Metal 3D Printing of Low-NO_x Fuel Injectors with Integrated Temperature Sensors

Presented by:
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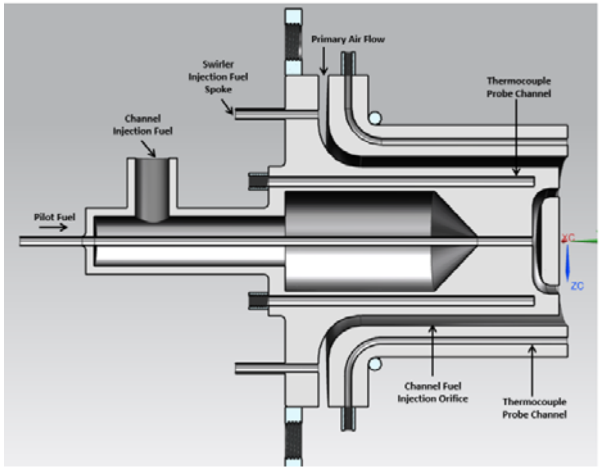
Motivation

- The purpose of the project is to fabricate low-NO_X fuel injectors for natural gas turbine combustors with electron beam additive manufacturing
- Low NO_X injectors are conventionally manufactured with a multi-step machining and welding process
- Additive manufacturing enables the design and fabrication of complex internal cavities and channels for placement of sensors (i.e. Thermocouples)

SLM Printer

EBAM Printer

Fuel Injector with internal cavities



Problem Statement

- Electron beam additive manufacturing sinters powder to improve the fabrication process
- Sintered powder obstructs fluid flow channels and sensors placement cavities
- A method to remove sintered is required in order to fabricate end use parts

Electron Beam Additive Manufacturing

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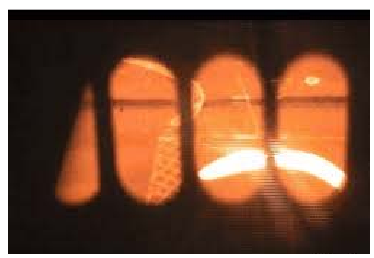
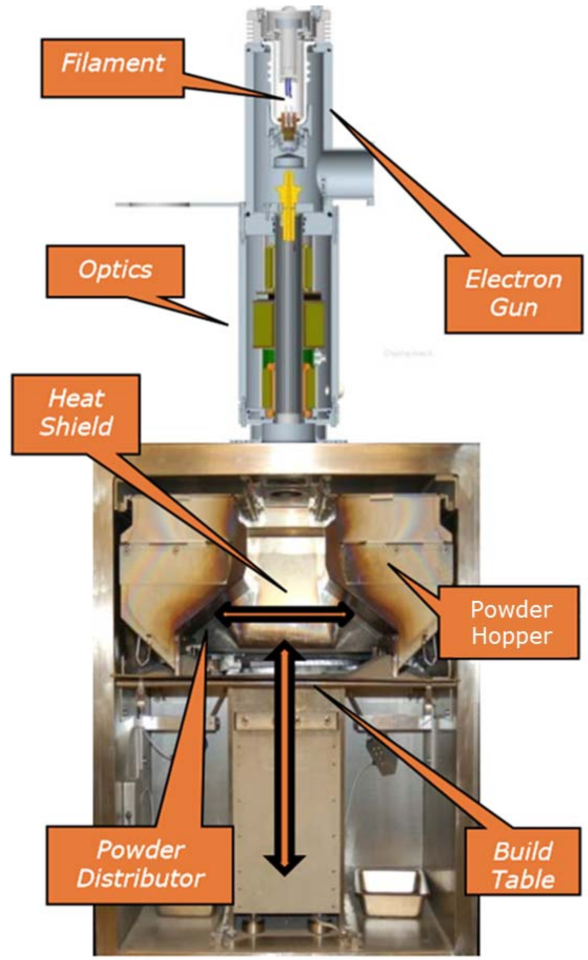
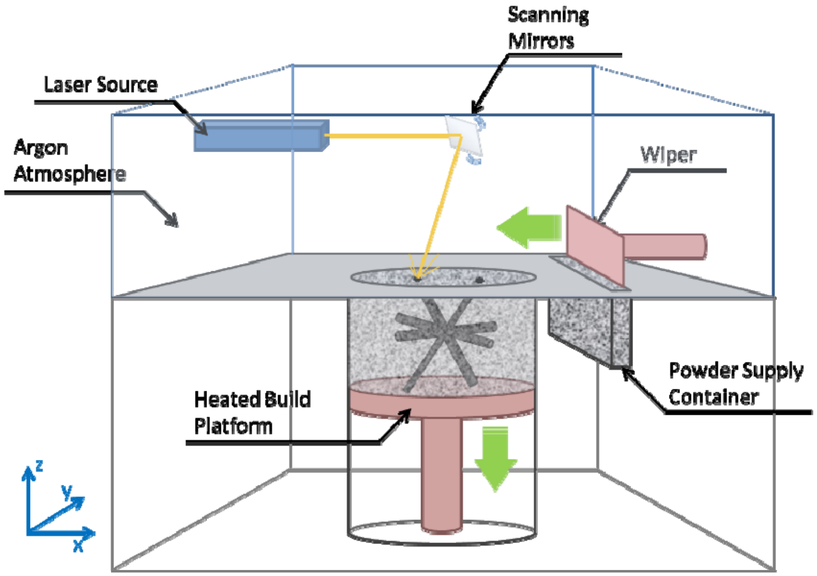
- Superior control of thermal profile – fabricated at elevated temperature
- Design Freedom
- High Temperature capabilities
- Built in a vacuum chamber

