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Energetic Materials Additive Manufacturing (EMAM) for CAD/PAD Applications

Presented to:

2022 CAD/PAD Technology Exchange

Presented by:

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Background

- Additive manufacturing (AM) is a prominent technology being developed and implemented throughout a wide range of industries and applications. However, it is currently underdeveloped for use with energetic materials.
- Therefore, a real need exists to study, develop, and adapt AM techniques to advance the manufacturing capabilities of Navy and Air Force critical solid propellants.
- Propellant grains used for CAD/PAD application have strict specifications and requirements to ensure only consistent and reliable grains are used. The traditional manufacturing method struggles to maintain the consistency necessary to meet these high standards, resulting in low production yield of usable propellant grains due to the form anomalies and large ballistic variability.
- By applying the precision and repeatability of AM processes to the production of propellant grains, we hope to meet the manufacturing consistency required for the strict reliability and system performances of CAD/PAD applications.

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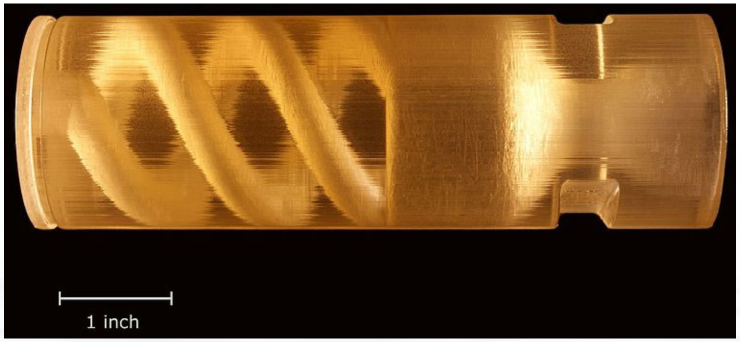
Potential for AM Energetic Materials

- No longer bound by traditional form factors
  - Ability to pursue complex structures that could not be previously produced, including internal structures
- Use of novel materials and formulations
  - Explore the use of more efficient energetic materials, change performance of energetics used as desired (gradients, blends, etc.)
- Different workflow from traditional manufacturing
  - Quick turnaround on QC issues
  - Safe remote production
  - Economically sound low volume production
- Works to supplement traditional manufacturing
  - Fill gaps in production as needed
  - Use in tandem with traditional manufacturing
  - Use in production of only certain parts



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IHD EMAM Team Expertise and Resources

Personnel:

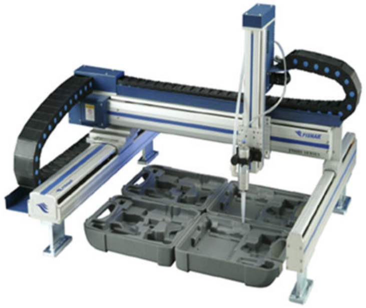
- 6-member team with Chemical Engineering, Mechanical Engineering, and Chemistry experience.

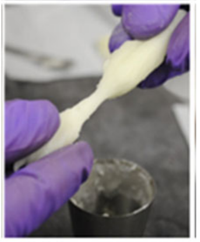
AM Techniques:

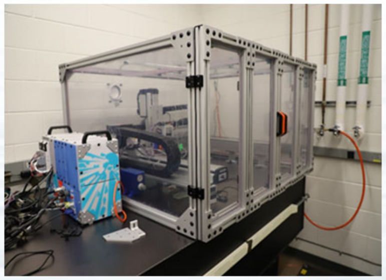
- Formulations
- RAM mixing
- Programming
- Design of Experiments
- Data Collection and Analysis

Facilities and Equipment:

- 3D printing lab and storage vaults
- Three 3D Printers
- Webcams and live data collection software for continuous monitoring of the printing process
- Inert simulant material for convenient testing of new materials/geometries
- A temperature and humidity-controlled enclosure box







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AM Feasibility: HES 5808

Hercules Experimental Smokeless (HES) 5808

- HES 5808 is a composite propellant used in a variety of CAD applications for aircrew escape systems.
- The traditional manufacturing method for HES 5808 is to mix the ingredients with solvent to form a malleable dough, extrude it into gun-type propellant grains, then dry to remove the excess solvent and moisture.
- This traditional manufacturing method suffers from a high rejection rate due to physical anomalies such as cracking, curved grains, and dilated/collapsed perforations.
- HES 5808 propellant formulation was chosen for an initial AM feasibility study due to its simple formulation, which could be adjusted for AM use without deviating from its formulation requirements, as well as its relative low sensitivity to friction, impact, and static discharge.

