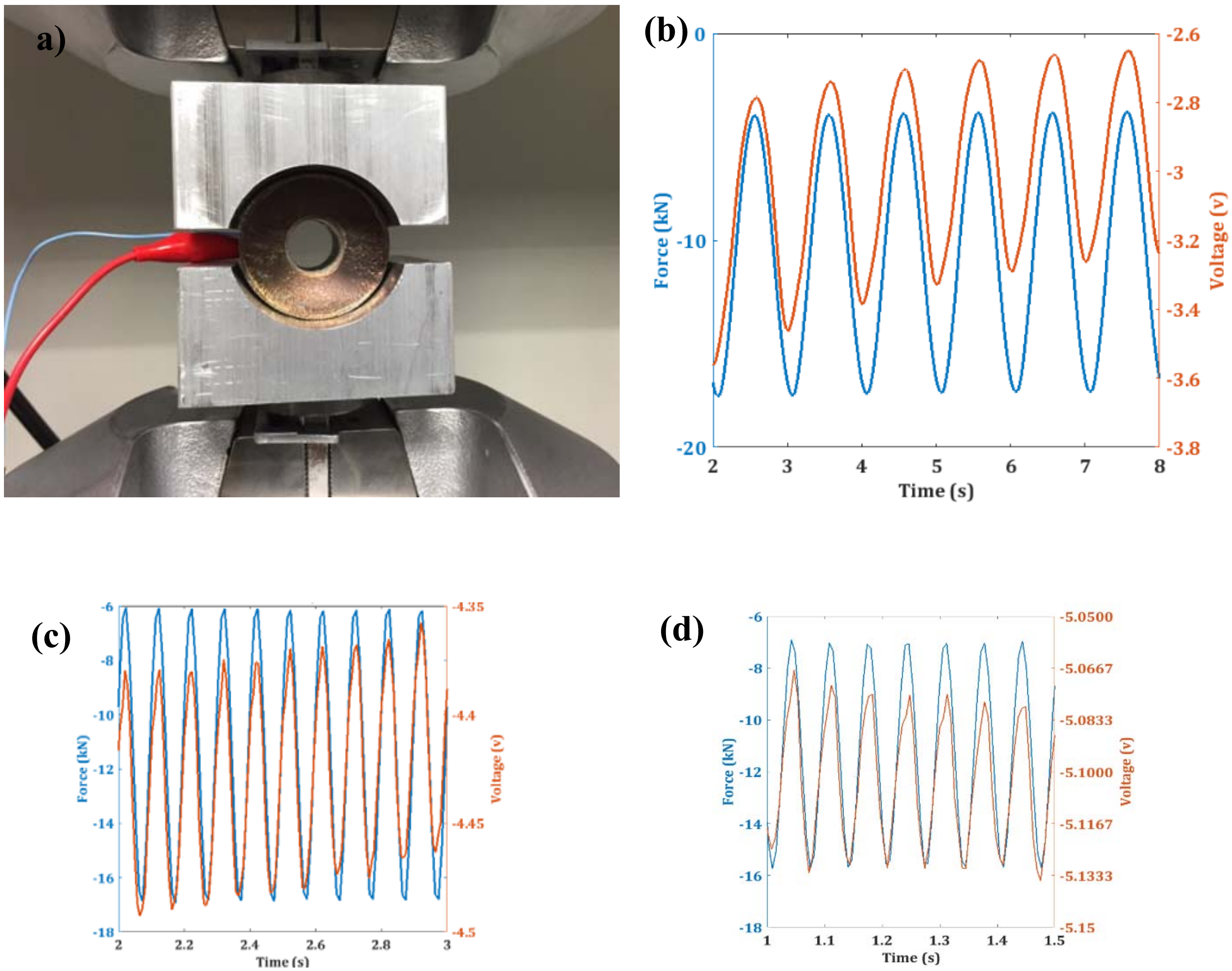




Masking plate

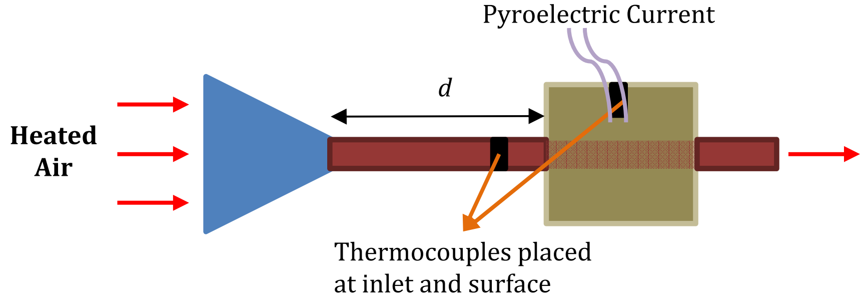


Pressure Sensing

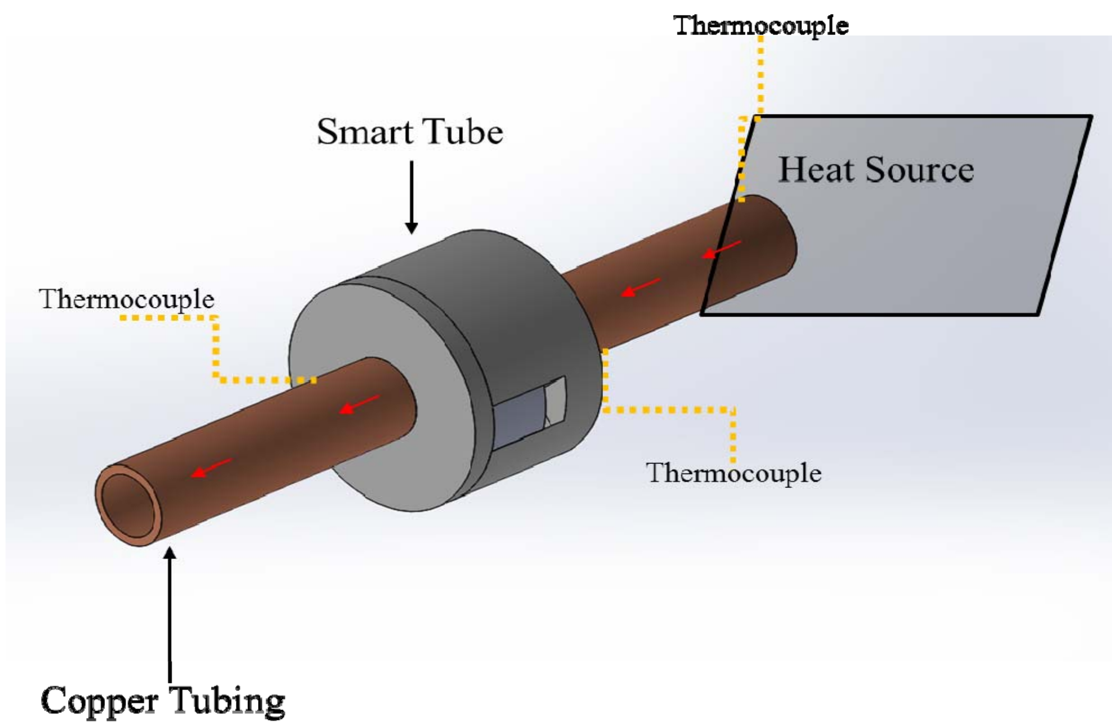


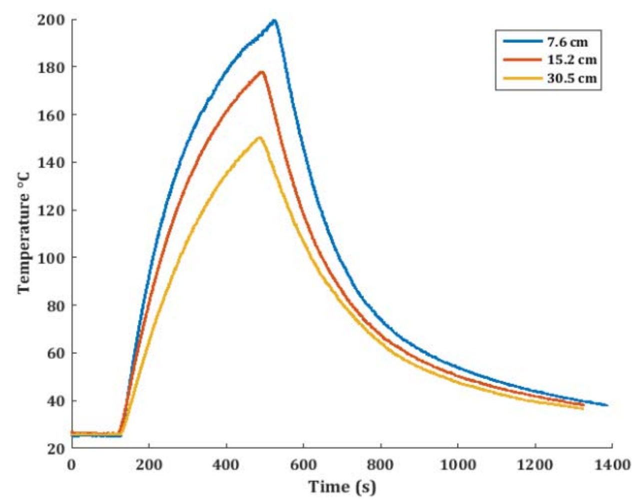
- Force sensing with embedded sensor demonstrated
- 1,5,10 Hz of dynamic force was used
- 0.04, 0.011 and 0.0064 (V/kN) of sensitivity was achieved
- Lower sensitivity caused by sensor packaging clearance and force loading directions