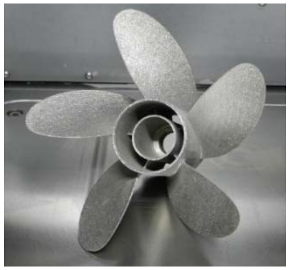




Selective Laser Melting (SLM)

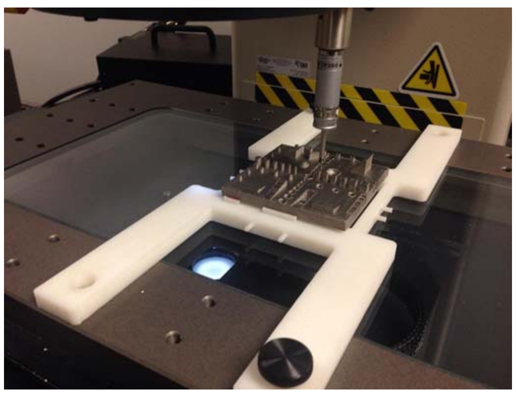
- Powder bed fusion process – same as electron beam additive manufacturing
- Better surface finish than EBAM
- Fabricated at low temperatures; can require post heat treatment
- Does not sinter powder



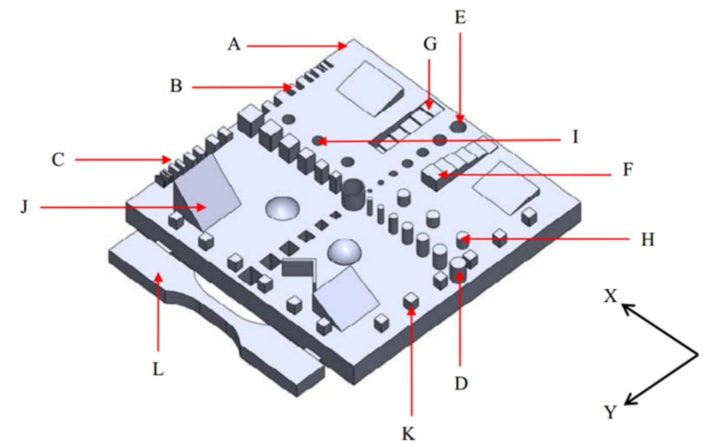


Dimensional verification

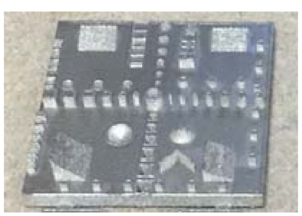
- A ranking model was used to evaluate the dimensional accuracy of the three EBAM machines, A2X, A2, and S12



Coordinate measurement machine and jig

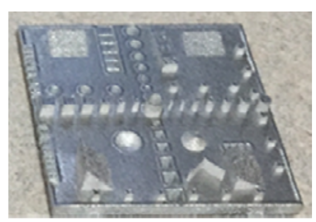


Letter	Feature	Factor Tested
A	Square base	
B	Lateral ridges (+)	
C	Lateral ridges (-)	
D	Descending cylinders (-)	
E	Descending cylinders (+)	Dimensional accuracy
F	Staircase (-)	
G	Staircase (+)	
H	Cylinders (-)	
I	Cylinders (+)	
J	Ramps	Surface roughness
K	Rectangular prisms	Linear displacement error
L	Tensile bar	Ultimate tensile strength