Vertical and Horizontal Cross Sections of Some HES 5808 Propellant Grains

Photo credits: NSWC IHD, Systems Engineering Department

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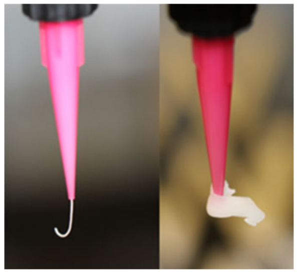
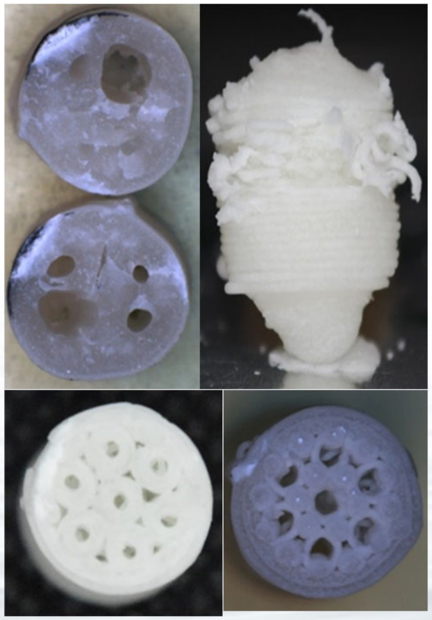
HES 5808 Printing: Important Considerations

- The printer must be precise enough to provide the necessary resolution for the propellant grain features, including the 0.33 mm-diameter holes.
- Devices and processes must be implemented to control environmental factors such as temperature and humidity, which directly interfere with material extrusion and drying processes, over the course of the year.
- An optimal tool path must be generated to guarantee the proper line spacing, gap fill, and layer height needed to properly fill-in the grain without clogging the perforations.
- The HES 5808 formulation must be formulated, stored, and printed in a manner that prevents the formation of clumps that could clog the small (0.25 mm) nozzle.
- The material formulation must have the correct amount of solvent in order maintain its structure through the printing and drying process.





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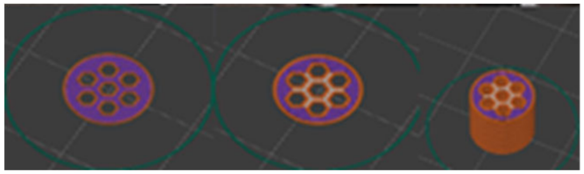
HES 5808 Printing Components

- Hardware

- Software



- Formulation

Photo credits: NSWC IHD, Systems Engineering Department

Hardware: Fisnar F9000N Printer

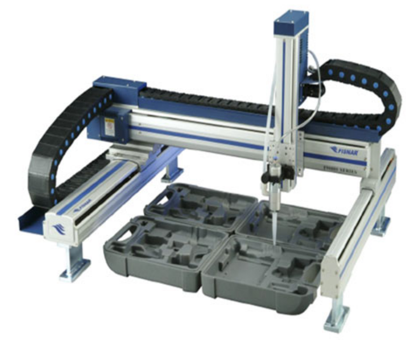
<u>Hardware Development</u>

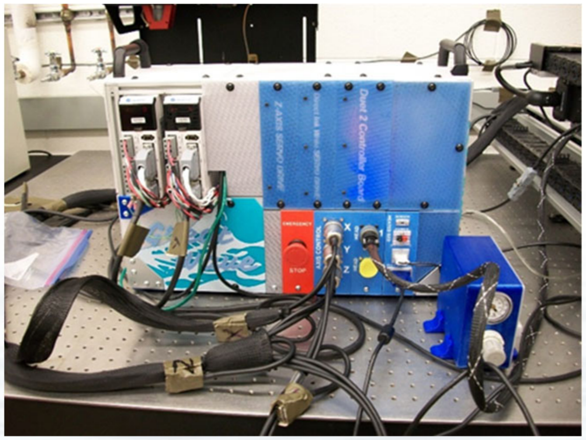
- Fisnar F9000N – COTS gantry robot originally intended for in-line industrial automation for large paste dispensing such as solder, lubricants, epoxy, etc.