Temperature Sensing

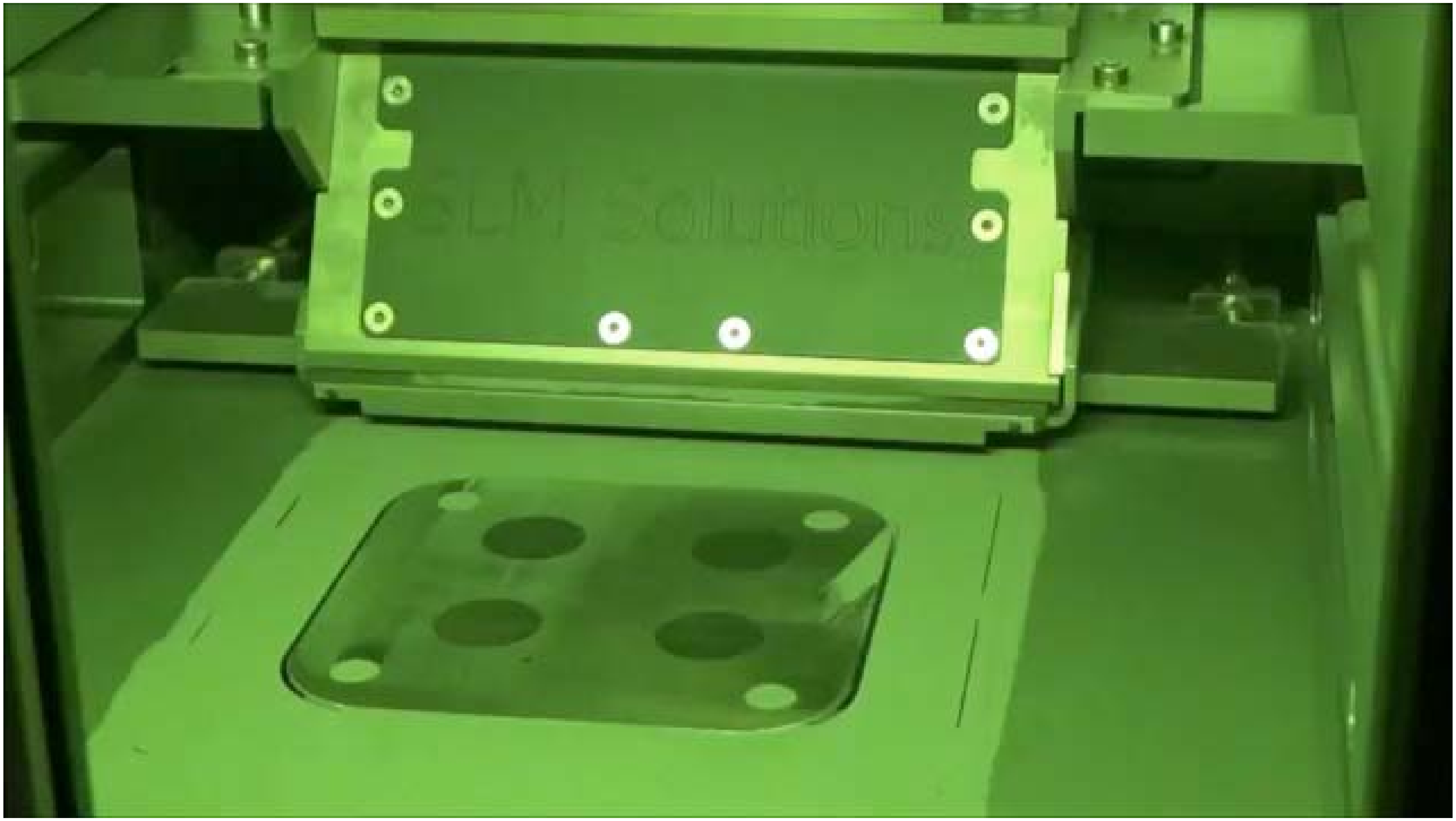


Sensed temperatures of 198 ºC, 178 ºC, and 150 ºC for 7.6 cm, 15.2 cm and 30.5 cm long tube sections