Arcam A2X

Arcam A2



Arcam S12

Dimensional Verification Results

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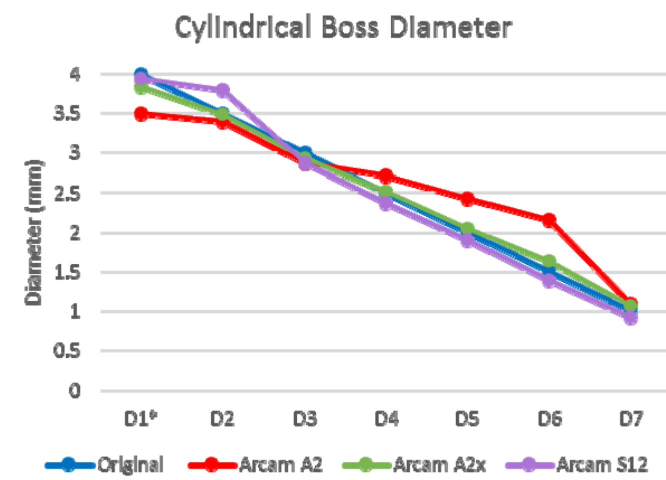
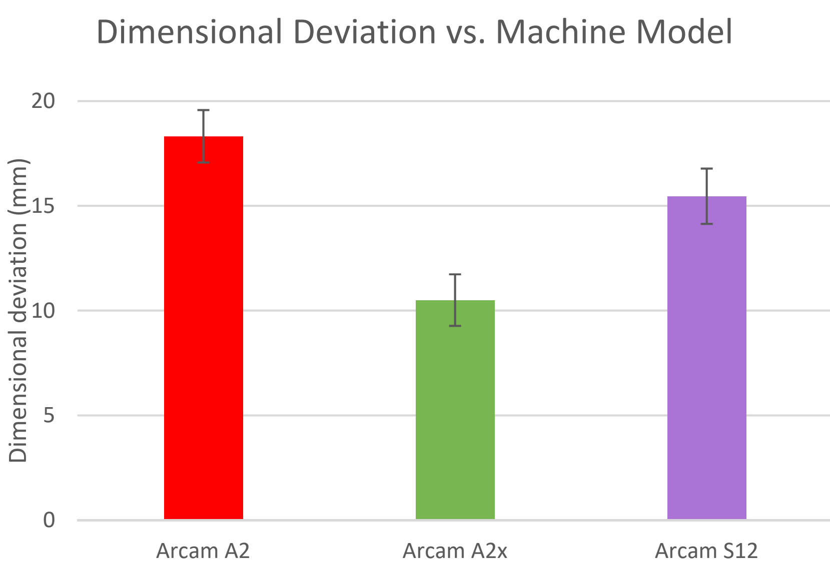
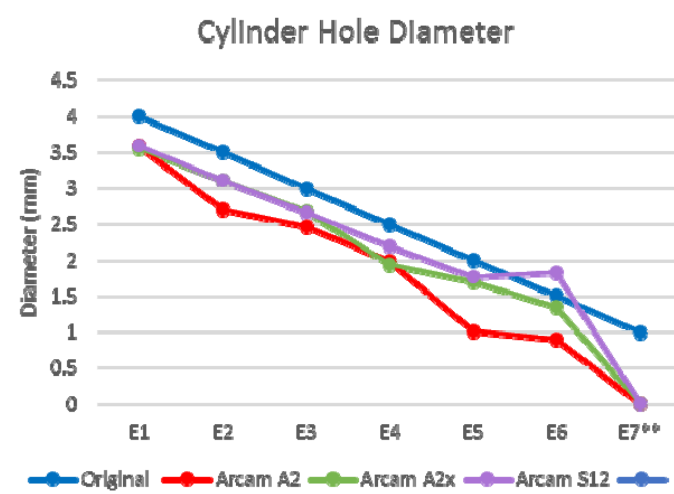
- Features smaller than 2.5 mm tended to deform
- Wall thickness was greater than designed – possibly due to surface roughness