- The machine's controller box was completely replaced with open-source AM hardware to allow for more precise tool pathing, adjustable dispense rate, in situ analysis, and the use of additional software, such as Duet3D/RepRap.

- The extrusion head was completed redesigned to be powered by a DC motor in order to handle materials with heavy solid loadings, such as energetic materials.

- A pneumatic press pushes the energetic material out of the syringe and into an auger, which in turn is able to extrude the material through nozzles of 0.41, 0.25, and 0.20 mm in diameter.





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Hardware: B9Creator and EPAX Printers

B9Creator (DLP Projection Stereolithography)

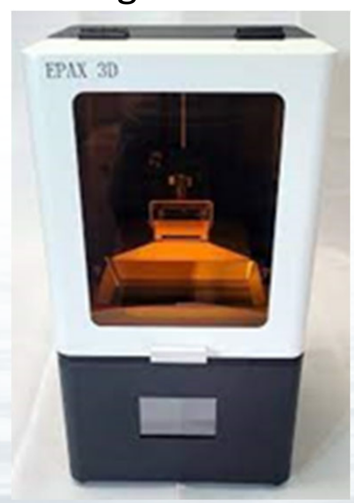
Commercial specifications:

- Modified projector cures entire x-section
- Builds UV sensitive resin layer-by-layer
- 104 x 75 x 203 mm build volume
- Z layer height min. 0.025 mm

EPAX X1-DJ

Commercial specifications:

- Dental Jewelry Resolution
- Light source closer to LCD screen
- 3.5-inch Color TFT Touchscreen
- 115 (L) x 65 (W) x 155 mm (H) build volume
- XY resolution ~ 0.047mm; Z layer height min. 0.01 mm
- 405 nm wavelength resins



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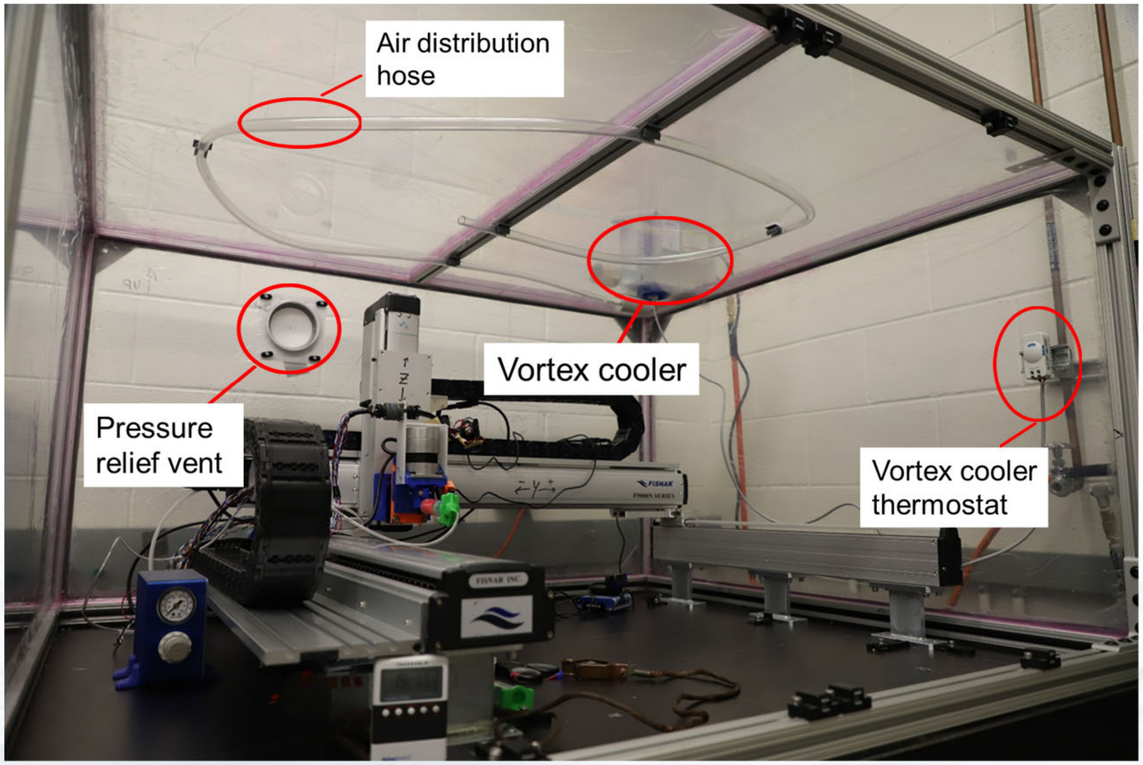
Hardware: Enclosure (cont'd)