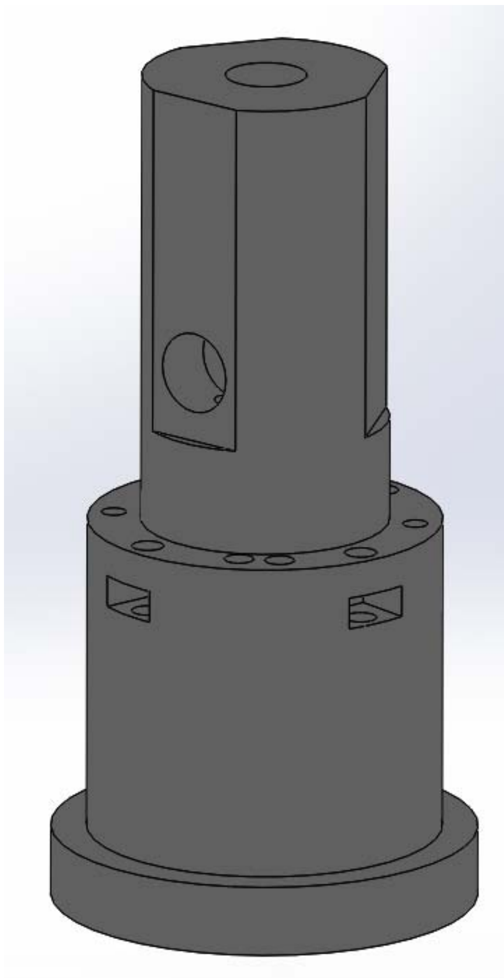




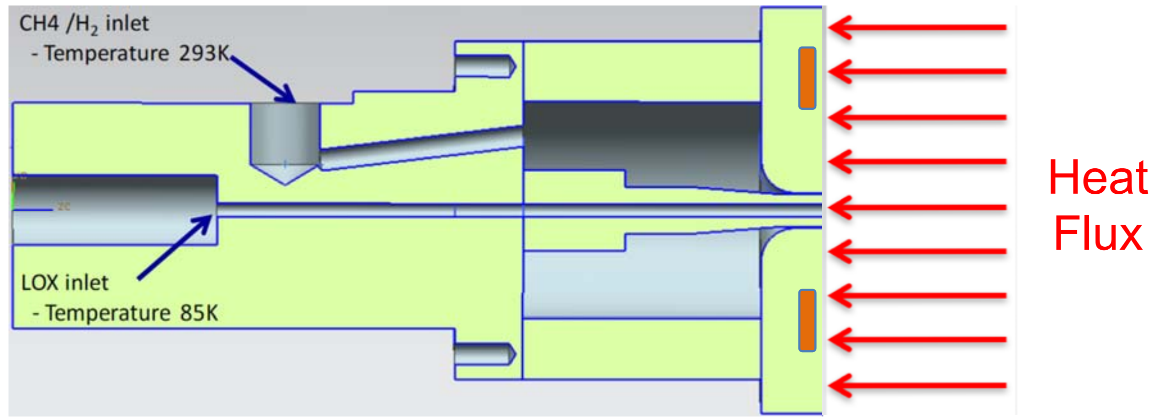
Selective Laser Melting Demo

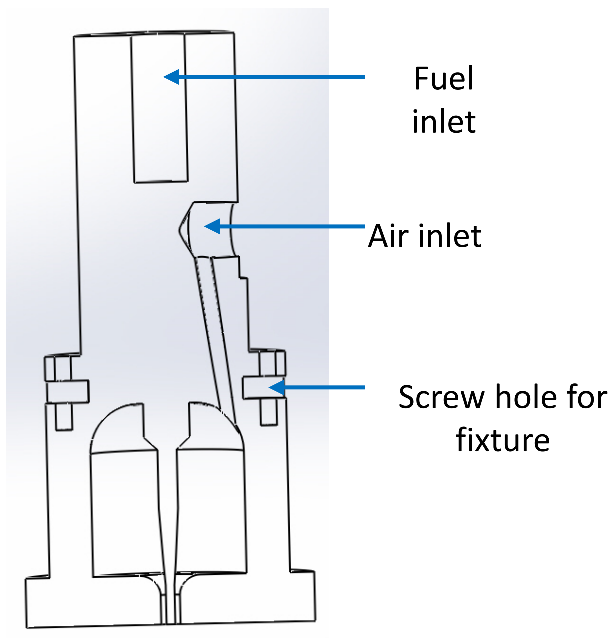


CAD Drawing of Smart Injector



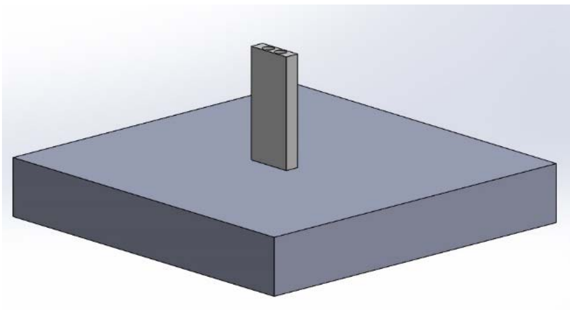
3D View



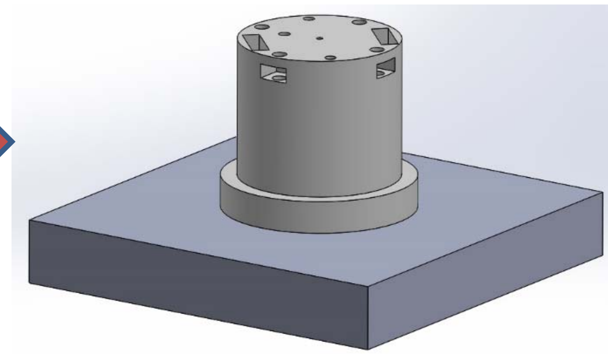


- Thermal soak-back sensing
- Allows for operation at lower safety factors
- Higher temperatures and higher efficiencies

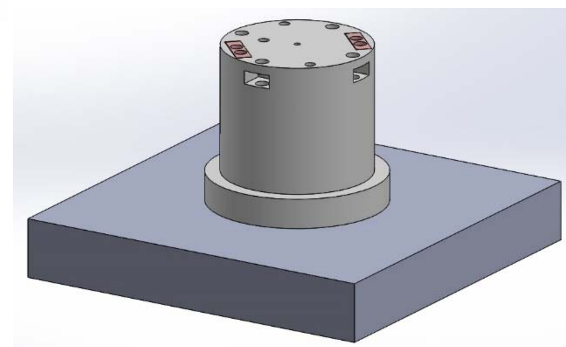
Design of Smart Injector Fabrication



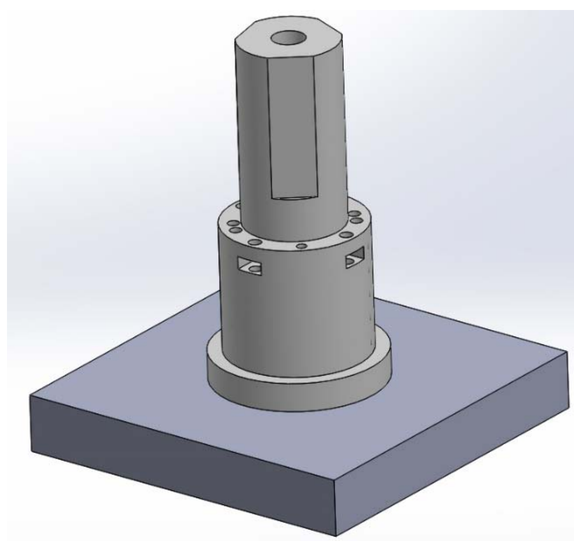
Fabrication of insert part



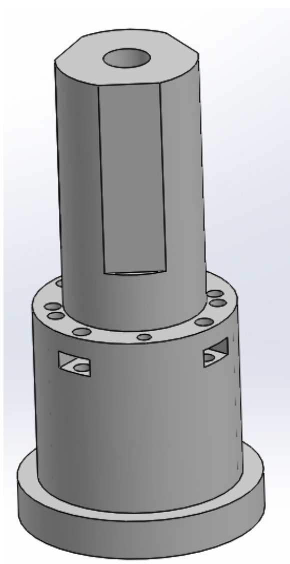
Fabrication of bottom part



Sensor assembly



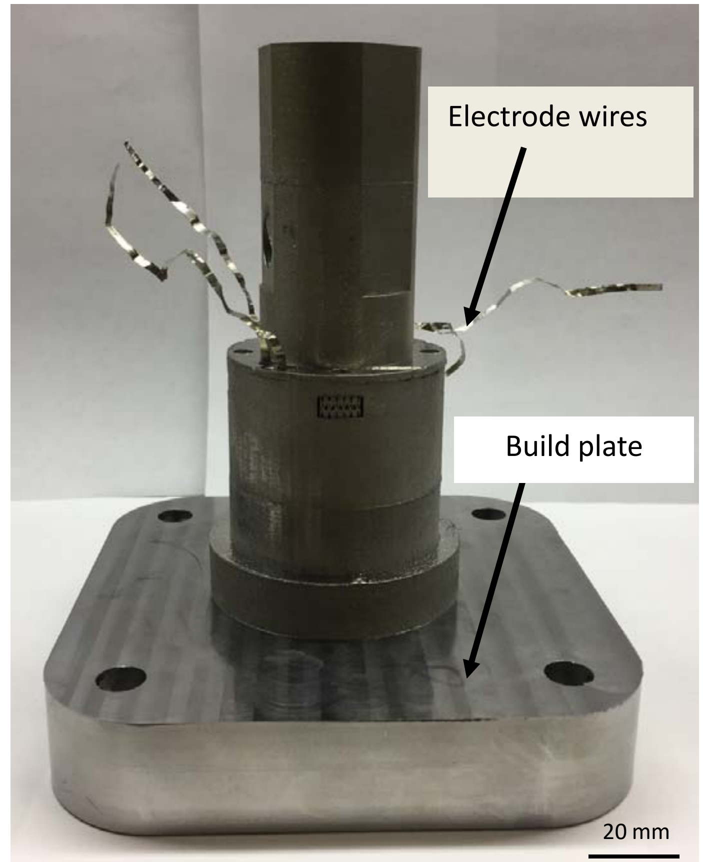
Fabrication of entire part



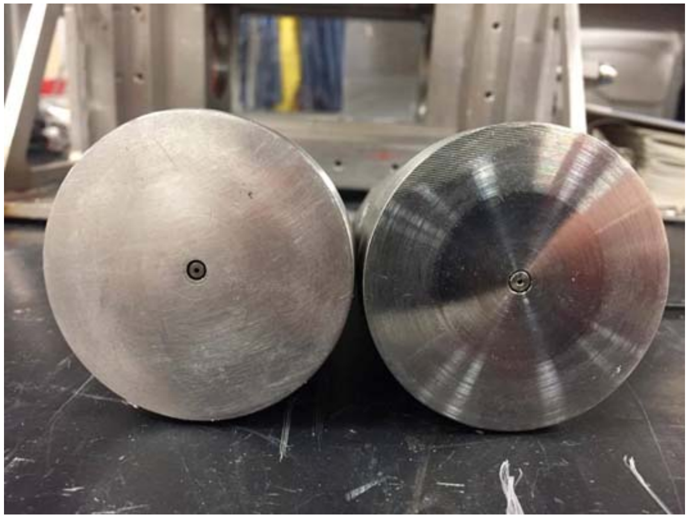
Final smart part

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



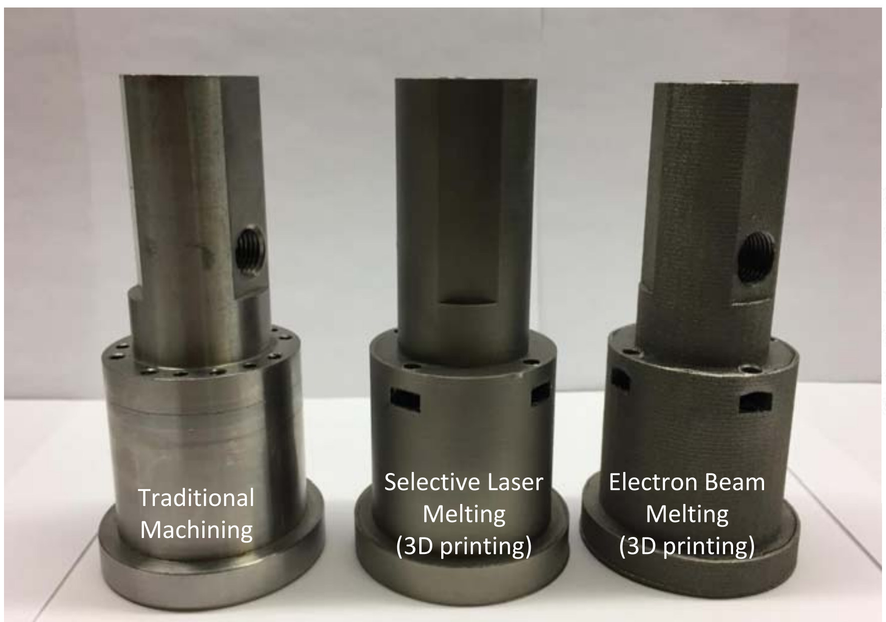
Surface Roughness Comparison between SLM, EBM, and Machining