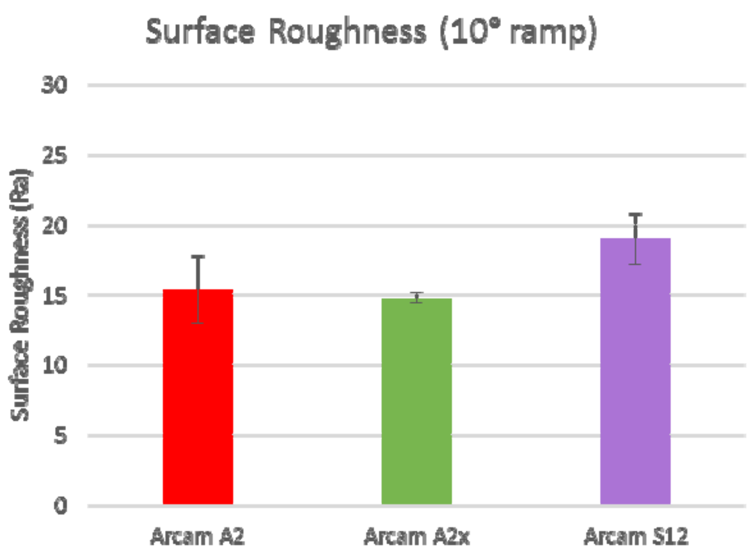


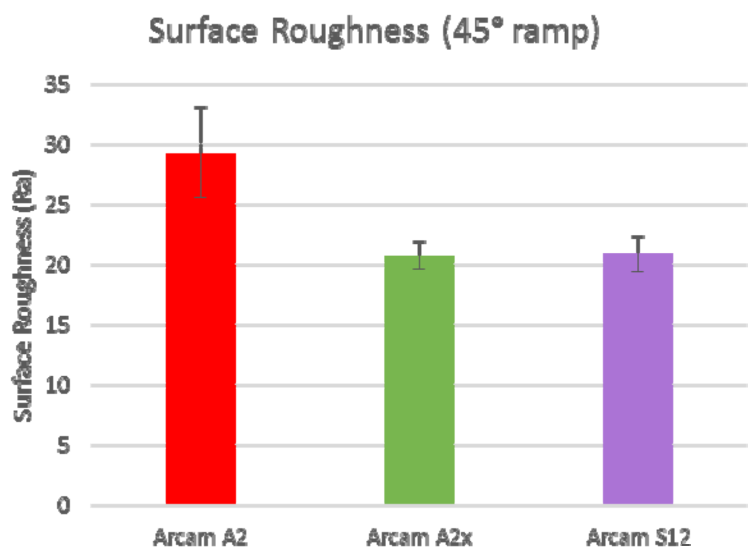




Surface roughness

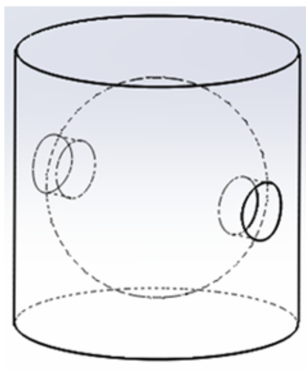
- Surface roughness was measured on two ramp features



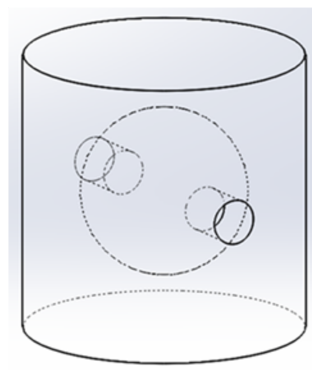


Preliminary powder removal evaluation

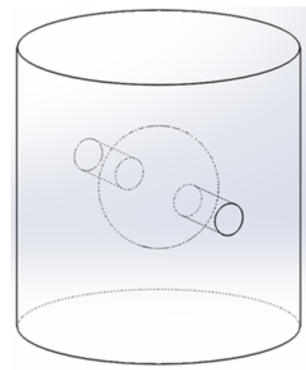
- Powder removal methods were testing on several wall thicknesses and orifice diameters (1, 2, 4, 6 mm)



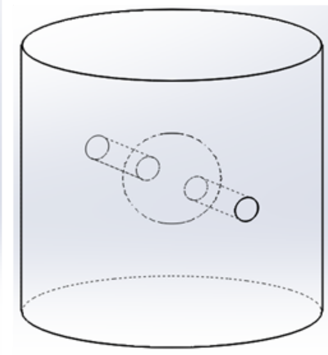
19mm cylinder
(4mm channel)



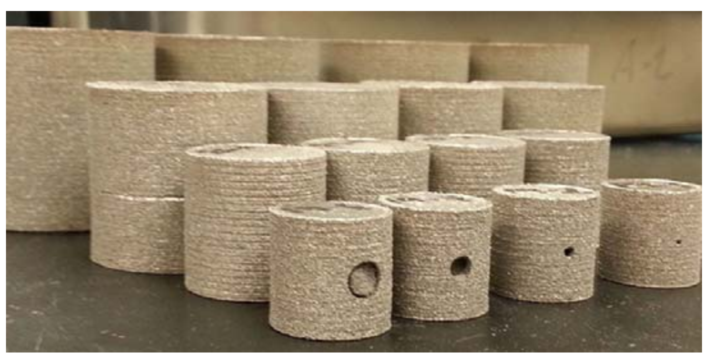
25mm cylinder
(4mm channel)



35mm cylinder
(4mm channel)

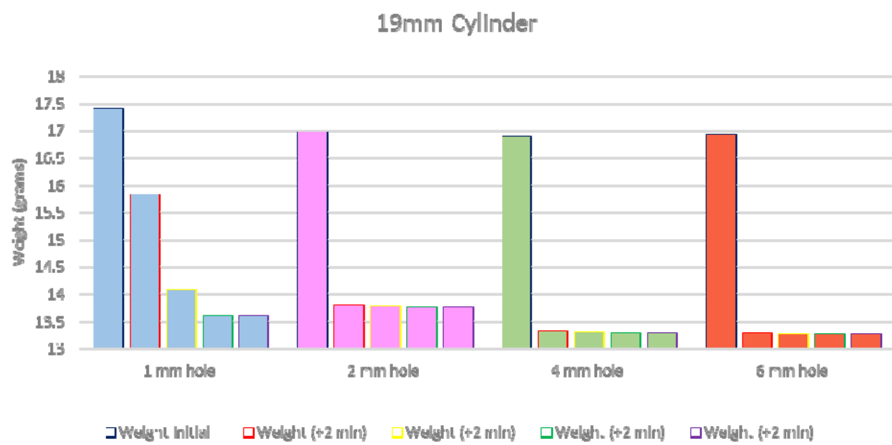


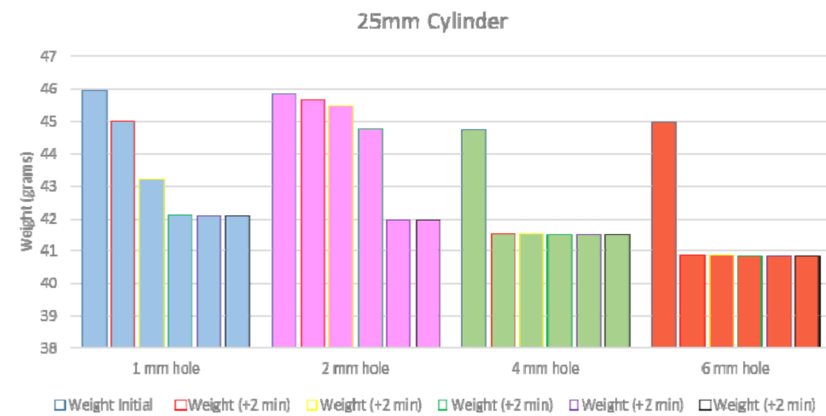
45mm cylinder
(4mm channel)