- During previous printing campaigns, ambient temperature and humidity at extremes negatively influenced print quality.
- An enclosure was designed/constructed around the printer to control printing conditions.
- Enclosure is complete, ready for printing.
  - Control provided by vortex cooler – solid state, uses dried, filtered, pressurized house air to cool the entire enclosure.
  - Can set desired temperature using thermostat – electronically regulated.
  - Positive pressure system and pressure relief to ensure regular flow of dry air into enclosure.
  - Easy-to-open accordion doors to facilitate working on printer.



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Software: Slicer Settings

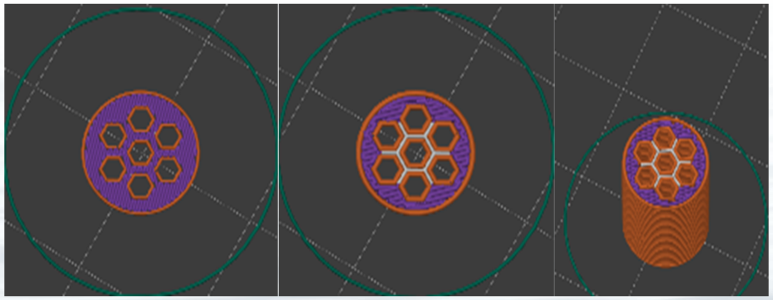
Printing parameters are important!

- Print parameters must be chosen carefully to maximize accuracy, object resolution, and repeatability.
  - Print head movement speed
  - Extrusion nozzle diameter
  - Extrusion rate and pressure
  - Choice of solvent(s)
  - Temperature and humidity

Photo credit: NSWC IHD, Systems Engineering Department

Printing Software is important!

- The printer slicer software will map the locations where the material is to be deposited.
  - Line spacing
  - Printer head line path
  - Optimal geometry
  - Gap fill
  - Layer height



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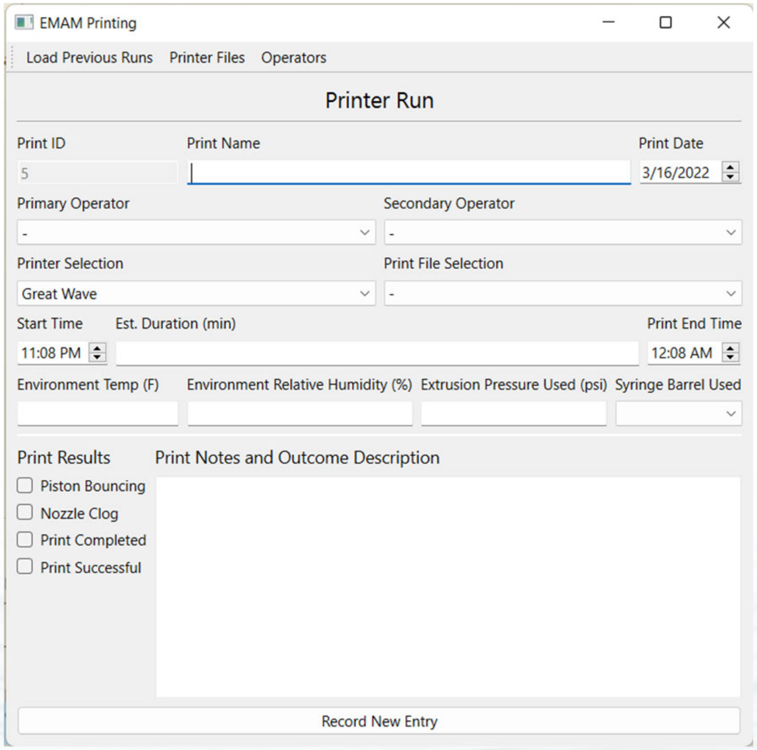
Software: Custom Data Intake Form