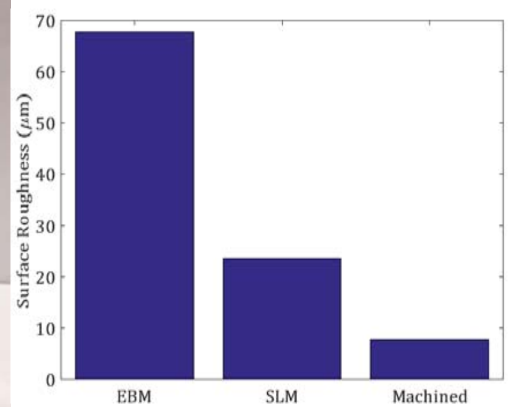


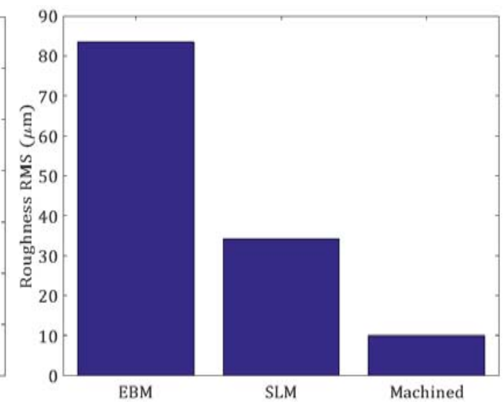
Cost:

EDM Machined: $6,000, 2 months

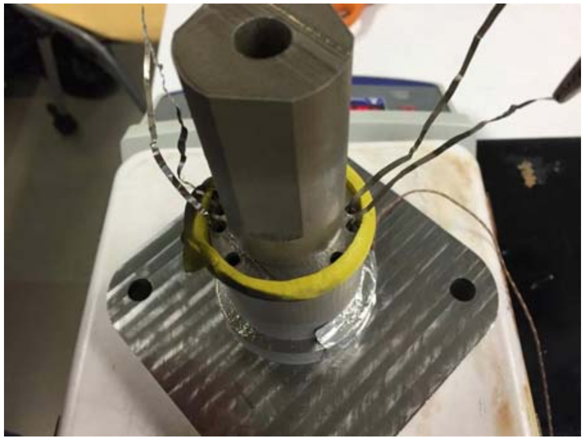
SLM 3D printing: $1,500, 2 days

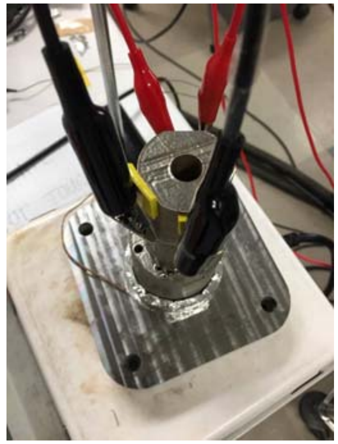


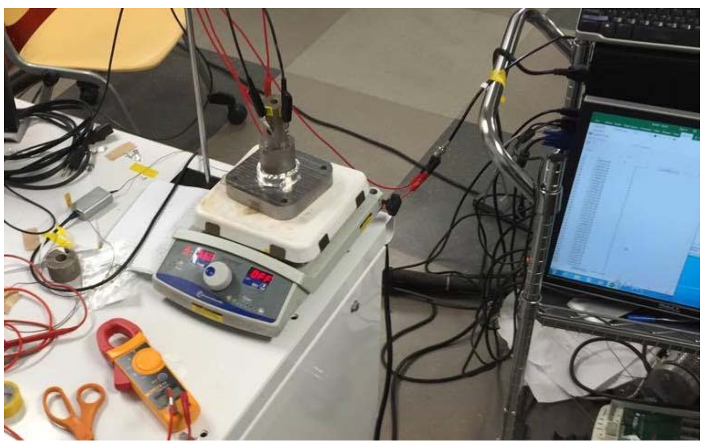


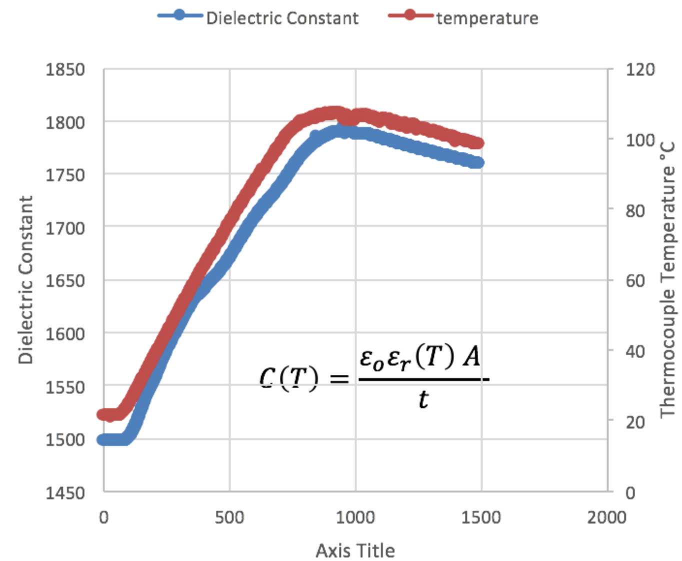


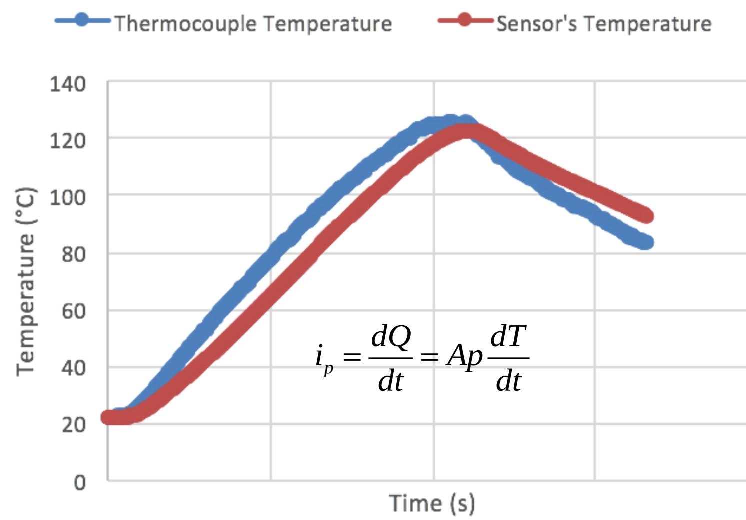
Preliminary Temperature Sensing Setup of the 3D printed injector











In-situ Sensing Demonstration Procedures

Pre-test

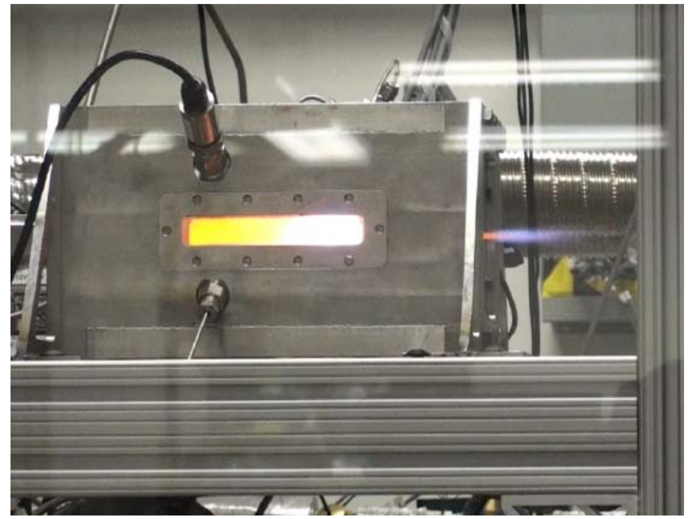
- Prove that each valve is working properly
- Make sure all readings are correct from pressure and temperature transducers and flow meters (ambient or zero)
- The line will be pressurized and Snoop will be used on each connection to check for leaks.