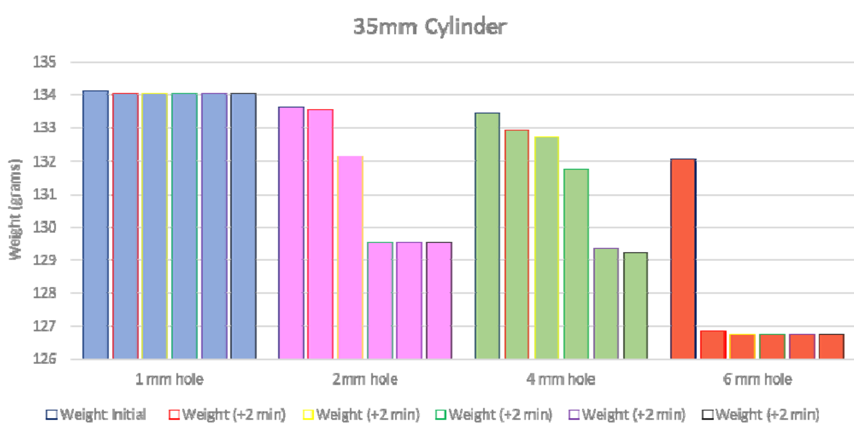


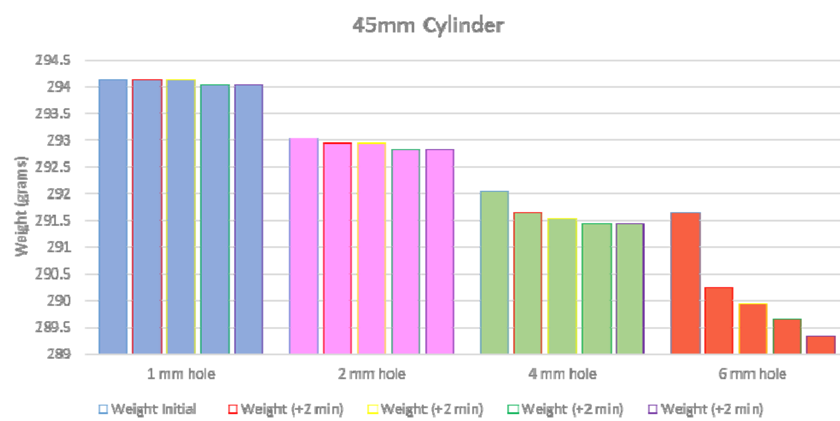
Preliminary powder removal evaluation

- After applying ultrasonic vibration









Powder Removal Methods

- Powder Recovery System (PRS)
- Vapor Blast
- Ultrasonic
- Ultrasonic & Hammering
- Chemical Etching
- Liquid Nitrogen & Ultrasonic

Powder Recovery System (PRS)