- Easy data collection form, relays data directly into Postgres database
- Print ID auto-increments
- Date & time initialize automatically



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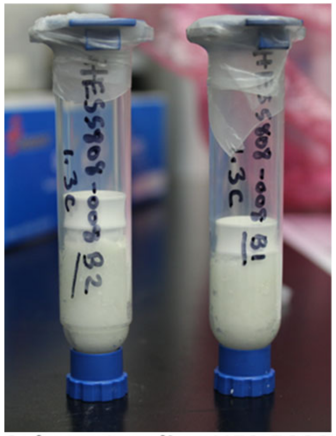
HES 5808 Formulation

<u>Energetic Feedstock Development</u>

- No changes were made to the original HES 5808 formulation. All the ingredients, composition, and processing solvents are identical to the traditional manufacturing method.
- The energetic feedstock is manufactured in a RAM mixer, which was found to be more suitable for AM applications due to its mix efficiency and consistency.
- The energetic feedstock is then loaded into syringes that is adapted to interface the AM gantry.
- Key parameters for the energetic feedstock development:
  - Mix homogeneity
  - Solvents loadings
  - Packing of HES 5808 inside the syringe (no bubbles)



Solvent Loading HES-5808

Photo credit: NSWC IHD, Systems Engineering Department

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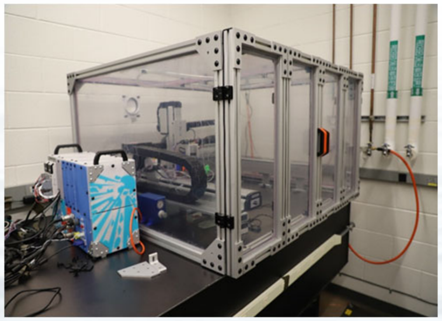
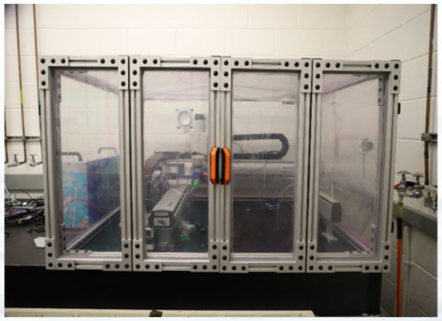
Achievements

- Developed the hardware, software, and formulations improvements necessary to achieve the resolution required to print HES 5808 propellant grains for CAD/PAD devices.
- Developed an inert simulant material to facilitate fast and easy testing of potential new materials and geometries.
- Demonstrated DLP printing of grain form-factors with COTS resins, currently working on developing custom resins for use with energetic materials.
- Developed a printing parameter model to assist in the optimization of printing parameters.
- Developed methods for preparing the formulation ingredients that have improved both formulation consistency and print quality.
- Designed and constructed an enclosure box.