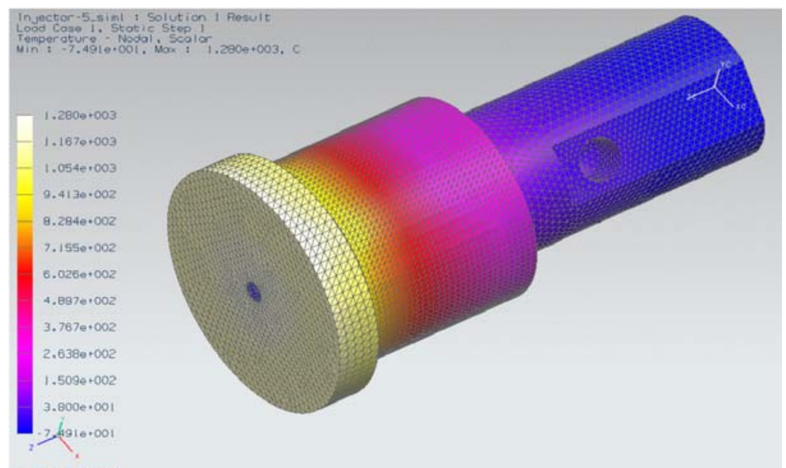
Measuring pressure drop across the system (Cold flow testing)

- 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

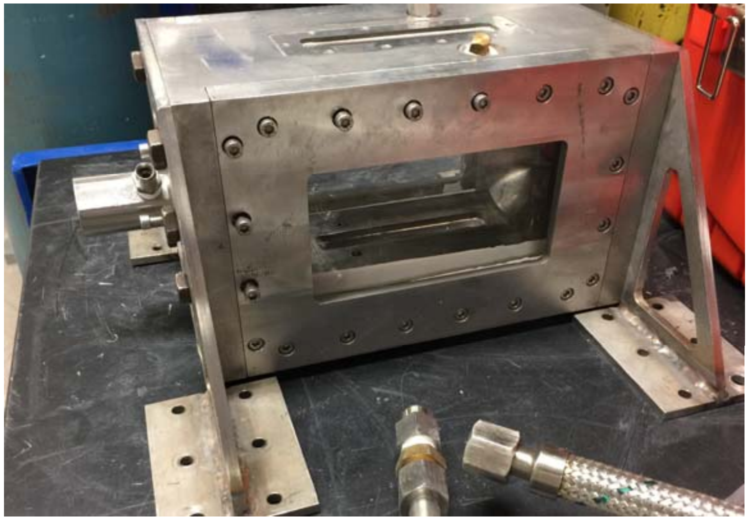
Hot firing test

- 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.

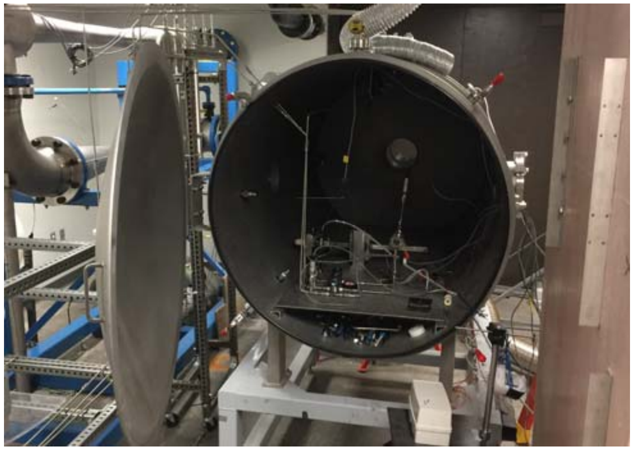




Smart Fuel Injector Testing Setup



Multi-purpose Optically Accessible Combustor (MOAC)



MOAC System

- 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

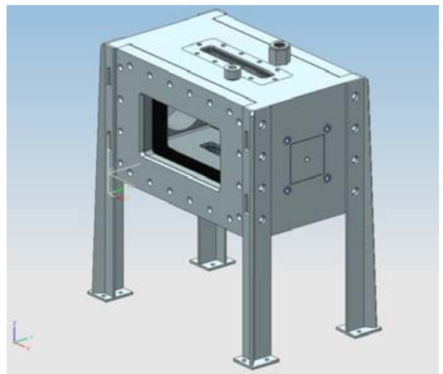
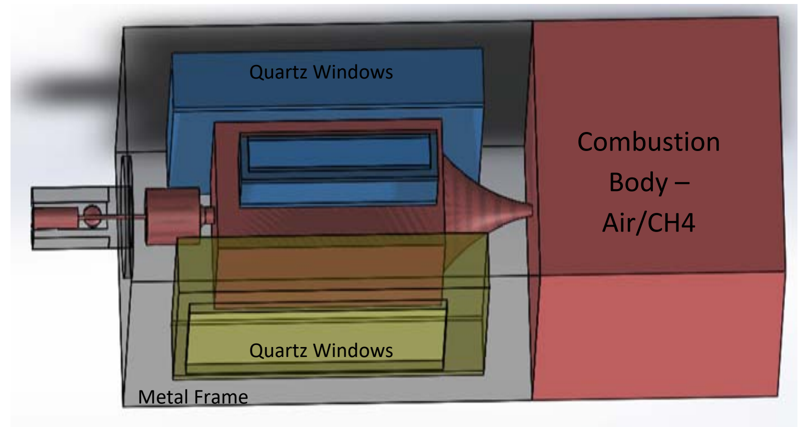
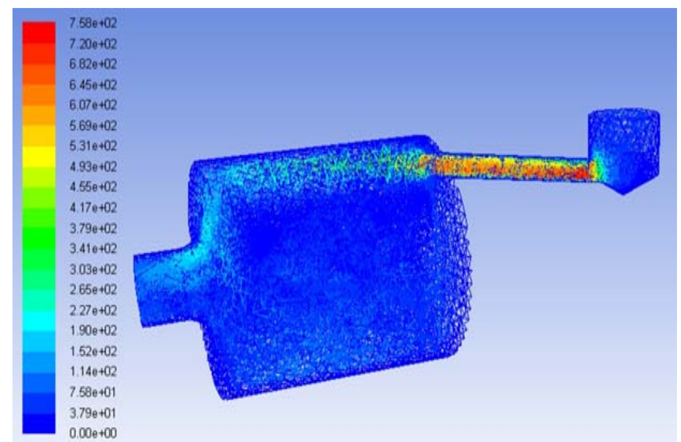