Vapor Blast

Ultrasonic

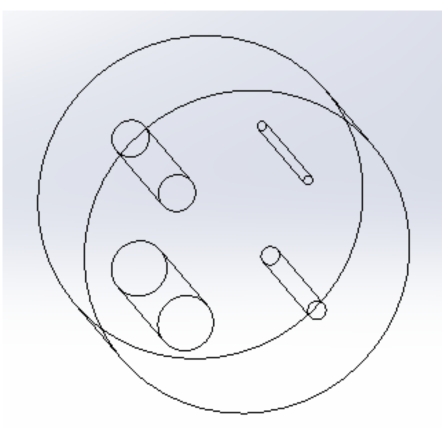
Liquid Nitrogen

Chemical etching

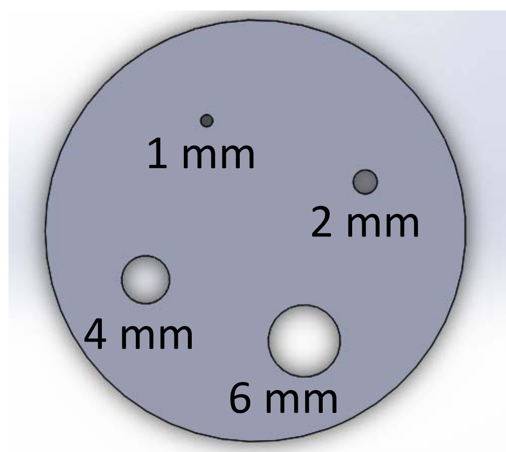
Hammering

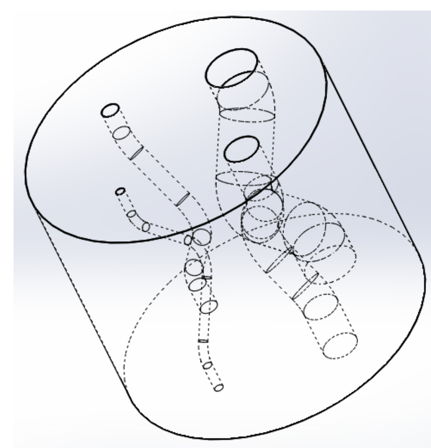
Methodology

- To evaluate powder removal methods, a design of experiments was created



Straight holes



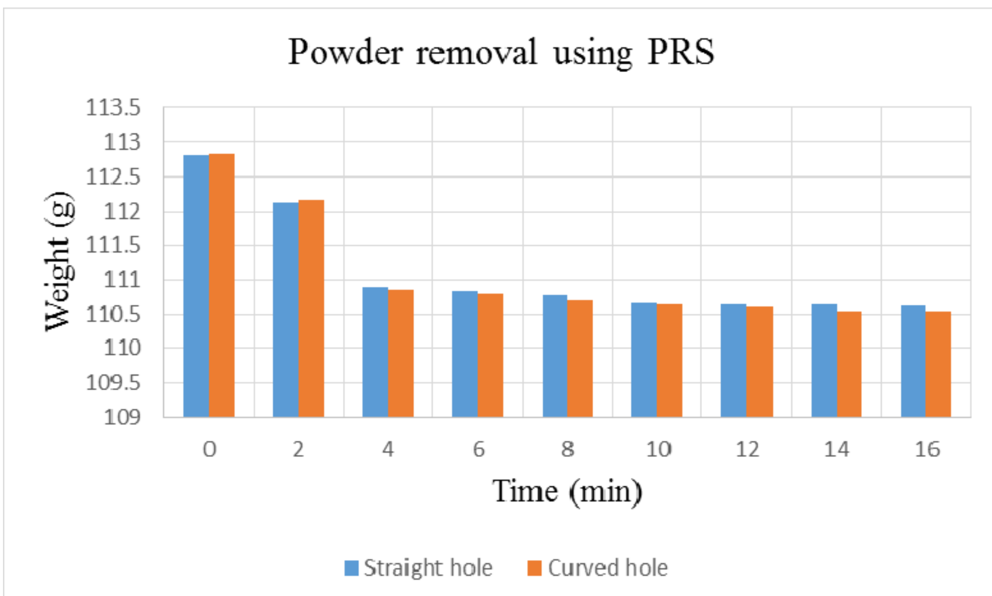


Curved holes

Powder Recovery System (PRS)

- Pressurized air blasts metal powder
- Powder is recovered and reused
- After 6 minutes the part was clean

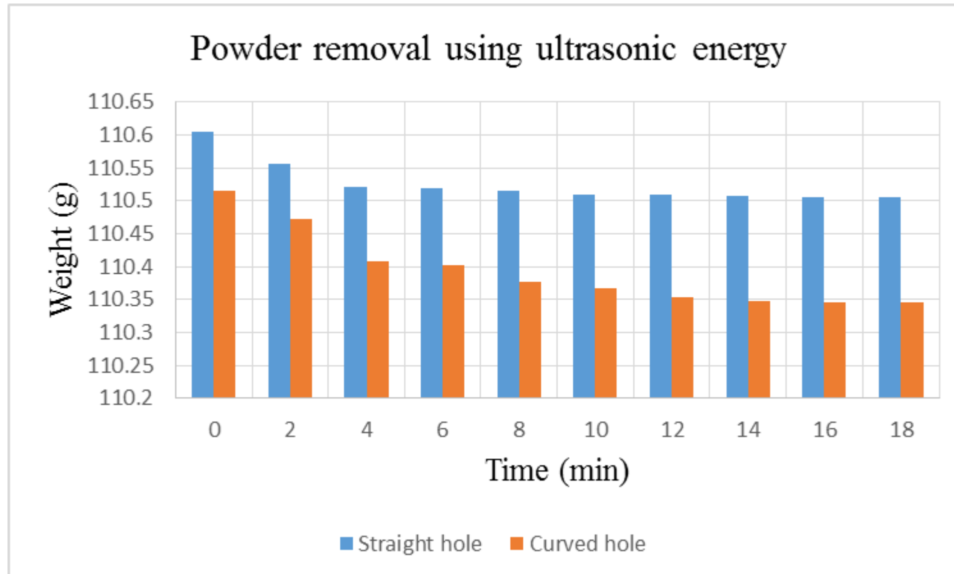
Part after printing



PRS

Ultrasonic

- Ultrasonic vibrations are applied to the part to break up sintered powder
- After 6-8 minutes weight change stagnated