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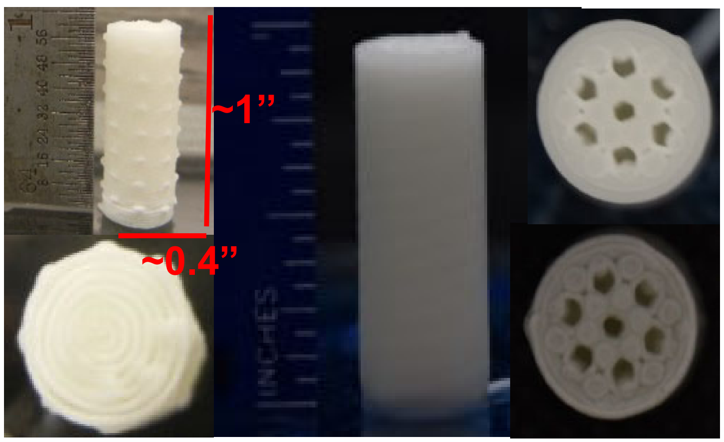
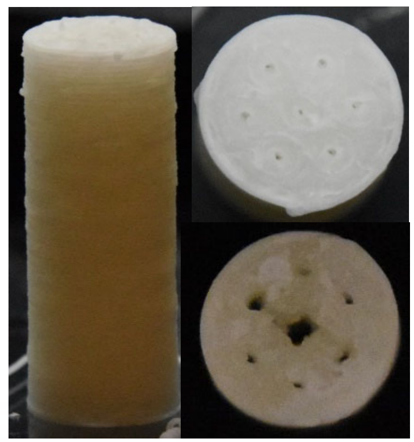
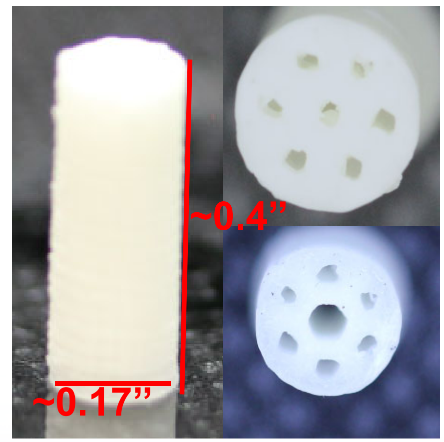
DIW Grain Development Over Time







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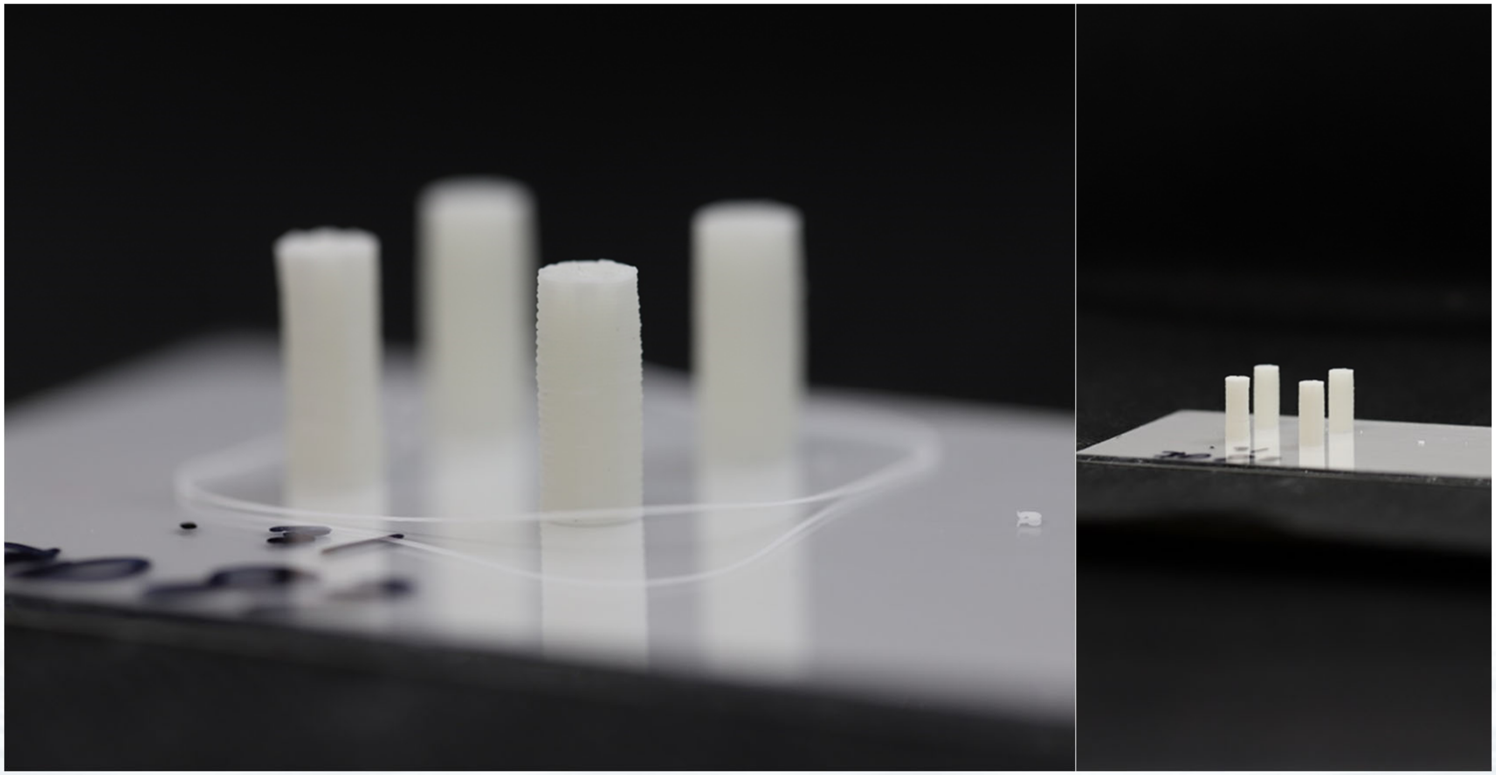
Printed Grains