Fig 1. MOAC CAD model

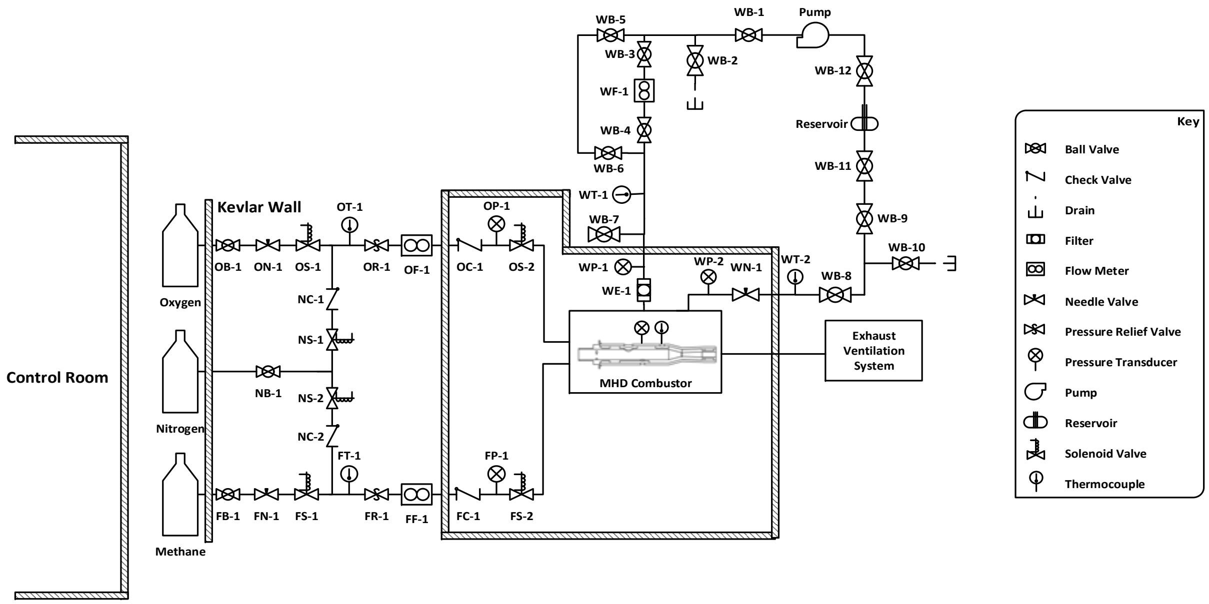
Fig 2. MOAC assembly

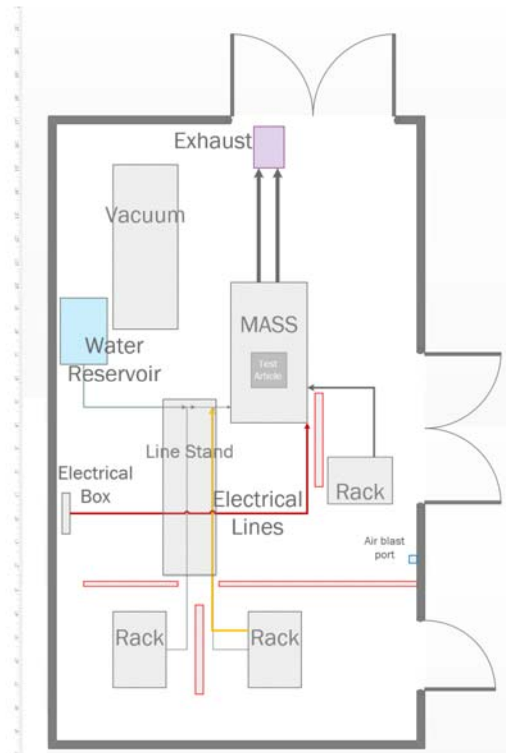




Modeling of the Surface roughness vs Pressure drop

Schematic and bunker diagram





Pressure drop and flow rate test of machined injector

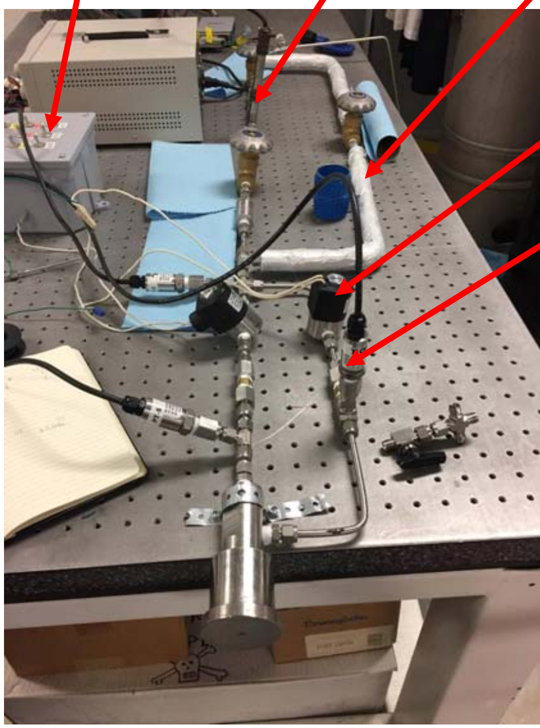
Solenoid valve control

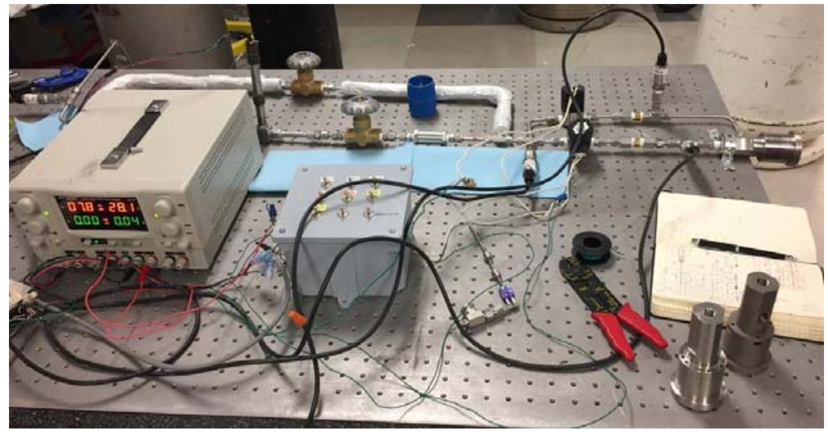
Flow meter

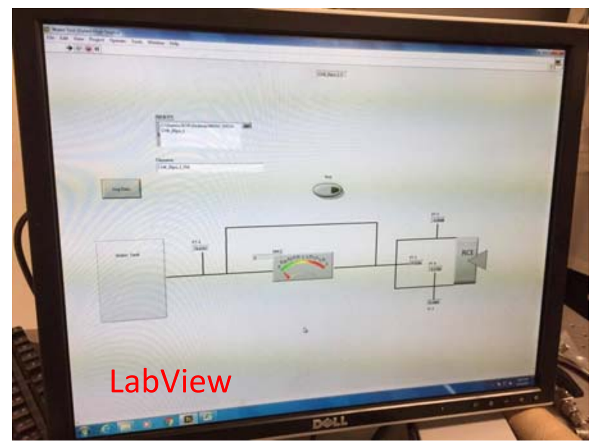
Bypass

Solenoid valve

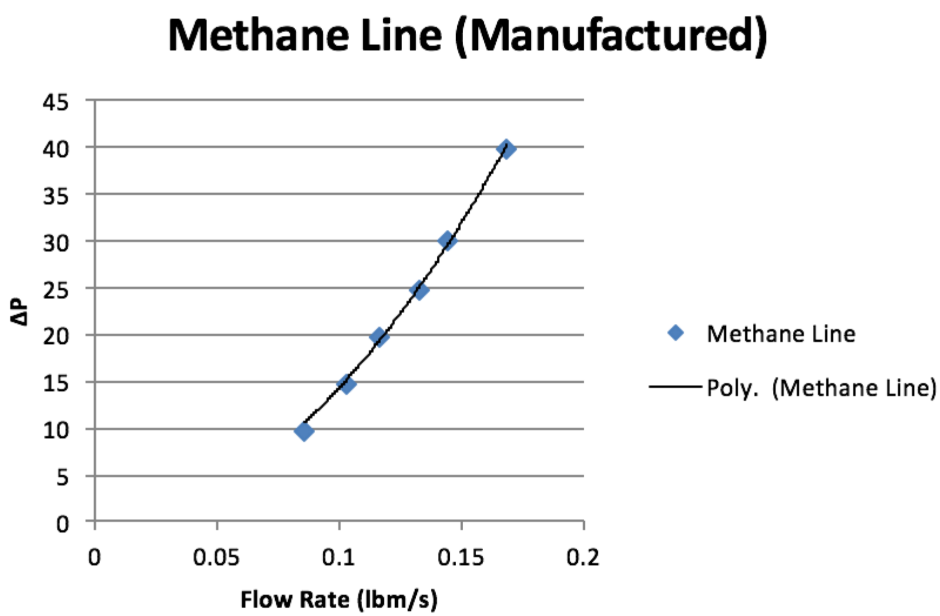
Pressure transducer

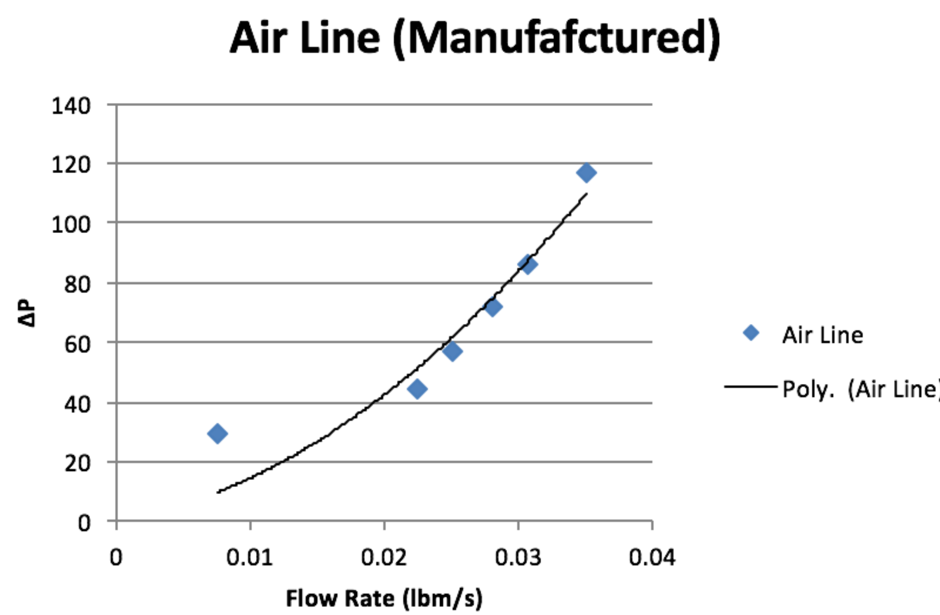






Flow rate and pressure drop results of machined injector

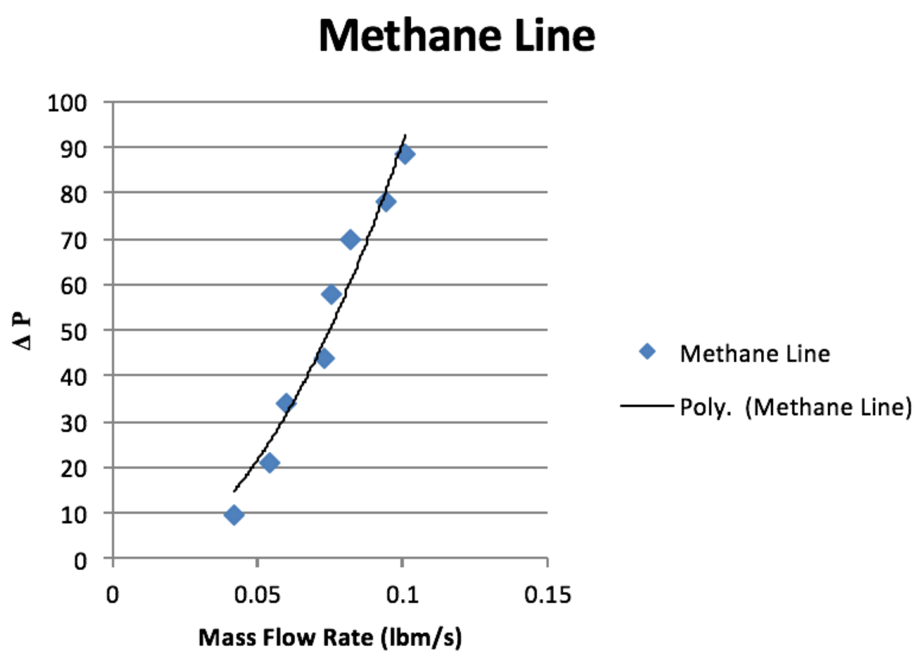


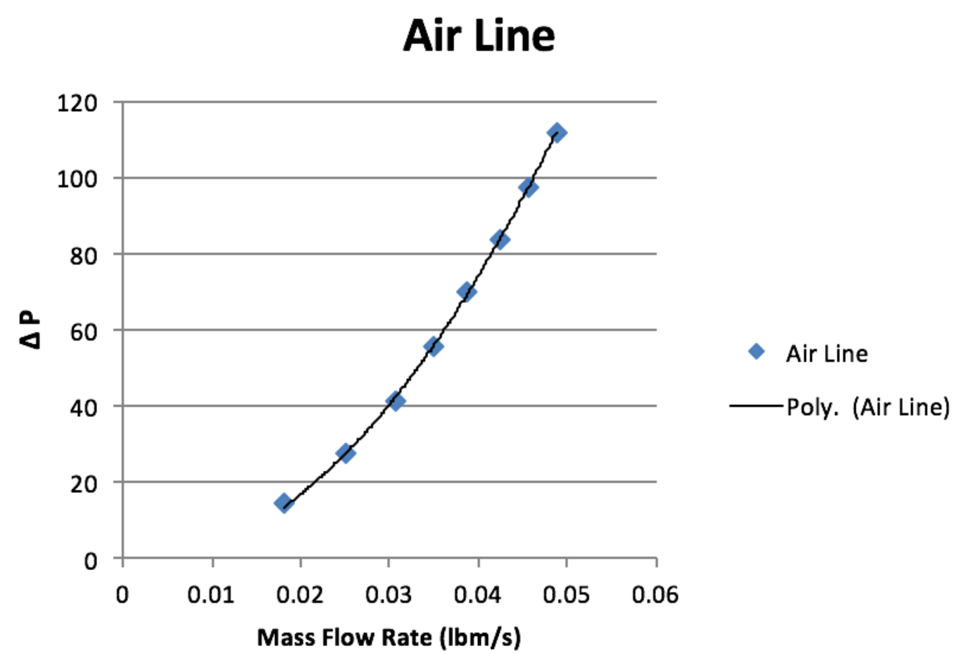


Pressure drop and flow rate test of 3D printed injector



Flow rate and pressure drop results of 3D printed injector

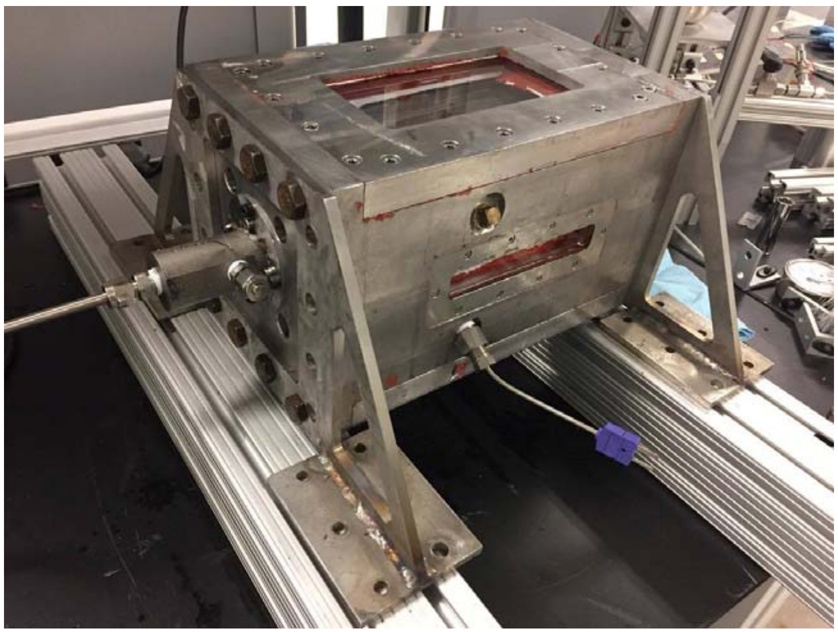


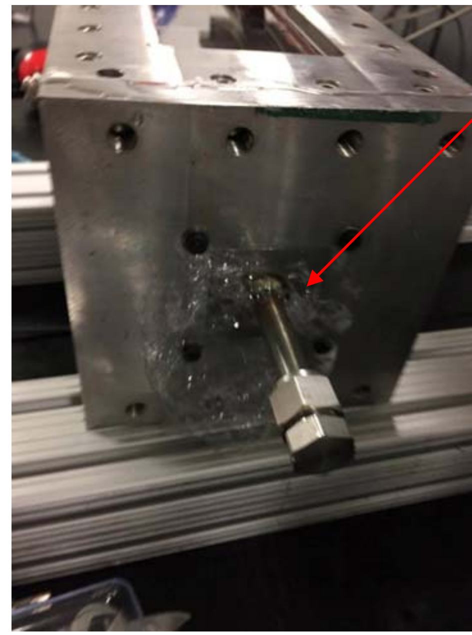


Insertion of 3D printed injector

Electrodes

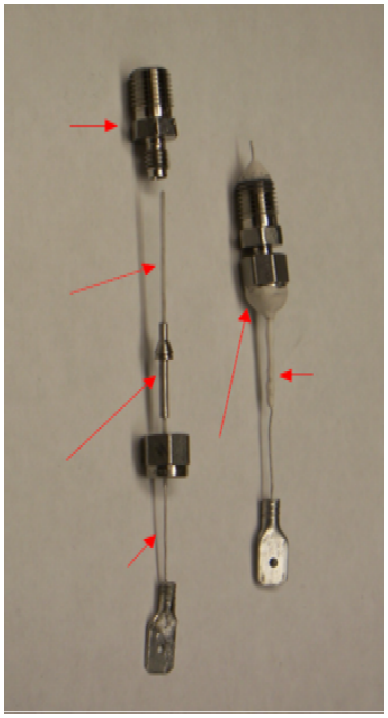
Leak test using helium



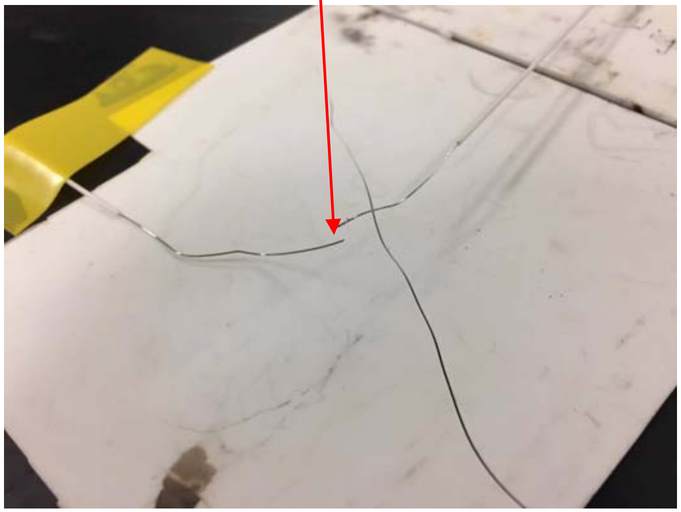


Leak

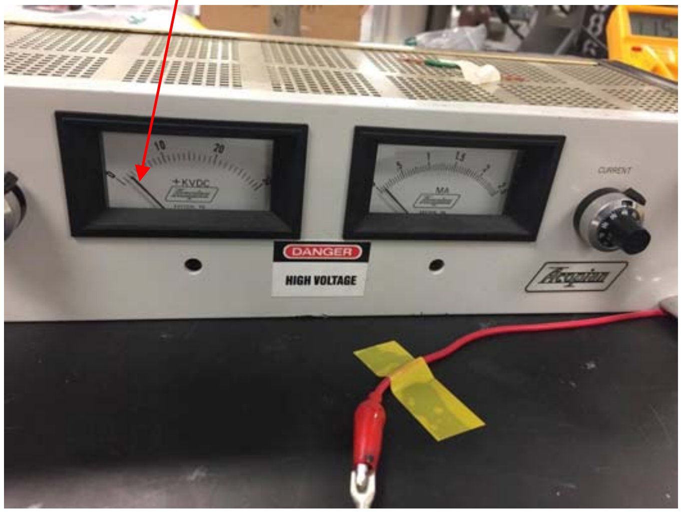
Spark electrodes fabrication and testing



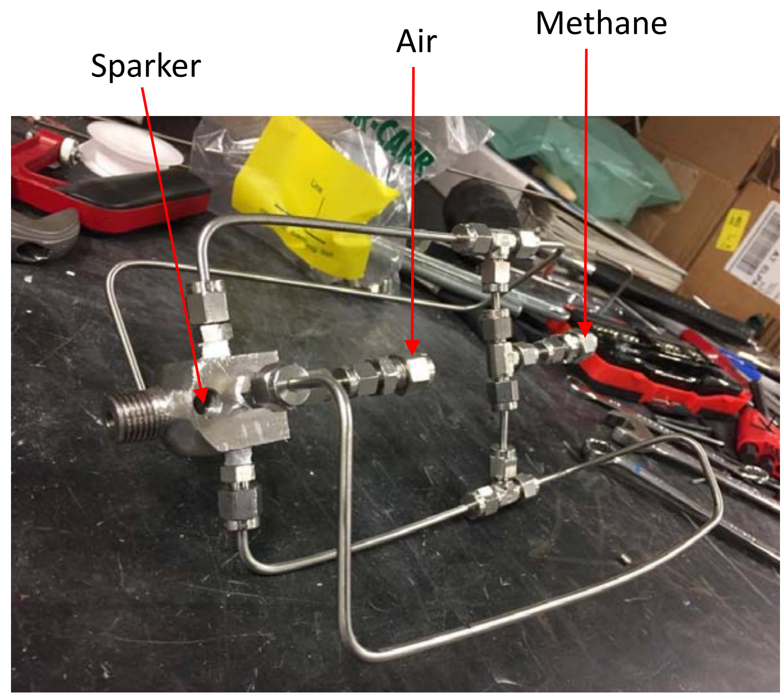
Spark



4-5 kV



Torch igniter assembly



Hot fire testing of CH_4 and air using a 3D printed injector

Stoichiometric equation for combustion of CH4 and air:

$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H2O + 7.52N_2$