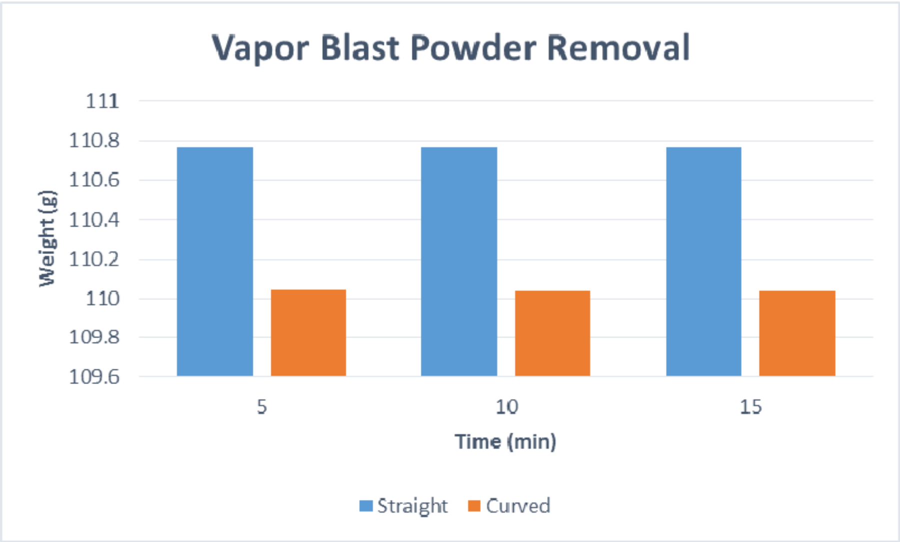


Ultrasonic application wand

Ultrasonic controller

Vapor Blast

- Parts were blasted with a slurry of sand and water
- Vapor blasting was found to be ineffective

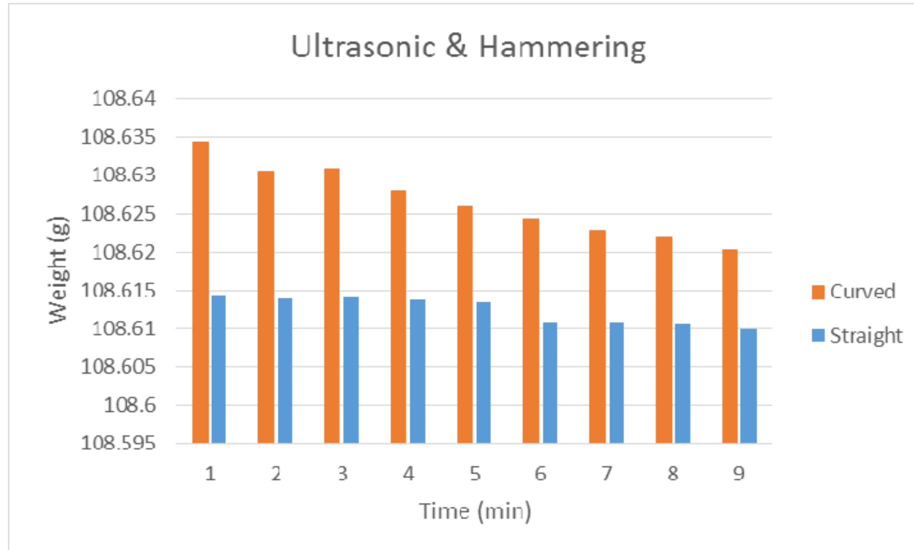


Vapor Blast Station


Parts after blasting

Ultrasonic and Hammering

- Testing consists of 1 minute ultrasonic vibration followed by 1 minute of hammering
- Effective after the first application for straight channels
- Effective after 6 minutes in curved channels



1 minute ultrasonic vibration

1 minute rubber mallet

Light was shown through the holes to assess powder removal

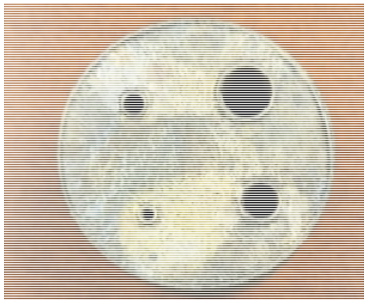
Chemical testing

- Two etchants were tested, Kroll’s reagent and Kellers etch
- Solutions were applied directly to specimen, no change was observed after 60 seconds
- Specimens were placed in both solutions for 22 hours; no effect

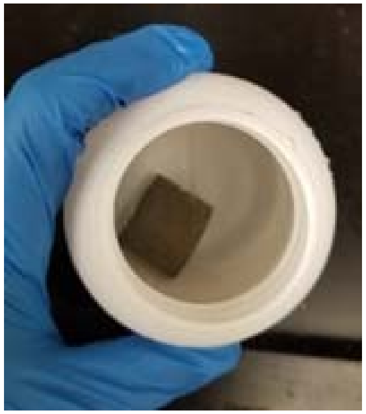
Kroll’s Reagent
- 92 mL Distilled water
- 5 mL Nitric acid
- 2 mL Hydrofluoric acid

Kellers Etch
- 190 mL Distilled water
- 5 mL Nitric acid
- 3 mL Hydrocloric acid
- 2 mL Hydrofluoric acid