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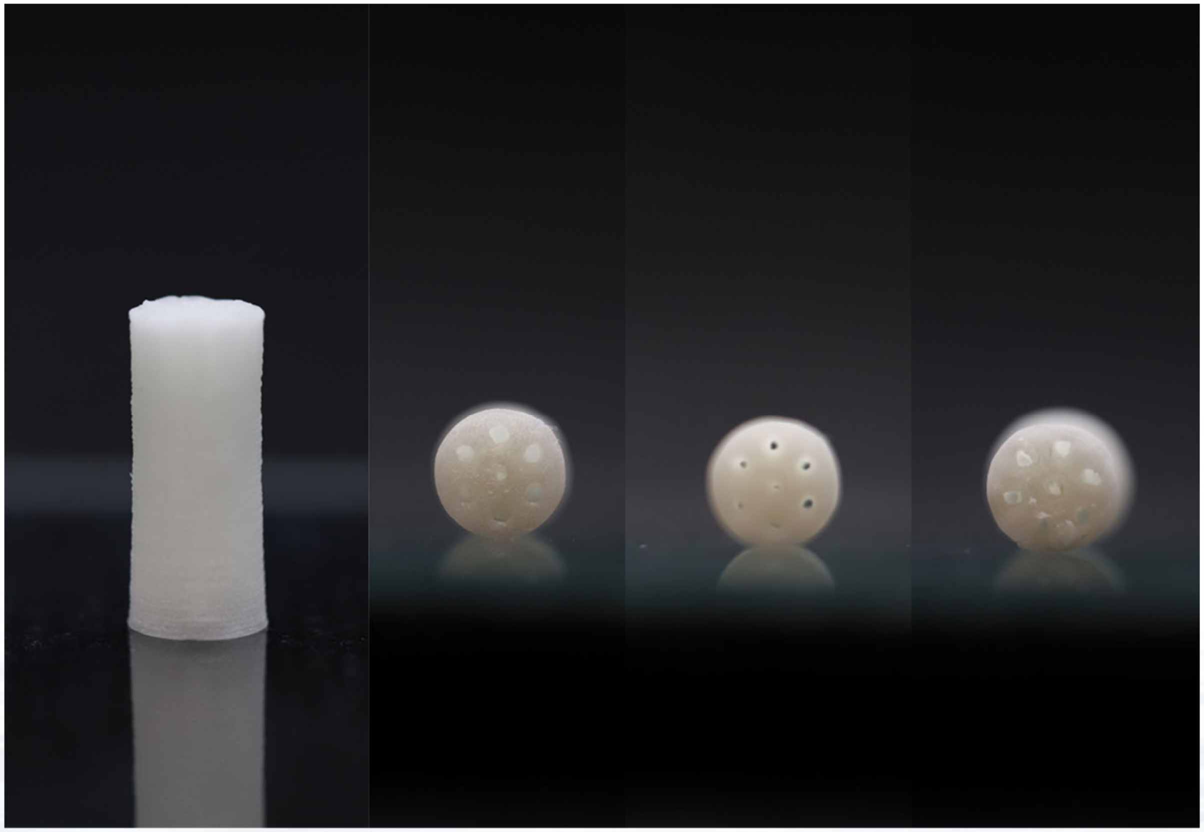
Printed Grains