Molecular weight of CH4 = 16.043 g/mol
Molar mass
C = 12.011 X 1 atom X 1 mole
H = 1.008 X 4 atom X 1 mole
Molecular weight of $2(O_2 + 3.76N_2)$ = 274.66 g/mol
Molar mass
O = 15.9994 X 2 atoms X 2 moles = 64
N = 14.007 x 2 atoms x 7.52 moles = 210.66 g/mol

$O/f = \frac{274.66}{16.043}$

$O/f = 17.16$

Chamber Pressure	Units	20	25	30	35	40	45
Methane flow	LPM	4.9	6.85	8.22	9.59	10.96	12.32
Air flow	LPM	93.26	109.63	131.54	153.45	175.36	209.6
Fuel tank pressure	PSI						
Air tank pressure	PSI						

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). cstar was used to calculate the total flow rate exiting the chamber at the throat as follows:

$$c^* = \frac{P_o * A_t}{\dot{m}}$$

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:

$$Q = H_p - H_r$$

or

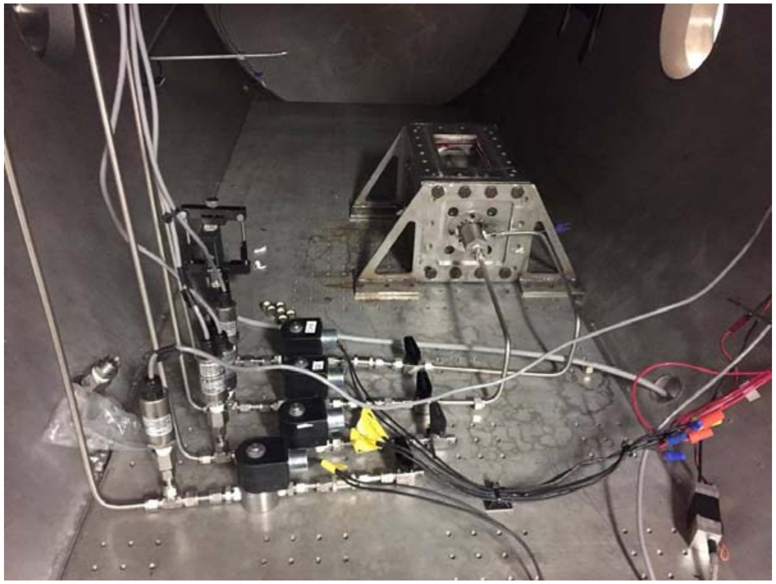
$$Q = (LHV)_{methane} * \dot{m}_f$$

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:

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

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

- Gonzalez, J., Mireles, J., Lin, Y., and Wicker, R., 2017,“Economical analysis of different metal 3D printing technologies,” *Additive Manufacturing*, in review.
- Hossain, M., Gonzalez, J., Mireles, J., Choudhuri., Lin, Y. and Wicker., R., 2017. “Interfacial tuning of Electron Beam Melting 3D printing in ‘Stop and Go’ Metal Fabrication”. *Additive Manufacturing*, in review.