After Kellers etch

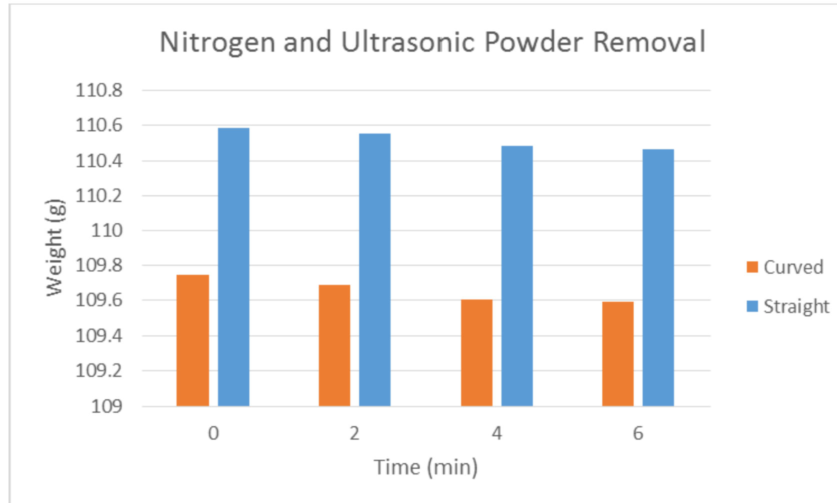


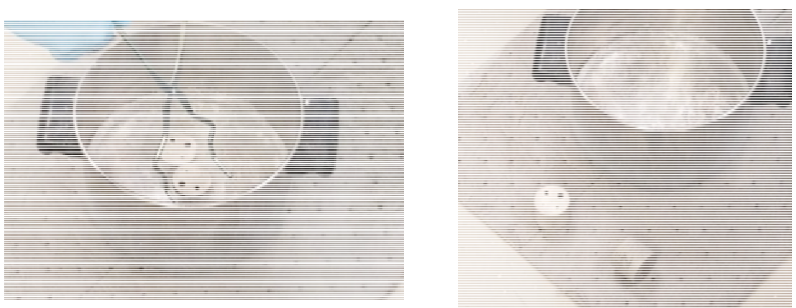
After Kroll’s reagent



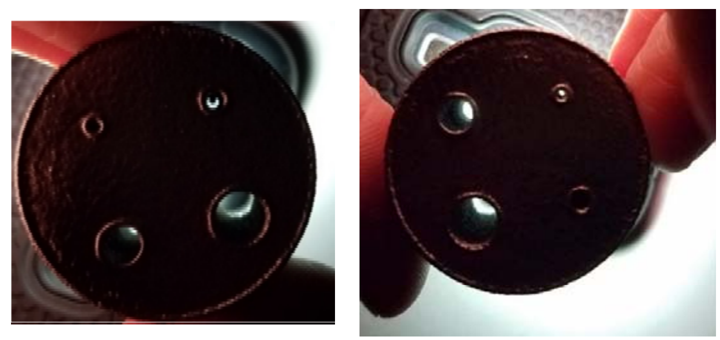
Liquid Nitrogen and Ultrasonic

- Parts were placed in liquid nitrogen for 30 seconds and followed by 2 minutes ultrasonic vibration
- All the holes were cleared after the first application





Parts dipped in liquid nitrogen



Holes after liquid nitrogen and ultrasonic vibration

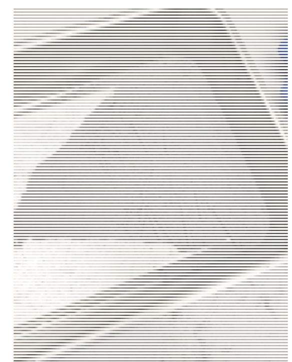
Sample Part: Fuel Injector

- A sCO_2 injector design was used as a component level test part
- Was not fully cleaned, still in progress

Removal of support structures

Ultrasonic vibration, 0.082 lbs powder removed

PRS applied to the large orifices, 0.218 lbs powder removed



LN_2 and ultrasonic, 0.258 lbs powder removed

Conclusion

- The evaluation of powder removal methods has identified the most effective
- Design complexity and wall thickness can inhibit these methods

Testing Method	Results
Powder recovery system	Effective – external orifices
Ultrasonic	Effective
Vapor Blast	Ineffective
Ultrasonic & Hammering	Effective
Chemical testing	Ineffective
Nitrogen & Ultrasonic	Effective - Best

Future work

- Continue removing powder from the sCO_2 injector
- Fabricate Low-NO_X injector and apply effective powder removal methods

Acknowledgements

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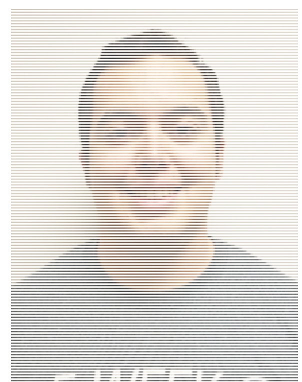
- Program Manager: Maria Reidpath

PI: Dr. Ahsan Choudhuri

Co-PI: Dr. Ryan Wicker

Manager: Philip Morton



UG student: David Saenz

Thank You
Questions?