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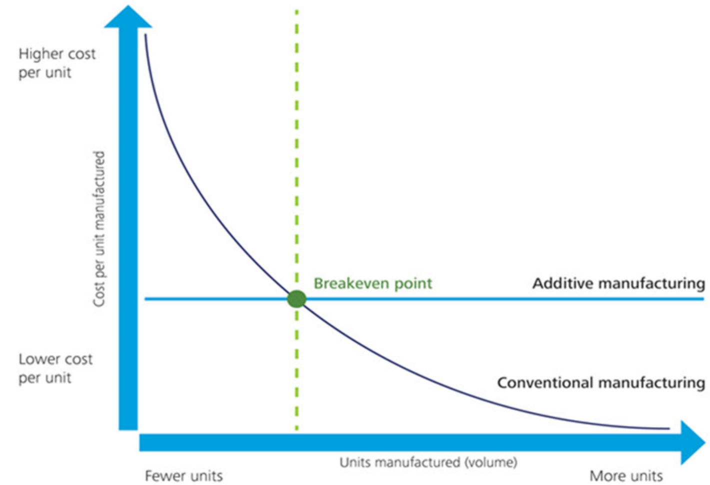
Path to Viability

- AM has been deployed throughout industry as an attractive technology for low-volume production of specialized parts for as-needed applications.

- As our AM manufacturing capacity improves, additive manufacturing of HES 5808 can become a suitable method of filling gaps in production from the traditional manufacturing process.

- The long-term potential payoff for the AM HES 5808 is the "layer-by-layer" precision that could provide a reliable and consistent propellant with predictable ballistic output, thus eliminating the need for the excessive ballistic tailoring and evaluation currently needed for the traditional propellant.

- Production capacity could be increased by implementing additional printers and extrusion heads. Other AM techniques, such as UV curing, can be explored to reduce the need for further processing such as extensive drying cycles.



Source: Mark Cotteleer and Jim Joyce, *3D opportunity: Additive manufacturing paths to performance, innovation, and growth*, Deloitte University Press, http://dupress.com/articles/dr14-3d-opportunity/, accessed March 17, 2015.

Next Steps

Top Level Milestones

- Upon successful completion of the R&D phase and Technology Maturity phase, the project team will submit the final formulation and technical information for the determination of the energetic material qualification requirements.
- After obtaining approval for material usage, the AM propellant shall be evaluated in the cartridge.
- If the AM propellant can meet the ballistic requirements, the appropriate design reviews will be conducted to ensure all technical requirements are met and generate the approval to use the AM HES 5808 in the application.

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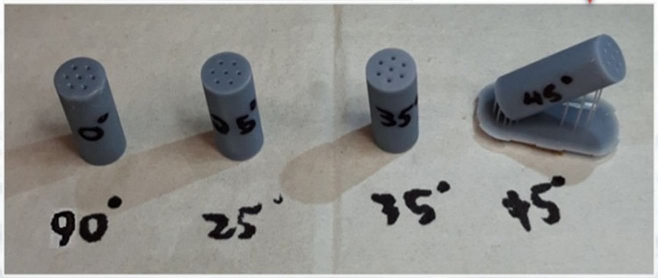
Other Methods for Improving EMAM AM Capabilities

- Investigation of additional AM methods for energetic printing, such as SLA (detailed in other presentation).
- Incorporation of in-situ monitoring to better understand materials during the printing process.
- Investigating and assessing the AM viability of existing and AM tailor-made energetic materials.
- Machine learning methods to assess and improve print quality.
- Investigating printing of novel geometry not capable of production via traditional methods.



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EMAM DIW Efforts for Printed Energetic Capabilities

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