- Martinez, R., Hossain, M., Mireles, J., Lin, Y., and Wicker, R., 2017,“Design, Fabrication, and Testing of smart tube with embedded smart materials using electron beam melting technology ,” *Smart Materials and Structures*, in review.
- Hossain, M., Mireles, J., Wicker, R., 2017,“Computer vision enabled ‘stop and go’ alignment process in metal 3D printing,” *Computer-aided design and manufacturing*, in review.
- Gonzalez, J., Mireles, J., Lin, Y., and Wicker, R., 2016,“Characterization of ceramic components fabricated using binder jetting additive manufacturing technology,” *Ceramics International*, in press.
- 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.
- Gaytan, S., Cadena, M., Karim, H., Delfin, D., Lin, Y., Espalin, D. MacDonald, E. and Wicker, R., 2015, “Fabrication of barium titante by binder jetting additive manufacturing technology,” *Ceramics International*, 41, 6610-6619.
- M. S. Hossain, J. Mireles, and R. Wicker, “Method of Fabrication for the repair and augmentation of part functionality of metallic components”, U.S. Patent Pending, filed with U.S. Patent and Trademark Office, October 2015
- 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

- 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

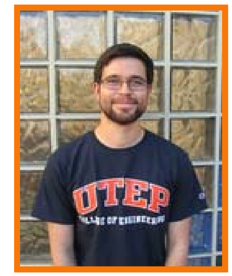
NavAir

Exxon Mobile

Intel, inc

Intel, inc

Intel, inc



Intel, inc

Arconic

Thank you

Questions?